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ANDERS BERGMAN

In situ Calibration of Voltage
Transformers on the Swedish
National Grid

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ABSTRACT

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Voltage transformers are used on high voltage power transmission systems to obtain a suitable level of input voltage for energy meters. The amount of electrical energy transmitted on the systems is very high and measuring errors may have substantial economic consequences.

In Sweden virtually all voltage transformers are capacitor voltage transformers (CVTs). Concern has been voiced both nationally and internationally regarding the stability of CVTs over time. Some previous studies have been made, but the number of studied objects were fairly low and the results are not indisputable. The knowledge of the actual performance of CVTs is therefore limited and it has been decided to calibrate *in situ* all voltage transformers on the 130 kV to 400 kV power networks in Sweden.

The design of a measuring system for *in situ* calibration is discussed and the total measuring uncertainty is estimated. The uncertainty analysis is based both on measurements and on theoretical considerations. The calibration results are shown to be traceable to national and international standards with a total uncertainty of $\pm 0.022\%$ for the voltage ratio and ± 0.9 mrad for the phase displacement. It is shown that, in contrast to popular belief, the voltage drop on substation high voltage busbars due to the load current contributes considerably to the total uncertainty.

The program for *in situ* calibrations has been in operation since 1989 and results have been obtained for 549 CVTs. The scale of this investigation is considerably wider than has hitherto been reported in the literature. An analysis of the results obtained show that the mean ratio error for the population of CVTs agrees well with the value expected at the installed burden. The mean value of the installed burden is 20 VA with a standard deviation of 13 VA. This is lower than the range of burdens that the CVTs are designed for, and the ratio errors measured are consequently close to the upper class limit. Phase displacements are inside the limits for an accuracy class of 0.2 for most units, including those with other accuracy classes. An analysis of the change in ratio error as a function of the year of manufacture shows a trend of 0.04% voltage ratio change per year of age for classes 0.5 and 0.6 whereas the trend for class 0.2 is negligible.

The failure rate for the CVTs is discussed, regarding excessive errors as a failure. The mean drift rate of the ratio error of CVTs is moderate or low, but the random change is substantial for all accuracy classes and is taken into account in the analysis of the failure rate. The mean time between failure is found to be 104 years for the population examined. It is suggested, based on the observed drift and failure rates, that the interval between calibrations on CVTs should be in the range 5 to 20 years.

The present practice of IEC 186 to verify voltage transformer accuracy for the range of 25% to 100% of rated burden is shown not to be consonant with the distribution of burden values in Swedish substations and the range 0-100% is suggested.

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Legend

NIST	National Institute of Standards and Technology, USA.
NBS	National Bureau of Standards, now renamed NIST, USA.
PTB	Physikalisch-Technische Bundesanstalt, Braunschweig, Germany.
EPRI	Electric Power Research Institute, USA.
SP	Swedish National Testing and Research Institute.
NUES 420	Mobile reference transformer rated at $396/\sqrt{3}$ kV to $110/\sqrt{3}$ V.
NUEO 400	In-house reference transformer rated at $396/\sqrt{3}$ kV to $110/\sqrt{3}$ V.
TAB	Transformer calibration bridge.
VM	Vector meter.
Instrument transformer	A transformer intended to transmit an information signal to measuring instruments and protective or control devices. [1]
CVT	Capacitor voltage transformer
Capacitor voltage transformer	A voltage transformer comprising a capacitor divider unit and an electromagnetic unit so designed and interconnected that the secondary voltage of the electromagnetic unit is substantially proportional to the primary voltage, and differs in phase from it by an angle which is approximately zero for an appropriate direction of the connections. [1]
Phase displacement	The difference in phase between the primary voltage and the secondary voltage vectors, the direction of the vectors being so chosen that the angle is zero for a perfect transformer. The phase displacement is said to be positive when the secondary voltage vector leads the primary voltage vector. It is usually expressed in minutes or centiradians. [2]
Accuracy class	A designation assigned to an instrument transformer the current (or voltage) error and phase displacement of which remain within specified limits under prescribed conditions of use. [1]
Class index	Conventional designation of an accuracy class by a number or a symbol. [3]
Complex error	The difference vector between the secondary voltage and the primary voltage transformed by the nominal ratio. Ratio error and phase displacement are expressed as a complex number.

In-phase error	The real part of the complex error.
Quadrature error	The imaginary component of the complex error.
Burden	(of an instrument transformer) The impedance of the secondary circuit. <i>Note.</i> - The burden is usually expressed as the apparent power absorbed by the secondary circuit at the rated secondary current (or voltage). [1] (of a voltage transformer) The admittance of the secondary circuit expressed in siemens and power factor (lagging or leading). <i>Note.</i> - The burden is usually expressed as the apparent power in volt-amperes at a specified power factor and at the rated secondary voltage. [2]
Installed burden	The total burden connected to the terminals of an instrument transformer in a substation.
Metering	The measurement of electrical energy for billing purposes.
Voltage make-up box	A set of terminal blocks intended for connection of the secondary terminals of a three-phase set of instrument transformers, housed in a weatherproof enclosure close to the set of instrument transformers.
Traceability	Property of the result of a measurement or the value of a standard whereby it can be related to stated references, usually national or international standards, through an unbroken chain of comparisons, all having stated uncertainties. [4]
Accuracy	(of measurement) closeness of the agreement between the result of a measurement and a true value of the measurand. [4]
Uncertainty	(of measurement) parameter, associated with the result of a measurement, that characterises the dispersion of the values that could reasonably be attributed to the measurand. [4]
ppm	parts per million.
g	an acceleration equal to 9.81 m/s^2 .
Compressed gas capacitor	A high stability capacitor insulated with gas under high pressure, normally of coaxial design.

1. Introduction

Measurement of the energy flow on power transmission lines must of necessity be made with the aid of instrument transformers to transform the actual currents and voltages to levels suitable for use in energy meters, i.e. up to a few A, and approximately 100 V. This transformation may be made with different degrees of accuracy, but as a result of many considerations, accuracy classes 0.6, 0.5, 0.3 or 0.2 have at different times been considered sufficient in Sweden. As a general trend, accuracy requirements have become more stringent in later years, with 0.2% accuracy being commonly required for metering purposes in Sweden since 1978.

The reason for the increasing requirement on the accuracy is traceable to the increasing focus on economics and to the insight that energy, and in particular electrical energy, is a scarce commodity that must be utilised as efficiently as possible. As a measure of the importance of economic considerations, the total metered energy on the Swedish main power transmission lines was over 30 000 million SEK in 1989. An imagined systematic measurement error of only 0.1% would correspond to 30 million SEK! More to the point is the case of a utility selling energy at one point of the network and buying at another. A systematic measuring error is here quite possible, and would lead to an unfair cost for either the network or for the utility. This cost would be deducted from the margin of profit and would be important for the economic result.

In Sweden almost all voltage transformers on the 400 kV national grid are capacitor voltage transformers, CVTs, some of them more than 30 years old. CVTs were chosen over inductive voltage transformers when the 400 kV network in Sweden was built. An important factor in this choice was the economic advantage of using the coupling capacitors, already needed for power line carrier communication systems, also for voltage measurement. Around 1985 concern regarding the accuracy and stability of especially the older capacitor voltage transformers led to the initiation of a project to calibrate voltage transformers *in situ* and with the normal operating voltage applied. As a result, the Swedish State Power Board, the Swedish National Testing and Research Institute and the utility Sydkraft co-operated in launching the project in 1988, with the first calibrations being made in 1989.

The task to integrate the newly purchased reference transformer, measuring bridge and instrument van into an efficient and accurate measuring system for the purpose of *in situ* calibration of voltage transformers was undertaken by SP in 1988, with the author as project leader. The task included specification of additional equipment, methods to achieve a suitable environment

for the instruments in the instrument van, screening for interference control, etc. The measuring procedures employed in the field were formulated and adapted by the author to the specific circumstances of the substations through discussions with all parties involved in the work. The procedures for the calibration of the measuring equipment were also formulated by the author.

Since 1992, the Swedish power network is owned by the Swedish National Grid, a network operator that provides network transmission capacity to the several producers and utilities using the network. This reorganisation, which is part of the present drive to introduce a free market in Sweden for electric energy, means that the transmitted energy on the National Grid may now be sold and bought many times between the producer and the end user, adding to the incentive for accurate measurement.

Besides the economic factors, there are technical advantages to being able to measure with precision. If the state of the network is accurately known, it is possible to utilise it more efficiently than otherwise by minimising transfer losses through adjustment of the node voltages of the network to obtain an optimum load distribution on the network. The stability of the power network in the case of a sudden loss of a large load, is another concern where increased accuracy is beneficial. The stability to sudden load loss is mainly influenced by the power lost, the load on the remaining network and on the short-circuit impedance of the network. Economic considerations show that there is a trade-off between the risk for load loss induced instability and the transmitted power. The uncertainty of the power measurement is one of the factors in the evaluation of the stability margin of the network.

There are also other factors that must be evaluated to establish the permissible load. For example both snow storms and lightning storms increase the risk for ground faults on the network and must be taken into account. Inclement weather may necessitate changes in the operating conditions of the network, such as reducing the power flow into afflicted areas. Actions associated with snow storms must be based mainly on meteorological forecasts. Lightning can however be localised by measurements of its electromagnetic field. In Sweden there is a fully automatic lightning localisation system that covers all of Sweden. The system is used on-line by the operator of the network in order to decrease the consequences of lightning flash outages. The system is also used to determine if personnel can be permitted to work on, or close to, substation high voltage equipment. It is, as a matter of course, used by the Power Control Authority of the Swedish National Grid during the *in situ* calibration work to determine if lightning is so close to the calibration site that the operations must cease for safety reasons.

The calibrations of voltage transformers *in situ* are made with the normal operating voltage applied and under severe ambient conditions both as regards atmospheric conditions and as regards electrical environment. Special measures are needed to assure stability of the calibration system and to ensure control of interference. Much effort has been extended to ensure this goal. In fact, when all influence factors have been taken into account, the estimated accuracy in the calibration system is equal to, or even exceeds, the capabilities of many production testing facilities for voltage transformers.

Two very skilled engineers have been included in the *in situ* work team from SP on a full time basis since 1988 to ensure the continuity and knowledge required for the work. They both work directly under the author with the calibrations in the field.

The scale of the work seems to be internationally unique, with a long-term goal to calibrate all voltage transformers used on the 400 kV and 220 kV networks and also most of those on the 130 kV network, in total of the order of 1200 transformers. At the time of writing of this thesis the work had progressed to 549 calibrated CVTs. A small number, 24 units, of inductive voltage transformers had also been calibrated. The number of CVTs calibrated in the Swedish calibration project reported here exceeds by far that of other investigations known by the author. Very important is also that the units calibrated represent the full number of CVTs installed in each substation, i.e. there is no bias in the results due to a previous selection process. The results obtained are thus representative for the population of voltage transformers in Sweden.

Although the measuring equipment is very accurate, it does produce a small error. The error of the equipment in a controlled environment is known through calibrations traceable to national and international standards. The field measuring equipment is, with the exception of the reference transformer and the measuring cables, used in a controlled environment. During the course of the measuring season, the reference transformer is subjected to a variety of electrical and environmental conditions, which may induce new errors in the measurements. Interference from the high voltage circuit may also introduce errors. All measuring equipment included in the mobile system is calibrated before and after each measurement season (April through October) by comparison against reference standards at SP in Borås. Specifically, the mobile reference transformer is compared with a reference transformer stationed at SP in Borås.

Previous international experience of *in situ* calibrations has shown that extraneous influences often distort the results, sometimes severely. A

comprehensive study of the uncertainty of the measuring system is therefore essential for the credibility of the calibrations. This paper presents a detailed analysis of the measuring system as regards both the uncertainty of the measuring system itself as well as other possible sources of errors. An evaluation of the total measuring uncertainty is included and serves as the basis for the estimate of the uncertainty for the field calibrations.

A review is made of previous international experience of both *in situ* calibrations of voltage transformers and of the performance of capacitor voltage transformers in the field. The metrological background for the Swedish system is briefly introduced with a discussion of SP as the National Measurement Institute for Sweden.

To achieve good calibrations in the field, a thorough control of extraneous parameters that may influence the measurement is necessary. The concept for the measuring system and the components used is introduced in Chapter 3. Interference suppression and transient protection are of central interest and are discussed in detail. Included in the interference suppression philosophy is the power supply to the instruments. The power supply is designed to provide a high degree of interference suppression.

The circumstances under which the calibration results are gathered are important for the evaluation of the performance of the voltage transformers in the field. The procedures followed during the calibrations in the field are described in Chapter 4.

The error of an instrument transformer may be defined in a polar form or in a Cartesian form. The definition used in IEC 186 [2] of the error of an instrument transformer is in the polar form, whereas the operating principle of most instruments used to measure the errors provides a reading in the Cartesian form. The analysis in Chapter 5 shows that the difference is small for reasonable values of the errors.

The phase displacement of an instrument transformer is usually expressed in minutes or in a suitable fraction of radians. In the present paper mrad will be consistently used, but, as a courtesy to the reader, the corresponding value expressed in minutes will in most cases be given in parentheses. Where sources have given results in minutes, these have been consistently converted to mrad with the original value in parentheses.

Treatment of uncertainties must be made in a systematic and recognised manner. The method recommended by Working Group 3 of the Technical Advisory Group on Metrology (TAG 4) of the International Organization for Standardization (ISO) is introduced in Chapter 6 for later use in the Thesis.

The detailed analyses in Chapters 7 through 11 of the uncertainty in the calibrations include not only the customary contributions from the reference transformer and measuring instruments but also the contributions from the measuring cable and the effect of long distances in the substation between the connection points for the reference transformer and the test object. In fact the analysis shows that the voltage drop due to load current on the high voltage busbars may be one of the dominating contributions to uncertainty.

The history and general characteristics of the capacitor voltage transformer are introduced in Chapter 12 as background for the analysis of the results obtained in the *in situ* calibrations.

The stability and life expectancy of capacitor voltage transformers have been a question of certain debate. The results of the *in situ* calibrations are discussed in Chapter 13 and an evaluation of the stability is made for the entire population of voltage transformers as well as for sub-populations. The failure rate is discussed with the aid of tentative criteria for failure based on non-acceptable ratio errors. The results obtained, form an important back-ground information for the formulation of the rules and regulations for the coming free market for electric energy in Sweden. Traceability of energy measurements and accuracy requirements are expected to be very important aspects of the rules for the market.

The possible correlation between the ambient temperature, the solar irradiation and the phase position of the CVT is analysed for class 0.2 CVTs to determine the possible influence of these parameters on the results of the calibrations.

Constraints in connections between CVT and the measurement circuit often will introduce additional resistance in the measuring circuit, leading to measuring errors. The author has chosen to evaluate the stability of CVTs for zero burden in order to obtain results valid at the terminals of the CVT. Because of the constraints it is not possible to determine if a CVT is within its class for its burden range and evaluations relating to compliance with accuracy class limits have been omitted. The measuring error valid in the control house will be different due to voltage drop caused by the burden current in the cables from the CVT to the control house. Evaluation of the measuring error in the control house has not been part of the work reported here, but it may be assumed that the influence is moderate with regard to the burdens found and to the cross section and length of cables.

A general discussion of important side issues is given in Chapters 14 through 16. Included in this is the behaviour of the measuring system for non-standard operating conditions, i.e. harmonics and transients, are, as well as views

on safety in this type of high voltage work. A few non-trivial problems have been encountered during the work. These are discussed and the impact on the measurements is stated.

In conclusion, the feasibility of *in situ* calibrations is discussed and possible impact of the results on standards is shown. The stability for the capacitor voltage transformers *in situ* has been determined for a large population and the results can be used to determine suitable repetition intervals between calibrations.

2. Calibration of measuring systems on high voltage networks

2.1. International experience

2.1.1. Measuring systems

Systems for *in situ* calibration have been reported among others by Hillhouse, Petersons and Sze [5], Povey [6], Dooher and Davis [7] and Iwanusiw [8] [9].

Hillhouse, Petersons and Sze used a capacitive voltage divider and a current comparator to calibrate the CVT. Their system is also known as the EPRI-NBS Field Calibration System. The capacitive voltage divider was calibrated against a compressed gas capacitor on site and immediately prior to the calibration of the CVT. The method is cumbersome but the accuracy was good with a total estimated uncertainty of $\pm 0.021\%$ for the voltage ratio and ± 0.3 mrad for the phase displacement, as related to the measuring equipment itself. Effects due to external influences in the substation, such as voltage drops along busbars, were not discussed. The possibility of induced currents in the low voltage part of the measuring circuit was not discussed and the published information does not permit an evaluation of the possible influence on the uncertainty of the calibration. The results obtained in the Waugh Chapel substation are however reminiscent of the author's experience with the Swedish measuring system when interference has been present in the low voltage circuit. Similar problems were also reported for calibrations performed in the Willow Glen substation, and will be discussed further in the next section where it will be shown that the influence may have been as large as 1% for the voltage ratio and 10 mrad for the phase displacement. In further publications [10] [11], Hillhouse stated the measuring uncertainty to be $\pm 0.1\%$ for the voltage ratio and ± 0.3 mrad for the phase displacement. No explanation was given why the estimate for the uncertainty in ratio error had been increased by a factor 5 but it is surmised that the new figures pertain to the total calibration situation in the field and that certain problems with interference discussed in [13] may have prompted the use of higher figures. Hillhouse [12] also reported problems encountered with charges trapped in the low voltage arm of the measuring system in conjunction with high voltage switching operations. The trapped charges gave a residual d.c. voltage on the low voltage arm of the capacitive voltage divider, changing the capacitance of the low voltage arm. The estimated influence on the calibration results was small and could not explain the large variations seen for Waugh Chapel and Willow Glen substations.

Povey proposed the use of any convenient nearby bushing capacitive tap to establish a reference capacitive divider. This divider was calibrated at low voltage against a resistive divider. This ratio was then used for the high voltage calibration. Povey estimated the uncertainty to be better than $\pm 0.1\%$ for the voltage ratio and ± 0.87 mrad (± 3 minutes) for the phase displacement. He did not consider the possible effects on ratio of the reference capacitive divider due to increased voltage, and his assumption that the ratio is the same at low and high voltage is not supported.

Dooher and Davis used an oil insulated inductive voltage transformer together with a voltage transformer comparator for the calibration of CVTs. The transformer was mounted on a truck and equipped with a hydraulic system to raise and lower it from the reclining to erect position at site. The total uncertainty for the measuring system itself was estimated to be better than $\pm 0.06\%$ for the voltage ratio and ± 0.87 mrad (± 3 minutes) for the phase displacement. On-site tests were performed and indicated that the uncertainty estimates were relevant. No discussion of site-specific effects was included.

Iwanusiw discussed a system employed on a regular basis to calibrate capacitor voltage transformers on the Ontario Hydro 230 kV network. The measuring system used a truck-mounted standard capacitor, a low voltage auxiliary capacitor and a capacitance bridge to measure the voltage ratio and phase displacements. The measuring uncertainty was not discussed. The measurement scheme was based on eight measurements with different extra burdens applied to the capacitor voltage transformer. The errors at installed burden, at zero burden and at standard burden could then be calculated from the results. The system had proved to be a useful tool to either verify proper operation of the capacitor voltage transformer or to pinpoint error sources.

2.1.2. Results obtained for installed CVTs

The extensive use of capacitor voltage transformers on the power network, as is the case in Sweden, is found only in a few countries in Western Europe. For example in Germany most voltage transformers are of the inductive type.

Whether or not the limited use of CVTs for revenue metering is the cause, little information has been published on the performance of CVTs in the field. A literature search for papers discussing the performance of CVTs *in situ* during the last 15 years disclosed only a few major contributions, most of them reported at a workshop organised in 1983 by EPRI in Gaithersburg, USA.

Hillhouse [10] gives an overview of the results obtained with the EPRI-NBS Field Calibration (Prototype) System. It has been used for the calibration of a total of 61 CVTs in six different substations in USA. Some of the substations were visited more than once to clarify dubious results. The majority of the CVTs,

51 units, was intended for metering purposes and had an accuracy class of 0.3 in accordance with ANSI C57.13. Of the 61 CVTs calibrated, 39 were calibrated in the control room with the installed burden connected. Of these 39, approximately half were within their class limits.

The results obtained for the Waugh Chapel 500 kV substation exhibit, as mentioned earlier, a large scatter of the results in a pattern that resembles the pattern obtained when there is a common-mode interference voltage added as an error voltage to all three phases. The results suggest that the interference could be as large as 1% in the ratio or 10 mrad in the phase displacement. This interpretation of the results in Waugh Chapel must however remain unsupported since no further data have been reported. Another publication [13] does however address such problems with common mode interference voltage with the NBS system in the Willow Glen substation.

In the Brighton 500 kV substation six newly installed metering class (0.3) inductive cascade voltage transformers were calibrated at zero burden. Factory calibrations on these units agreed excellently with the field results, the difference was less than 0.02%.

At the Eddystone 230 kV substation ten CVTs for protection purposes were calibrated and found to be within the relaying class for low burdens (<50 VA). Three metering inductive voltage transformers were also calibrated and found to be within tolerance limits.

In the Willow Glen 500 kV substation three calibrations were performed at intervals close to one year. Substantial changes were found that could not be accounted for other than by actual changes in the CVTs themselves. A further report discussing the three calibrations is however available [13]. The conclusion drawn in this report is that there probably was a common bias voltage of approximately 0.3 V present on all three phases per bay in the first set of measurements. Such a voltage added vectorially to the respective phase voltages will give rise to unequal ratio error changes and phase displacement changes for all three phases. The ratio error corresponding to this voltage is approximately 0.5% and for the phase displacement it would be 5 mrad. The surmised bias voltage is thus far larger than the estimated uncertainty of $\pm 0.1\%$ and this casts serious doubts on the validity of the calibration results. A thorough theoretical and experimental review could not identify a probable source for this bias voltage and the doubts regarding the reliability of the data obtained could not be wholly relieved.

In the Juniata 500 kV substation all data were obtained in the control room with installed burdens. Most of the data points obtained were within the accuracy class for protection specified for the CVTs.

Both Hillhouse [10] and Hendricks [¹⁴] report the results obtained in Doubs and Eastalco 500 kV and 230 kV substations with the EPRI-NBS system. Out of a total of 24 CVTs calibrated, seven were out of their accuracy class and were subsequently replaced. One of the units was afterward subjected to a factory re-calibration that agreed favourably with the field results. Hendricks raised the question of a possible error from the voltage drop due to the flow of load current on the bus conductors and estimated the maximum uncertainty as 0.7 mrad (2.4 min). No appreciable uncertainty contribution from this effect was foreseen for the voltage ratio.

Lucas [¹⁵] shows the results obtained for 17 capacitor voltage transformers returned to the factory for servicing or repairs. Thirteen of these were deemed to be very stable whereas the other four had various errors up to 2 %. The sample is however not representative since the CVTs were returned to the factory for repairs due to observed damage or malfunction.

The accumulated results obtained with the EPRI-NBS Field Calibration System include a large number of units that were found to be out of their accuracy class. The results can be construed to imply that capacitor voltage transformers are not sufficiently stable to warrant their use in circuits for revenue metering. The unrelieved doubts regarding the accuracy of the results do however strongly underline the importance of verification of the accuracy, stability and lack of susceptibility to interference of the measuring system used.

2.2. Organisation

The *in situ* calibrations are being performed as a joint venture of the Swedish National Grid, Vattenfall Utveckling and The Swedish National Testing and Research Institute (SP), with the two latter performing the work on behalf of the Swedish National Grid. The Swedish National Grid is owner and operator of the power networks from 130 kV and up.

2.2.1. Safety and planning

Planning of measurement activities and contacts with operational personnel responsible for the switchyard in which the calibrations are to be done, are handled by Vattenfall Utveckling, formerly a subsidiary organisation of the former Swedish State Power Board, now reorganised as a company under the name Vattenfall Engineering.

Vattenfall Utveckling is responsible for the safety of all personnel involved in the calibrations. They handle the practical details of contact with local personnel regarding both practical aspects of the work in the substations

and the formal matters of acquiring the permits required to perform work on the substation.

The Swedish National Testing and Research Institute (SP), on the other hand, is responsible for the quality of the measurements and for maintaining traceability of calibration. One man from Vattenfall Utveckling, together with one man from SP, form the work team travelling with the mobile calibration system.

2.2.2. Measurement quality

All measurements involved in the field calibrations of CVTs are performed by the expert staff from the high voltage laboratory at the SP in order to guarantee the quality and accuracy of the measurements. The author of this thesis is head of the high voltage laboratory at SP since 1988 and is also responsible for the *in situ* measurements.

SP is, among other duties, the National Measurement Institute for electrical quantities in Sweden and provides the basic calibration services for Sweden. As a National Measurement Institute SP also maintains the basic units for the electrical quantities.

The d.c. voltage is maintained with a group of Weston cells, which are regularly calibrated with the Josephson effect. The uncertainty of the maintained unit for voltage is better than ± 0.00001 %.

The unit for resistance is maintained by means of a group of 1 ohm Thomas resistors regularly calibrated with the Quantized Hall effect. The uncertainty in the maintained unit for resistance is better than ± 0.00002 %.

The unit for a.c. voltage is maintained by calibration of precision a.c. voltage sources with multi-junction thermal converters. The uncertainty of the maintained unit for a.c. voltage is better than ± 0.0002 % at 1 kHz and 1 V.

For the calibration of voltage transformers, SP maintains several reference transformers. Two of these reference transformers are rated for a maximum a.c. system voltage of 400 kV. Both transformers have been calibrated at Physikalisch-Technische Bundesanstalt (PTB) in Braunschweig, Germany with an uncertainty of ± 0.003 % for the voltage ratio and ± 0.03 mrad (± 0.1 minutes) for the phase displacement. One transformer is used in the mobile calibration set and is calibrated at SP in spring, prior to the field measurements and in the autumn after the field measurements. The calibration is carried out as a comparison with the other transformer, which is permanently stationed at the high voltage laboratory at SP. The calibration is further augmented by intercomparing all standard transformers at SP in a chain starting at 100V/100V and up to the highest levels and verifying that all transformers are stable.

2.3. Future trends

The price for electrical energy will, as judged by most observers, continue to increase. This will maintain and even augment the interest for accurate energy measurements.

The former Swedish State Power Board has recently been re-organised into several independent organisations. One consequence is that the national power network is now owned by a governmental body, The Swedish National Grid, whereas the organisation that handles energy production and final distribution has been retained in the hands of the state owned limited company Vattenfall. Vattenfall is the largest of several companies transmitting energy on the network. Pricing of energy transmission is based on energy transmitted and this leads to a natural increase in the interest for correct metering on the network, an interest that is shared equally by all parties.

A free market for electric energy is presently being introduced in Sweden and will require that the transmission systems for electric energy are available to all operators on the network. Billing of energy will take place at all connection points and there will be a need for accurate and indisputable measurement of the energy transmitted at these points. It is foreseen that there will be a need for a program to verify the accuracy of the energy measurement on a periodic basis in order to satisfy the requirements posed by the free market.

In recent years there has been a dramatic increase in the number of thyristor converters and other equipment injecting harmonic currents on the power networks, mainly the networks for lower voltages. This trend is not peculiar to Sweden but represents a world-wide trend. Due to the high short-circuit power of modern power networks, the resulting voltage harmonics are moderate. The harmonic currents cause power losses in the network and may also interfere with the operation of other equipment. Electric power distributors have an interest to reduce the harmonic currents on their networks and are currently discussing remedies like prohibiting the injection of current harmonics, or applying cost penalties to them. A need for accurate measurement of the harmonic currents, as well as both active and of reactive power in the presence of harmonics, is therefore foreseen for the near future. Among many other uncertainties for such measurements, the accuracy of the current and voltage transformers is largely unknown at frequencies other than the fundamental. The response of these transformers to harmonics and the response of the energy meters is certainly a matter of interest for the future.

3. Description of the measuring system

3.1. General

The ambition for highly accurate measurements was established early in the preparative stages for the *in situ* measurement project. In order to realise this ambition it is necessary to make a careful choice of measurement method, ratio standard and measuring instruments and to control the environment for the measurements.

The principle adopted for the Swedish calibration system is similar to the system used by Dooher and Davis [7]. It is based on the use of a multiple-ratio inductive reference transformer against which the output voltage of the object under test is compared. The voltage comparison between the reference transformer and the object under test is made by means of an automatic transformer calibration bridge with a computer interface used for readout of data. For the rare case that the ratio of the object under test cannot be matched by the reference transformer, a six decade precision inductive voltage divider is employed as matching element.

The reference transformer is mounted on a flat bed lorry wagon that serves as a moving platform for the transformer. This mobile transformer is designed for a highest system voltage of 420 kV and has a rated lightning impulse withstand voltage of 1425 kV and a power frequency withstand voltage of 630 kV.

Measurement of the burden on the object under test is made by measuring the consumed power with a vector meter operating at the fundamental of the power frequency. The burden is calculated as the power that would have been consumed at the rated secondary voltage.

The measuring equipment is housed in an air conditioned Mercedes van configured as a Faraday cage. Connections between the instrument van, the reference transformer and the object under test are made with special measuring cables. Auxiliary measuring equipment is available for the measurement of environmental conditions.

The Swedish system is intended for a systematic measurement of all voltage transformers on the Swedish National Grid. This necessitates that the results of the measurements must be reliable and that the measuring system should be easy to handle. This has been ensured by several means:

- calibrations of measuring equipment are directly traceable to national and international standards
- extensive interference control applied to measuring circuits and measuring equipment
- careful transient protection of measuring equipment

Figure 1. The instrument van in a substation

- routine checks for interference on the measurements
- automated system for the collection of measurement data
- manual routines to estimate the relevance of the results

All the measurements are referred to the voltage make-up box in the substation yard. There is one such box for each three-phase set of voltage transformers. The leads from each voltage transformer enter this box and there they connect to the cables running into the control room. The voltage make-up box allows disconnection of the voltage transformer in a safe and controlled manner from the control room load by opening links in the terminal blocks.

3.2. Mobile reference transformer

The mobile reference transformer is manufactured by Messwandlerbau GmbH in Bamberg, Germany. It is an SF₆ insulated inductive type transformer that is type designated NUES 420. The insulation medium SF₆ is sulphur hexa-fluoride, which has excellent properties as high voltage insulator. The SF₆ tank is a metal vessel with a capacitively graded bushing for the high voltage connection.

The accuracy class of the transformer is 0.02, but the stability of the voltage ratio of the transformer is approximately an order of magnitude better. The deviations from the nominal ratios of the transformer have been accurately determined in calibrations performed both at PTB and in-house at SP. The

uncertainty in the result is substantially decreased below the class limit by applying correction terms to the measured values.

Electrically, the NUES 420 is a cascade connection of two transformers, consisting of one main transformer in the SF₆ tank with a 1000:1 ratio and of a tapped intermediate dry type transformer in a separate hermetic metal vessel. The intermediate transformer also comprises components for ratio and phase displacement corrections for each ratio. The available ratios are (407, 396, 385, 220, 154 and 132)/√3 kV to 110/√3 V.

Figure 2. Simplified schematic diagram of the mobile reference transformer set

The induction in the transformer is kept well below the knee point in the magnetic characteristic of the core material. This choice ensures stability of the ratio as well as precluding any ferro-resonance since the inductance is almost voltage independent. Ferro-resonance may occur between a voltage dependent non-linear inductance and capacitances on the high voltage bus.

The high voltage bushing of the NUES 420 has a capacitively graded body enclosed in a fibre glass reinforced epoxy resin insulator. The insulator is covered on the outside with silicon rubber sheds to achieve a suitable creepage distance.

Due to the length of the bushing of the NUES 420, it must be transported in the prone position. The transformer is attached to a heavy metal frame with a pivot and a hydraulic cylinder. With the aid of these it can be raised from prone to vertical. The transformer can be mechanically locked in position at every 15 degrees of arc from 30 to 90 degrees. Also on the frame is a gas refilling system used to fill the transformer to operating pressure with SF₆ before applying voltage, and to evacuate it to a pressure slightly above atmospheric, before moving either the wagon or changing the tilt of the transformer.

The flat bed wagon is custom built for use with the reference transformer. It is furnished with a tarpaulin hood that moves on rails to cover the wagon

Figure 3. The mobile reference transformer connected to the high voltage busbar

completely for transportation or to a position forward of the flat bed for operation of the equipment. In order to achieve sufficient stability and to level the bed,

there are four hydraulic jacks permanently affixed to the wagon chassis. The jacks are of a type that block the outlet in the unlikely event of a hydraulic oil pipe break, thus preventing the transformer from toppling.

The reference transformer is of a very sturdy design, but has anyhow been fitted with a seismic recorder that registers acceleration in three axes simultaneously. This record is made in preparation for the unlikely event of road damage to the reference transformer, in which case the record will make it possible to identify when the damage occurred. The recorder has a maximum scale of 5 g as compared to the stated maximum allowable acceleration of 15 g. During the time this recorder has been in operation there have been a few occasions with registrations approaching but not exceeding 5 g. Such peaks are however quite rare, and it is uncommon to see peaks above 2 g for a transport on roads of normal standard.

3.3. Instrument van

The instrument van is intended to provide a suitable environment for the measuring instruments as well as being a suitable work area for the personnel. The environment must be controlled both with respect to climate and with respect to electrical and magnetical interference.

The instrument van is built on a Mercedes Benz van chassis designed for a maximum total weight of 6.4 metric tons. The instrument area is located behind the driver's compartment and is completely surrounded by metal panels to form a complete Faraday cage with but a few concessions to practicality, three small windows, 0.5 by 0.3 m, and a sliding door where hinges and locking mechanism are used to obtain continuity of the shielding [16]. Behind the instrument compartment there is a small workshop area.

In the workshop area are also housed the heating, ventilation and air conditioning systems for the measurement compartment [17]. This system maintains the interior at 20 ± 3 °C under outdoor ambient conditions ranging from approximately -10 to +35 °C. At an ambient temperature lower than -10°C the interior temperature will vary more due to opening of the door, but with care it should be possible to perform measurements down to -20°C. Measurements are however normally not performed when the ambient temperature is below 0°C, due to load conditions on the power network.

Figure 5. Interior layout of the instrument van

The power supply to the instruments is provided via a three-phase, 11 kVA, isolation transformer with double screening between primary and secondary [18], [19]. For the power to the measuring instruments further filtering and transient protections is provided. The protective earth from the supply is not connected at the van and the secondary of the isolation transformer is instead connected to the van chassis. The van chassis is in turn earthed by a direct connection to the substation earth grid.

3.4. Instruments

The major instruments are the transformer calibration bridge, vector meter and variable burden complemented by a number of auxiliary instruments such as oscilloscope, multimeters etc. [20]. The transformer calibration bridge and the

vector meter are mounted in an instrument rack on a stable bench. The rack is mounted on helical stainless steel vibration dampers designed to operate as low-pass mechanical filters with a cut-off frequency substantially below the mechanical eigenfrequencies of the instruments. The TAB has been successfully tested in a vibration tester for withstand against vibration in accordance with IEC 68-2-36 Fdb with a spectrum 10 - 200 Hz, 0.01 g^2/Hz and 200 - 500 Hz, 0.003 g^2/Hz during 30 minutes in each major spatial axis. The intention of this test as specified in IEC is to ensure that the instrument will withstand normal vibrations in a vehicle on road.

3.4.1. Voltage transformer ratio calibration

The transformer calibration bridge is manufactured by Messwandlerbau GmbH, Bamberg, Germany and designated as type TAB. In the most sensitive range the uncertainty of the bridge is better than $\pm 0.003\%$ in the voltage ratio. The bridge measures the difference in the fundamental frequency voltage component between the object under test and the reference transformer in relation to the voltage from the reference transformer. The result is presented directly on displays as ratio error and phase displacement. All settings and measurement results of the TAB are available via an IEEE 488 data bus that is connected to a PC computer.

Figure 6. Block circuit diagram for the mobile calibration system shown for CVT error measurement

Important features of the mobile measuring system are indicated in figure 6, which is drawn to show the circuit for the voltage transformer calibration. The connections for the double screened measuring cable are shown. The earth point of the measuring system is referred only to the earth point of the tested voltage transformer, here shown as a capacitor voltage transformer - a CVT. The interconnections between instruments are shown with the exception of an IEEE data bus between measuring bridge and vector meter. The connection of the IEEE data bus between computer and measuring instruments is via an optical link. The measuring system is thus realised with an unambiguous earth point with a minimum of extraneous signal paths for interference.

The connection between the variable burden and the CVT is made with a separate conductor pair in the measuring cable. This scheme provides a screened connection of the variable burden without compromising the integrity of the measuring circuit between CVT and the measuring bridge.

3.4.2. Measurement of the installed burden

The block circuit diagram for burden measurement is shown in figure 7. The vector meter is used to measure the output voltage of the CVT and the load current drawn by the substation equipment. The vector meter provides a direct measurement of the reference quantity (in this case the voltage) with the other quantity (in this case burden current) presented as in-phase and quadrature components. The absorbed apparent power and the power factor are calculated

Figure 7. Block circuit diagram for the mobile calibration system shown for measurement of the installed burden

from the readings obtained. The burden of a voltage transformer is usually expressed as the apparent power that would have been absorbed by the secondary circuit at rated voltage. The value obtained for the apparent power at the actual voltage is therefore normalised to the value that would have been obtained at the rated voltage.

The vector meter may also be used for the measurement of the burden imposed by the variable artificial burden on the CVT during the ratio calibration. This is accomplished by measuring the burden current in the lead connecting to the variable burden with a current clamp and by temporarily switching the voltage circuit from the object under test to the voltage input of the vector meter. This measurement is very valuable since the resistance of the cable connecting the variable burden to the object under test will be added to the impedance of the variable burden and may significantly change the value of the burden from the nominal.

3.4.3. Computer control

During the course of a measuring season a very large number of measurements will be gathered and the work will often be performed under time constraints. There will furthermore be minimal chances of repeating a false measurement at a later date. An important part of the philosophy of measurement is to relieve the personnel of as many possibilities for mistakes as possible. This philosophy is realised by the incorporation of a computer control system into the measuring system.

Readout from the transformer calibration bridge (TAB) and from the vector meter (VM) is accomplished with a transportable PC computer. Measured data are collected in the computer and stored on the hard disk. The calibration record is printed on paper as a preview and a further copy is made on a floppy disk immediately after the measurement is finished. The final calibration certificate is printed at the home office from the floppy disk.

The computer program has been designed to be insensitive to mistakes by prompting for all parameters necessary and by refusing to accept impossible input data. Collection of data from the transformer calibration bridge and from the vector meter is accomplished via the IEEE 488 data bus. The IEEE bus is furnished with an optical fibre link to ensure total electrical isolation between computer and measuring equipment. A large effort has also been made to let the program handle all possible errors that can occur both as a consequence of operator mistakes as well as hardware and software errors. The main objective of the error handling implemented has been to avoid loss of important data.

3.4.4. Other registrations

Auxiliary instruments are used for registration of environmental parameters such as air temperature, pressure and humidity, solar heating and wind speed [²¹].

3.5. Measuring cable

The environment in a switchyard represents a severe environment both as regards interference and as regards climatic and mechanical stresses. No commercially available cables were found that were up to the standards required for the project where mechanical stability and screening requirements were regarded as paramount. A special cable was therefore designed and manufactured for use in the field calibrations [²²]. The cable is discussed separately in a later chapter.

3.6. Interference suppression

The measuring instruments require an environment reasonably free of interference and with a controlled climate to ensure reliable measurements.

The instrument van is a good Faraday cage with more than adequate screening for the present purpose. In the terminology used in IEC 801-4 [²³], the van interior should be conceived as a level 1 environment. The switchyard on the other hand is considered to be a level 4 environment. In order to achieve the level 1 interior environment, it is therefore essential to design and execute carefully the screening of the van and the filtering and over-voltage protection both on power and on signal conductors [18] .

In order to avoid interference on the signal conductors, all measuring cables are double screened, twisted pair cables. The twisting of the signal pairs ensures that the net coupling of magnetic interference is negligible. The use of double screening provides a means of having the outer screen connected at both ends, providing an extension of the Faraday cage up to the voltage transformers. The inner screen is connected at the instrument end only and acts as an electrostatic screen for the signal pair. The combined electrostatic screening of the two screens is excellent.

The active parts of the instruments are isolated from the van chassis. The system earth point is chosen as the earth point of the object under test, i.e. the CVT. The earth connection for the instruments is obtained via the measuring cable.

Measurement of the small currents (mA) in the twisted pairs of the measuring cables is performed with a clamp-on ampere-meter as a redundant daily routine to ensure that there are no interference currents in the measuring cables.

Figure 8. Screening and transient protection, conceptual diagram

Unwanted currents in the data bus (not shown in figure 8) are avoided by using an optical fibre interface between the computer and the measuring instruments.

The importance of the interference suppression can easily be understood by assuming a uniform interference current of 20 mA on the entire length of one of the signal conductors. With a cable length of 300 m the voltage drop would be 80 mV, a voltage that would be added to the normal signal voltage of 63.5 V ($110\text{V}/\sqrt{3}$). This voltage would correspond to 0.12% error! Avoiding interference is therefore essential to maintain the high reliability required of the measurements. Tests made in conjunction with the field measurements have shown that such a current magnitude is easily obtained with an unsuitable earthing scheme.

Routine checks of the current magnitude in the conductors at the entrance in the instrument van invariably indicate values less than 2 mA and most of the time less than 1 mA. These currents can be shown to arise from the capacitive coupling between the live conductor and the neutral conductor and screen in the cable and not from external sources. These capacitive currents are non-uniformly distributed over the cable length and the influence is therefore moderate. The exact influence of such currents is discussed later in conjunction with discussion of the measuring cables and their influence on the measurements.

3.7. Transient protection

Transient protection of the measuring equipment is required to avoid damage to the equipment. To a certain extent this goal coincides with the interference

suppression discussed above, but the main focus is on damage prevention. Placement of over-voltage limiting devices is shown in figure 8.

The connection point in the van for the measuring cable is furnished with over-voltage protection on both conductors in the signal pairs. The over-voltage protection consists of a varistor in parallel with a gas discharge tube.

There is also a varistor at one end of the reference transformer secondary winding connected between the winding and substation earth. This varistor is used to avoid high potential on the secondary winding when the object under test - the CVT- is not connected and earth reference for the measuring circuit therefore is missing.

The varistors used are standard types with energy absorption capacities of a few Joules and a maximum operating voltage of 110V rms. Varistors provide virtually instantaneous clamping of over-voltages. In order to protect the varistors in the event of a very high surge, and also to provide a backup protection in the event of a failure of the varistor, there is a parallel gas discharge tube with a rated ignition voltage higher than the limiting varistor voltage. The gas discharge tubes can absorb high continuous currents since the conduction takes place with very low voltage drop across the device, and are therefore suitable as backup devices.

The transients encountered in a switchyard can be substantial. An example given in the Swedish Standard SS 436 15 03 [²⁴] indicates that high voltages may occur in the switchyard due to switching operations and to earth faults. The transients reported are typically in the frequency range 0.1 to 10 MHz and the energy content is therefore moderate. Such cases are however often associated with oscillations in the network at the network resonance frequency, which is normally of the order of kHz. This oscillation gives rise to capacitive currents that cause potential rise of grounding points with respect to true earth. A voltage of more than 10 kV can easily be obtained in the earth point of a CVT with respect to true earth. The earth points of the CVT and of the instrument van are interconnected via the earth grid in the substation. Since the size of the earth grid is much smaller than the wavelength of the kHz oscillation, there will be no appreciable voltage drop between the two points and no stress on the over-voltage protection is foreseen for this mode of over-voltage.

The amplitude of the very high frequency oscillations also mentioned above is more difficult to estimate, but it seems safe to assume a voltage at the CVT ground point does not exceed 10 kV at 100 kHz. Assuming further that the signal cable is 100 m long with a purely inductive impedance of 1 $\mu\text{H}/\text{m}$ and that the duty cycle of the oscillation is 1% and continues for 2 periods of mains frequency, then the transferred charge into the varistor is 7 As. This gives an

energy dissipation that is above the withstand level for the metal oxide varistors used. The current is sufficiently large that the current will be commutated into the gas discharge tubes in line with the co-ordination of the protective devices. The gas discharge tubes have a very low arc voltage and the dissipated energy will be low and within the withstand for the devices. The estimation is gross, and in the opinion of the author very conservative and the stress on the over-voltage protection should in the actual case be safely less than estimated.

The measuring system has been in use for the measurement of a very large number of voltage transformers *in situ*. During this time there have been a large number of close-by operations of disconnectors with a fair amount of arcing. Implemented operating procedures require the signal cables to be disconnected during any switching operations to minimise the risk of equipment failure. There has however been a number of cases when the signal cables have remained inadvertently connected. This has never caused any malfunction in any of the instruments in the instrument van. There have been a few cases of damage to the instruments, but these were caused by improper handling, not by transients. In conclusion there have been no indications of any transients occurring within the van and the transient suppression has proved to be quite adequate for its purpose.

3.8. Instrument power supply

Several functions in the instrument van require electrical power. Apart from the instruments themselves, there is a heating and ventilation system providing fresh air, an interior lighting system and an air-conditioning system that maintains the interior temperature close to 20 °C during summer conditions.

The mains installation in the van is electrically isolated from the incoming a.c. power by means of a three-phase isolation transformer to ensure that interference is not conducted on the mains to the measuring instruments.

The isolation transformer is rated for 11 kVA and its insulation between primary and secondary is rated for 10 kV rms [19]. As shown in figure 9, the transformer is furnished with double screens that serve to reduce the electrostatic coupling of high frequency transients and common mode interference to a negligible level. The separation of the van earth and the power earth is an important aspect of the interference control philosophy employed for the instrument van. The separation ensures that interference currents into the van are reduced to a minimal level. The safety of the installation is assured by earthing the star point of the transformer secondary and the van chassis to the substation earth grid.

The transformer is equipped with a tapped primary to permit connection of the van power supply system to any of several possible mains voltages.

Figure 9. Instrument van power supply circuit

The stability of the power supply to the measuring instruments is enhanced by the use of a resonant magnetic stabiliser. The magnetic stabiliser is a transformer-like device whose iron core is driven to partial saturation. Combining the characteristics of the saturated core with a parallel capacitor a resonant circuit is obtained which stabilises the output voltage with an output variation of only 1 - 2% for input variations of up to 20%. The energy available in the device is sufficient to bridge missing half-periods of the mains voltage. The operating principle of the stabiliser also provides a transient suppression of typically 40 dB.

A further enhancement of the interference reduction in the power supply to the measuring system is obtained by the use of an isolation transformer with very low coupling capacitance between the windings. The secondary winding of the transformer is centre tapped with the tap connected to the van chassis earth. The two phase conductors are protected with two varistors also connected to the van chassis earth.

All the measures described above have as a common goal to increase the impedance between the mains power supply and the instrument circuits. This results in noise voltage and transients being reduced to a negligible level in the measuring system.

3.9. Calibration procedures

To maintain a high standard of measurement it is necessary to calibrate the measurement equipment at regular intervals both to ensure that drift is negligible and that no damage to the equipment has occurred.

Before and after each measuring season all equipment is calibrated against the reference standards at the Swedish National Testing and Research Institute (SP) in Borås.

The instruments and equipment used are very stable, and indeed the changes observed between calibrations are on the same order as, or even less than, the uncertainty in the calibrations itself. There is therefore no reason to assume that there are any significant changes due to drift during a measuring season.

The integrity of all measuring cables is checked before and after each measuring season. The test includes check for insulation faults with a 500 V d.c. insulation tester and test of the continuity of the cables by measuring the series resistance values for all conductors.

4. Measurement procedures

4.1. Preliminary actions

For the operations on site certain considerations are important. The switchyard is a potentially hazardous area and the safety of the personnel must never be put into jeopardy. A second important consideration is the stability of the power network. All calibrations are performed on the live network and mistakes, for example in making connections to the secondary circuits of the instrument transformers, could lead to a protective circuit operation that disrupts the power flow in the substation. It is also remotely possible that a larger part of the network could be caught up in such an event in a sort of "domino" effect. Due to these and other considerations all major and minor operations on site with a direct bearing on the safety and/or on the availability of the substation are covered by a detailed operations write-up that is individually tailored for each substation. The sequence of events followed is more or less fixed and will be shortly described in the following.

On site, the instrument van is placed in a suitable position and earthed. Power is connected to put the air conditioning into operation and to let the instruments warm up.

The reference transformer NUES 420 is placed in a suitable position close to a bus or an overhead line and earthed. In many Swedish switchyards there is a normally unenergised bus usually designated as the C-bus. Where available, this bus is used since it may be connected and disconnected with impunity. In many other cases the power flow can be redirected so that one bus is free-running. This bus can then be connected and disconnected without affecting the power flow in the network. In cases where no unenergised bus can be made available, the usual practice is to open one transmission line at the far end and use this line for the connection of the reference transformer. Since the line is open at the far end, it will be possible to connect and disconnect this line as needed.

A voltage withstand test is performed on the transformer after raising it to an upright position and filling it to operating pressure with SF₆ gas. This test consists of energising the transformer from the secondary and measuring the voltage and current on the secondary side. Current and voltage values are used as the main indicators that the insulation is sound. As a supplementary measure a PD measurement is performed. The sensitivity for active part-to-earth partial discharges (PD) is moderately good with a response of 22 pC per mV oscilloscope reading. For partial discharges that are predominantly in series with the active part, a sensitivity of 2 pC/mV is obtained. Typical background noise

level when measuring with the transformer NUES 420 in a substation is 3 mV_p . The background noise originates mainly from corona on the high voltage busbars in the substation. The minimum detectable PD level is therefore on the order of 100 pC for active part-to-earth PD and 10 pC for series PD.

The transformer is energised after the tests, but only after communication with the operations centre for the high voltage network.

All measuring cables used in a substation for the connections between reference transformer, instrument van and test objects are fully tested with 500 V d.c. to ensure that there are no defects in them. This operation is performed with a standard insulation tester. Between the insulation tester and the cable there is a connection box with a rotary switch used to switch in all conductors in turn for testing. The full test for one cable takes less than 2 minutes.

4.2. Measurement of the installed burden

The first measurement performed is a determination of the installed burden, i.e. determination of the load on each voltage transformer. A block circuit diagram for this measurement is shown in figure 7. It is interesting that, although all individual burdens on each phase and between phases have the form of a complex impedance with inductive phase angle, the resultant burden imposed on a voltage transformer may be capacitive. Such cases can occur when a three-phase group of CVTs has loads connected both in delta and in star connections and the loads are unsymmetrical. This case has been found to be fairly common in Swedish substations with about one sixth of all installed transformers exhibiting a capacitive load.

4.3. Voltage transformer calibration

All voltage transformers in one phase in a substation are normally measured in sequence. When the proper connections have been made between the reference transformer, the instrument van and the test object, a measurement of unbalanced currents in the measuring cables to the transformer calibration bridges is made to ensure that there are no leakage currents that could interfere with the measurement. The actual measurement is initiated from the computer as an automatic sequence of measurement of the voltage ratio and phase displacement of the voltage transformer. Twelve readings spaced approximately 1 second in time are taken. The highest value and the lowest value are both discarded, and the mean value of the ten remaining is calculated and stored as the result of the measurement. The standard deviation of the ratio error is also stored as a measure of the spread in the measurement.

The value of the transformer error with the installed burden connected is recorded to be used both as a reference for future use and for comparison with data obtained with the variable burden.

In the next step all substation equipment is disconnected from the transformer. Important metering and protection circuits are in the interim arranged to receive control voltage from other instrument transformers in the substation.

For each voltage transformer a measurement of the error with the installed burden connected is performed, followed by a measurement of the error for several burdens ranging from zero to the rated burden and at a power factor of 1.0 and 0.8 lagging.

The measurement is made in the voltage make-up box in the substation yard and not directly on the transformer terminals. Depending on the exact construction of the voltage make-up box and the choice of cable between the transformer and the box, three different possibilities exist for the connection of the measurement. In some cases there are two separate circuits attached to the voltage transformer secondary winding enabling a true 4-wire connection to be made for measurements with variable burden. The four wire connection provides separation between measurement and burden circuits all the way to the transformer terminals and provides results that are directly comparable to factory calibration results.

In other cases the connection may be three- or two-wire and there will be an added error voltage due to the load voltage drop from voltage make-up box to the transformer terminals. In these cases only the no-load reading will be comparable to the factory calibration.

In the case that the ratio error recorded at the installed burden for the voltage transformer is considered too large, a readjustment of the output voltage of the transformer may be performed, followed by a renewed measurement. An error outside the range 0.0 to 0.2% is considered excessive for transformers used for metering purposes. For transformers used for protection and control, an error in the range -0.2 to 0.5% is usually considered adequate. Most of the CVTs in Sweden are of a type that is field adjustable in the ratio. Adjustment for the phase error is not available.

A comparison between the data obtained when the installed burden is connected and with a similar value for the variable burden is used as a quick, if somewhat imprecise, validation of the measurements. If the error of the CVT is the same within approximately 0.05%, the results are considered valid. The measurement of the output voltage from the CVT is made in the voltage make-up box and not on the terminals directly. It is often not possible to use the same

connection scheme between voltage make-up box and the terminals of the CVT in the measurement with the variable burden as for the installed burden. In such cases, the burden current will cause different additional resistive voltage drops in the connection between the CVT and the voltage make-up box in the two measurements and the uncertainty of the comparison will increase. The suitability of the comparison is furthermore often compromised by the fact that the exact magnitude and phase angle of the installed burden may be impossible to simulate with the variable burden and that the test object may not be stable.

4.4. Auxiliary information

Several auxiliary instruments are included in the complement of the instrument van. These are intended to be used to record environmental conditions that could have an effect on the measurement results.

The meteorological conditions are recorded with an aneroid barometer, wet and dry thermometers and a wind speedometer. The solar heating is determined by measuring the irradiation in the visible and near infra-red spectrum with a pyranometer. Fair weather/precipitation conditions have only been recorded the latest year of operation, but calibrations have not been carried out under heavy rainfall at any time.

Neither of the above measurements have any direct bearing on the measurement of voltage transformer errors, but are recorded to fill a possible future need in the evaluation of measurement results.

Full identification of the test objects is obtained from apparatus name plates and is included in the test records.

4.5. Concluding actions

Packing up after conclusion of the calibrations in one substation includes storing of measuring cables, reduction of gas pressure in the reference transformer to slightly above atmospheric and securing all items both in the instrument van and on the flat bed wagon. A complete backup of the entire hard disk of the computer is made after the completion of all measurements and before the instrument van is moved.

The procedure of measuring one substation with two busbars with one transformer each and two sets of line transformers, in total eight transformers, takes one week under normal conditions. Adverse conditions with, for example thunderstorms, will delay the operation accordingly.

5. Definition of voltage transformer errors

The relations between primary voltage $\underline{U}_p$ and the secondary voltage $\underline{U}_s$ of a voltage transformer are shown in the vector diagram in figure 10 below.

Figure 10. Vector relations between polar and Cartesian representations of voltage transformer errors

where:

- $\underline{F}$ is the complex error
- k_n is the rated transformation ratio
- δ is the phase displacement
- α is the real part of the relative complex error
- β is the imaginary part of the relative complex error

α is also known as the in-phase error and β as the quadrature error.

It is evident from this figure that there are two distinct possible definitions of the error of a voltage transformer, i.e. based on the polar or the Cartesian form for the representation.

The commonly used representation is the polar form with the phase displacement δ as the angle between the two voltage vectors. The phase displacement is counted positive if the secondary voltage leads the primary. The ratio error ε is defined as

$$\varepsilon = \frac{|\underline{k}_n \underline{U}_s|}{|\underline{U}_p|} - 1 \quad (1)$$

This form is the one used in IEC 186 [2].

The Cartesian representation adheres closely to the operation of most instruments used for the measurement of instrument transformer errors. In this representation, the relative error vector $\underline{F}/\underline{U}_p$ is decomposed into its in-phase and quadrature components α and β . For small errors the in-phase component is approximately equal to the ratio error and the quadrature error is approximately

equal to the phase displacement. The exact relation between these two alternate representations is:

$$\begin{aligned}\alpha &= (1 + \varepsilon) \cos \delta - 1 \\ \beta &= (1 + \varepsilon) \sin \delta\end{aligned}\tag{2}$$

This relation maybe deduced from the trigonometric relations in figure 10. An algebraic deduction is given by Bergman in [²⁵].

Both representations are, from the scientific point of view, completely equivalent, but in practice only the first one is used. However, although only the first definition is used, most measurements are made with instruments giving results in accordance with the second definition. The difference between the two representations is regarded as negligible for cases where the requirements are moderate, such as calibration of instrument transformers to verify compliance with standards. In the present context where the uncertainty of calibrations is to be determined, the difference must be evaluated.

Taking an example with a measurement providing a ratio error $\varepsilon=0.6\%$ and a phase displacement $\delta=9$ mrad, the in-phase and quadrature errors are obtained as

$$\begin{aligned}\alpha &= 0.5959\% \\ \beta &= 9.054 \text{ mrad}\end{aligned}$$

The difference between the two representations can therefore be estimated to be less than $\pm 0.0041 \%$ and ± 0.054 mrad, respectively.

The errors cited for this example are high and any instrument transformer exhibiting errors of this magnitude is unsuitable for metering purposes. The difference between the two representations also becomes less as the measured errors decrease.

6. Treatment of uncertainties

6.1. General

It is important that the uncertainty stated for calibrations is evaluated and expressed in a harmonised way to avoid misunderstanding of the meaning of the uncertainty. A method has been introduced by ISO (International organisation for standardization) in "Guide to the Expression of Uncertainty in Measurement" [26]. The concept of a confidence interval that corresponds in a realistic way with the required level of confidence is central to this method. The ISO/TAG 4 method will be used in this paper to evaluate uncertainty and a brief résumé of the method is given.

6.2. Outline and definitions

The method requires that all influence quantities should be treated as random, even if they may influence the result in a systematic way. Any known systematic influence should however be corrected for and not be included in the uncertainty. The quantity Y to be measured is viewed as an output quantity depending on a number of input quantities X_i ($i=1, 2, \dots, \nu$) according to a function G .

$$Y = G(X_1, X_2, \dots, X_\nu) \quad (3)$$

Input quantities include data from calibration certificates, results from measurements and influence quantities. The true values of X_i are generally not known and estimated values x_i are used as input data in the evaluation both of the estimate y of the quantity to be measured, and of the uncertainty.

The experimentally determined variance $s_{x_i}^2$ or its positive square root s_{x_i} , the standard deviation, is used as a measure of the uncertainty of the estimated values x_i . One can in many cases also use relative variance or relative standard deviation instead.

Contributions that are evaluated by applying statistical methods to a series of repeated measurements are designated as Type A contributions while those evaluated by other means are designated as Type B contributions.

6.3. Formulation of input data

6.3.1. Type A uncertainty, repeatedly measured quantities

When a sufficient number of measurements are repeated under the same conditions and with sufficient resolution, there will be an observable scatter in

the results. With n independent measurements, the estimated value x_i is given by the mean of the individual measured values $v_{i,j}$ ($j=1, 2, \dots, n$)

$$x_i = \bar{v}_i = \frac{1}{n} \sum_{j=1}^n v_{i,j} \quad (4)$$

An estimate of the standard deviation of the distribution of values s_{v_i} is given by

$$s_{v_i} = \sqrt{\frac{1}{n-1} \left(\sum_{j=1}^n (v_{i,j} - \bar{v}_i)^2 \right)} \quad (5)$$

An estimate on the standard deviation of the mean value x_i is given by

$$s_{x_i} = s_{v_i} \sqrt{\frac{1}{n}} \quad (6)$$

Note that if n is less than 10 or if the distribution is not normal (Gaussian), equation (5) may lead to an underestimation of the uncertainty. In this case other methods should be used to obtain a suitable estimate.

6.3.2. Type B uncertainty, single values and other influence quantities

If possible, the variance should be obtained from experience or from a known population distribution. When only upper and lower limits $a_{u,i}$ and $a_{l,i}$ can be estimated one may use

$$x_i = \frac{1}{2} (a_{u,i} + a_{l,i}) \quad (7)$$

for the estimated mean value, and for the estimated variance

$$s_{x_i}^2 = \frac{1}{12} (a_{u,i} - a_{l,i})^2 \quad (8)$$

If the difference between the limiting values is denoted $2a_i$ equation (8) yields

$$s_{x_i}^2 = \frac{1}{3} a_i^2 \quad (9)$$

These statements correspond to an assumed rectangular distribution of the influence quantities between their limits.

6.4. Calculation of the results

The result y of the measurement is the estimated value for the true value Y and is calculated by substituting the input data x_i for X_i in equation (3).

The variance of the output quantity is given by

$$s_y^2 = \sum_{i=1}^v \left(\frac{\partial G}{\partial X_i} \right)^2 s_{x_i}^2 \quad (10)$$

The partial derivatives are often called sensitivity coefficients. In many practical cases it is found that the partial derivatives are equal to one and equation (10) reduces to

$$s_y^2 = \sum_{i=1}^v s_{x_i}^2 \quad (11)$$

This case is obtained for example if the function G can be factorised in first-order polynomials in X_i .

The partial derivatives may also be experimentally determined by measuring the change in y directly for a certain change in x_i . In this case the knowledge of the function G is reduced to an empirical first-order Taylor expansion based on the measured partial derivatives. If the partial derivatives have been determined by estimating or measuring the maximum change Δy_i produced in the output y by a certain maximum change Δx_i in the input quantity x_i , we have the elementary relation

$$\frac{\partial G}{\partial x_i} \cdot \Delta x_i = \Delta y_i \quad (12)$$

The standard deviation of y with respect to the input quantity x_i is then simply obtained as

$$s_{y(x_i)}^2 = \left(\frac{\partial G}{\partial X_i} \right)^2 \cdot s_{x_i}^2 = s_{\Delta y_i}^2 \quad (13)$$

where $s_{\Delta y_i}^2$ is the standard deviation estimated for y_i .

The standard deviation s_y is a measure of the combined uncertainty of the output quantity Y . The overall uncertainty $\pm u$, shall be obtained by multiplying the standard deviation s_y by a factor k , also called the coverage factor

$$u = k \cdot s_y \tag{14}$$

In the present context a factor $k=2$ will be used. For quantities that have a Gaussian distribution this corresponds to a 2σ , or 95%, confidence level.

7. The reference transformer

7.1. Theory

The reference transformer used in the field calibration system is an inductive transformer. Such a transformer may be considered as a power transformer in which care has been taken to minimise the unavoidable errors of transformation.

In an ideal voltage transformer the secondary voltage is precisely equal to the primary voltage divided by the turns ratio of the transformer. Furthermore there is no phase-shift between the two voltages. The voltages are expressed as vector quantities:

$$\frac{\underline{U}_1}{\underline{U}_2} = \frac{N_1}{N_2} \quad (15)$$

where:

$\underline{U}_1$ and $\underline{U}_2$ are the primary and secondary voltages

N_1 and N_2 are the number of primary and secondary turns

A non-ideal transformer has a voltage ratio that differs from the turns ratio and there is also a phase shift between primary and secondary windings. The behaviour of the non-ideal transformer can be satisfactorily described with the aid of an equivalent circuit, which models the transformer with lumped constants. The equivalent circuit in figure 11 is modelled after Richter [34]. All circuit parameters in the equivalent circuit have been transformed to the primary side.

Figure 11. Primary equivalent circuit of voltage transformer

The parameters in the figure represent:

R_0 = the magnetising resistance

C_0 = the magnetising capacitance

L_0 = the magnetising inductance

$\underline{Z}_0$ = the combined magnetising impedance

R_1 = the primary winding resistance

C_1 = the equivalent primary capacitance

L_1 = the primary leakage inductance

$\underline{Z}_1$ = the total primary impedance

R_2 = the secondary winding resistance reduced to the primary

C_2 = the secondary capacitance reduced to the primary

L_2 = the secondary leakage inductance reduced to the primary

$\underline{Z}_2$ = the total secondary circuit impedance

R_B = the burden resistance reduced to the primary

C_B = the burden capacitance reduced to the primary

L_B = the burden inductance reduced to the primary

$\underline{Z}_B$ = the total burden impedance

On the basis of this equivalent circuit it is possible to calculate the error function of the voltage transformer. Richter [34] has done so, and has shown that for closed iron cores, equation (16) is a good approximation for the complex error $\underline{F}$.

$$\underline{F} \approx - \frac{\underline{Z}_1}{\underline{Z}_0 + \underline{Z}_1} - \frac{\underline{Z}_1 + \underline{Z}_2}{\underline{Z}_1 + \underline{Z}_2 + \underline{Z}_B} \quad (16)$$

In this equation the first term is recognised as the no-load error and the second term as the load-dependent error. The no-load error depends on the operating frequency and, since $\underline{Z}_0$ is voltage dependent, on $\underline{U}_1$. The load error depends on the burden impedance $\underline{Z}_B$. The burden impedance depends in turn on the operating frequency and the operating voltage.

A vector diagram can be used to visualise the voltage drops over the components and how these link the primary and secondary voltages. The equivalent circuit has been simplified by neglecting the capacitances to obtain the diagram in figure 12. The voltage drops over the components are drastically exaggerated to enhance the clarity of the diagram. This type of representation is discussed on page 103 ff. of [35].

From the equivalent circuit it is seen that the errors for a transformer depend in a complex manner on the magnetising current and the load current. In general an accurate voltage transformer will have compensation both for inherent

Figure 12. Vector diagram for primary equivalent circuit of voltage transformer showing how primary and secondary voltages are linked

phase and ratio errors. This is normally accomplished by adding reactive and/or resistive components at the low voltage side of the transformer. The effect of these additional components is however satisfactorily described by the equivalent circuit of figure 11.

Richter [34] further shows that the no-load error can be evaluated in its in-phase and quadrature components ε_0 and δ_0 as:

$$\varepsilon_0 = - \left[\frac{R_1}{1 + (R_1 \omega C_1)^2} \cdot \frac{1}{R_{0(U_1)}} + \left(\omega L_1 - \frac{R_1^2 \omega C_1}{1 + (R_1 \omega C_1)^2} \right) \left(\frac{1}{\omega L_{0(U_1)}} - \omega C_0 \right) \right]$$

$$\delta_0 = - \left[\left(\omega L_1 - \frac{R_1^2 \omega C_1}{1 + (R_1 \omega C_1)^2} \right) \cdot \frac{1}{R_{0(U_1)}} - \frac{R_1}{1 + (R_1 \omega C_1)^2} \left(\frac{1}{\omega L_{0(U_1)}} - \omega C_0 \right) \right] \quad 17)$$

From this it is evident that the winding capacitance will have a decisive influence on the no-load error of high voltage transformers with high winding capacitance and high winding resistance. Conversely for low voltage units this effect will be small. The effect of the winding capacitance can however be greatly reduced by

designing the winding with external capacitive grading to cancel the effect of the internal capacitance. The effect is effectively to reduce C_I to a very small value.

It is in principle possible to calculate the no-load error for a voltage transformer from this equation, but the actual values of the circuit parameters cannot be established with sufficient accuracy to permit the use of this method in practice. The equation does however point out the relations between the circuit parameters and the error of the transformer.

Räisänen [²⁷] has shown that, if the capacitances are disregarded, the load term can be evaluated to:

$$\varepsilon_B = - \frac{(R_1 + R_2)(R_1 + R_2 + R_B) + (L_1 + L_2)(L_1 + L_2 + L_B)}{(R_1 + R_2 + R_B)^2 + (L_1 + L_2 + L_B)^2} \quad (18)$$

$$\delta_B = - \frac{R_B(L_1 + L_2) - (R_1 + R_2)L_B}{(R_1 + R_2 + R_B)^2 + (L_1 + L_2 + L_B)^2}$$

The equations (17) and (18) for the no-load error and the load error can be visualised in a so-called Farber or Möllinger-Gewecke diagram [²⁸].

Figure 13. The relation between load and no-load error of a voltage transformer in a so-called Farber diagram

7.2. Initial calibration

Both the mobile transformer NUES 420 and the SP laboratory reference transformer NUEO 400 were calibrated first at the manufacturers works and then at PTB (Physikalisch-Technische Bundesanstalt) in Braunschweig in Germany. Of main interest is the calibration at PTB since it is based on a direct comparison with reference transformers that have been verified by basic methods to an uncertainty of less than ± 0.0005 % so that the total calibration uncertainty is ± 0.003 % for the ratio and ± 0.03 mrad (± 0.10 min) for the phase displacement. The calibration certificate from PTB does not state the level of confidence for their results, but according to a personal communication from Dr Latzel of PTB, the given uncertainty should be considered as a safe estimate that should be considered to be based on a 2σ confidence level.

The calibrations at PTB demonstrated that both transformers were within their respective specifications. The results also provided the transformation ratio for each transformer under controlled conditions, i.e. indoors and at $20\text{ }^{\circ}\text{C}$ temperature, with the uncertainty mentioned above.

The NUES 420 has subsequently been rebuilt by replacing the intermediate transformer and the PTB certificate can no longer be considered valid for this transformer. The corrections obtained in the annual calibrations performed at SP are however used in all calibrations involving the NUES 420 and are used instead of the initial values. The uncertainty of the annual calibration is of course larger than that of the initial calibration.

The laboratory reference transformer NUEO 400 was calibrated at a temperature of $7\text{ }^{\circ}\text{C}$ to obtain a measure of the temperature sensitivity. This test gave a maximum difference of 0.009% of the ratio as compared with a measurement at $21\text{ }^{\circ}\text{C}$. This proves with certainty that the calibration results obtained for the laboratory reference transformer NUEO 400 are valid in the high voltage laboratory at SP where a constant temperature of $22 \pm 1\text{ }^{\circ}\text{C}$ is maintained. The NUEO 400 is used only in the high voltage laboratory. The temperature dependence of the mobile reference transformer NUES 420 is discussed below.

7.3. Annual calibrations

The mobile transformer is calibrated each year immediately before the start of the field measurements as well as immediately after. The calibration is performed as a comparison against the reference transformer at SP in Borås. The estimated uncertainty in this calibration is ± 0.006 % for the ratio error and ± 0.07 mrad for the phase displacement with a coverage factor $k = 2$. This uncertainty has been estimated with the method prescribed by ISO/TAG 4 [26].

Figure 14. Ratio errors recorded in the annual calibrations of the mobile reference transformer. The calibrations were performed at the rated voltage for each ratio and at nominal burden (10VA resistive) and in the ambience of the high voltage laboratory at SP.

The calibration is performed as a comparison with a similar reference transformer permanently stationed at the high voltage laboratory of SP in Borås. The comparison is made with a transformer calibration bridge type Messwandlerbau TAB. The method is described in [29].

The stability for the ratio error is shown in figure 14, and the stability for the phase displacement in figure 15, for each ratio at 100% of rated voltage. The maximum recorded error is less than the 0.02% rated for the NUES 420. The cause for the observed long term variation is not known, but it could be attributed for example to harmonic voltage interference on the transformer calibration bridge or to actual changes in the mobile transformer NUES 420. The observed changes are on the same order of magnitude as the uncertainty of the calibration and, whatever the cause, in this evaluation it has been chosen to regard the variation as a stochastic variation between the limits observed, and with a rectangular probability distribution.

The maximum observed range for the change in the ratio error is 0.0080 % and for the phase displacement ± 0.087 mrad (0.3 minutes).

For the uncertainty in the calibration, the applicable standard deviation is one half of the uncertainty or 0.003 % and 0.035 mrad respectively.

The variation as evidenced by the annual calibrations is estimated as 0.008 % and 0.09 mrad respectively. This influence is a type A influence, but is, with regard the meagre statistical data, estimated as a type B with a maximum span equal to the variation width and the standard deviation has been estimated as the variation width divided by $\sqrt{12}$ as per equation (8). The standard deviation is obtained as 0.0023 % and 0.026 mrad respectively.

Figure 15. Phase displacements recorded in the annual calibrations of the mobile reference transformer. The calibrations were performed at the rated voltage for each ratio and at nominal burden (10VA resistive) and in the ambience of the high voltage laboratory at SP.

7.4. External capacitive coupling to active part

The mobile reference transformer NUES 420 is used in an environment with high electric field strength. This field could conceivably affect the reference transformer and produce an error. The design of the NUES 420 is such that the active part is enclosed in a pressure vessel made of cast aluminium which very effectively screens the electric field. In the only opening a capacitor bushing is mounted. The design of this bushing screens the opening from external electrical fields. In conclusion, external electrical fields do not penetrate the outer vessel and there is therefore no influence on the active part.

7.5. Temperature dependence

The error of an instrument transformer is to some extent dependent on the temperature of the transformer. The voltage drop across the resistance of the high voltage winding is one of the main contributions to the error of a voltage transformer. The vector diagram in figure 12 shows the main influence factors on the measuring error. The two main mechanisms behind the temperature dependence are the change in the winding resistance of the high voltage winding and the change in the relative permeability of the iron core. The change in iron core permeability changes the magnetising current I_0 . Both these effects influence the voltage drop across impedance $\underline{Z}_1$ (see figure 11). The load current I_2 does cause a voltage drop across the secondary impedance $\underline{Z}_2$, but since $I_2 < I_0$ and $R_1 \approx R_2$, the change in the resistive part of $\underline{Z}_1$ can be neglected. The leakage inductances L_1 and L_2 are mainly determined by the physical layout of the

windings on the core and therefore do not change appreciably with the temperature. The influence of changes in the capacitances is neglected since the transformer is designed with capacitive grading of the high voltage winding.

The resistance R_I of the high voltage winding varies with temperature according to the well-known approximate formula for metallic conductors

$$R_T = R_0(1 + \alpha T) \quad (19)$$

where R_T and R_0 are the resistances at actual and reference temperatures respectively, T is the difference between these two temperatures and α is the temperature coefficient of the conductor material.

The permeability of the core influences the magnetising impedance according to Richter [34] by

$$\begin{aligned} L_0 &= L_{air} \operatorname{Re}(\mu_r) \\ R_0 &= L_{air} \operatorname{Im}(\mu_r) \end{aligned} \quad (20)$$

where L_{air} is the inductance of the winding without core and μ_r the complex permeability of the core material.

A change in the magnetising impedance implies a change in the magnetising current and consequently a change in the ratio error and the phase displacement.

The material used for the core of the mobile reference transformer NUES 420 is ORSI 111 manufactured by EBG Gesellschaft für Elektromagnetische Werkstoffe GmbH in Germany. The manufacturer has not made any measurements of the magnetic properties versus the temperature for this material. Estimates of the temperature effects must therefore be based on other information.

Räisänen [27] has investigated the mobile reference transformer NUES 420 theoretically. He based the analysis of the temperature effect on the core on information available from Vacumschmelze GmbH, Germany, on a similar core material, Trafoperm N2. Both this material and ORSI 111 are oriented silica steel intended for transformer applications. The change in the relative permeability of Trafoperm N2 is non-linear, but it increases with increasing temperature in the normal ambient range. The magnetising current will therefore decrease with increasing temperature and will to some extent compensate the simultaneous increase in the winding resistance. Räisänen has estimated that the temperature dependent change in the ratio from 0° C to 30° C ambient temperature is less than -0.0045%. He estimated that the change in the phase error due to temperature would be negligible.

The temperature effect was also investigated experimentally by the author. The reference transformer NUES 420 was placed outdoors for over 16 hours. The outdoor ambient temperature was a stable +2°C during this time and the active

part of the transformer can be assumed to have attained a final temperature close to +2°C at the end of the 16 hours. The transformer was then quickly moved back into the high voltage laboratory and compared to the stationary reference transformer NUEO 400 at the highest and lowest ratios. Measurements were performed as three independent measurements at each of the levels 120%, 100%, 80% and 60% of the rated voltage. For the ratio $396 \text{ kV}/\sqrt{3}$ to $110 \text{ V}/\sqrt{3}$ the change in ratio error and the phase displacement for the NUES 420 from the room temperature of +21 °C to +2°C was $(-0.002 \pm 0.002) \%$ in the ratio and $(0.006 \pm 0.006) \text{ mrad}$ (0.02 ± 0.02 minutes) in the phase displacement. For the ratio $132 \text{ kV}/\sqrt{3}$ to $110 \text{ V}/\sqrt{3}$ the change was $(-0.004 \pm 0.002) \%$ and $(0.015 \pm 0.023) \text{ mrad}$ (0.05 ± 0.08 minutes).

The experimental investigation indicated an effect of the same order of magnitude as the theoretical investigation. With regard to the uncertainties in both the theoretical and the experimental investigations, it is however prudent to estimate the maximum error due to temperature as the sum of the observed experimental change and the uncertainty thereof, i.e. to $\pm 0.006 \%$ in the ratio and $\pm 0.038 \text{ mrad}$ (± 0.13 minutes) in the phase. This influence is estimated as a type B influence characterised by a difference between upper and lower bounds equal to $2a_i$. Equation (9) is applicable for the estimation of the standard deviation, giving $0.006/\sqrt{3}=0.0035 \%$ and $0.038/\sqrt{3}=0.022 \text{ mrad}$ respectively.

7.6. Mechanical strain

Mechanical strain in this context refers to normal strains resulting from transporting and operating the transformer. Gross mechanical strain due to accidents is not included since this would result in the NUES 420 having to be repaired, with unknown errors as a result.

Räisänen [27] has also discussed this problem, concluding that mechanical strains do not introduce errors into the readings obtained with the NUES 420. The results of the annual calibrations of the mobile transformer haven't given any certain indication of changes that could be attributable to mechanical strain and this effect is disregarded in the evaluation of the uncertainty of the measuring system.

7.7. Ageing

Ageing in transformers is considered to result from, humidity and other foreign substances acting on the insulation. It is manifested mainly by changes in the properties of the dielectric materials, i.e. the insulation, and thus the capacitive voltage distribution on the transformer. Oxidation may also affect conductors,

causing change in the conductor resistance. The core is generally not affected by ageing phenomena.

Since the NUES 420 is insulated by a hermetically sealed SF₆ insulation system, the active part is completely self-contained and free from environmental influences.

In conclusion, ageing does not introduce errors into the readings obtained with the NUES 420. This conclusion is also supported by the results of the annual calibrations.

7.8. Sensitivity to change in the burden

As can be seen from figure 11, the load on the transformer, the burden, draws a current I_2 that causes a voltage drop along the series impedances Z_1 and Z_2 .

Therefore both ratio error and phase displacements will vary linearly with the burden's absolute value. How the phase of the burden affects the errors is apparent from the Farber diagram in figure 13. The NUES 420 is factory adjusted for optimum results at a burden of 10 VA resistive.

Deviations from the nominal value of the burden on the NUES 420 will introduce an error into the readings obtained with the NUES 420. The variation of the error of the NUES 420 was recorded at PTB for three different burdens 0, 10 and 15 VA for the $132/\sqrt{3}$, $154/\sqrt{3}$, $220/\sqrt{3}$ and $396/\sqrt{3}$ kV ratios. The ratios $407/\sqrt{3}$ kV $385/\sqrt{3}$ kV were added later and have been tested for their burden sensitivity in the high voltage laboratory at SP.

As can be seen from the tables, the lower voltage ratios are more sensitive to changes in the burden. The uncertainty due to the estimated variation in the resistance of the burden can be calculated by assuming a maximum deviation of the burden of 0.25 VA, corresponding to a resistance variation of less than 2.5%. The actual resistance variation as verified by annual calibrations is less than 1%, but the assumption of 2.5% is sufficient for the present purpose. The maximum

Table 1. Ratio error of the mobile reference transformer NUES 420 at different voltage ratios and at different resistive burdens

Burden [VA]	$132/\sqrt{3}$ [%]	$154/\sqrt{3}$ [%]	$220/\sqrt{3}$ [%]	$385/\sqrt{3}$ [%]	$396/\sqrt{3}$ [%]	$407/\sqrt{3}$ [%]
0	0.08	0.067	0.035	0.03	0.037	0.033
10	0.012	0.013	0.001	0.005	0.013	0.0080
15	-0.021	-0.015	-0.016	-0.008	0.002	-0.003

Table 2. Phase displacement of the mobile reference transformer NUES 420 at different voltage ratios and resistive burdens

Burden [VA]	132/ $\sqrt{3}$ [mrad]	154/ $\sqrt{3}$ [mrad]	220/ $\sqrt{3}$ [mrad]	385/ $\sqrt{3}$ [mrad]	396/ $\sqrt{3}$ [mrad]	407/ $\sqrt{3}$ [mrad]
0	1.37	1.37	0.52	0.38	0.41	0.35
10	0.06	0.23	0.06	0.17	0.26	0.17
15	-0.58	-0.23	-0.2	0.09	0.17	0.09

change for any ratio due to uncertainty in the burden can therefore be estimated to $\pm 0.0017\%$ and ± 0.035 mrad (0.12 min). This influence is estimated as a type B influence characterised by a difference between upper and lower bounds equal to $2a_i$. Equation (9) is applicable for the estimation of the standard deviation, giving $0.0017/\sqrt{3}=0.001\%$ and $0.035/\sqrt{3}=0.02$ mrad respectively.

Table 3. Maximum change in the error of the mobile reference transformer NUES 420 at different voltage ratios due to an assumed change of 2.5% in the value of its nominal 10VA resistive burden

	132/ $\sqrt{3}$	154/ $\sqrt{3}$	220/ $\sqrt{3}$	385/ $\sqrt{3}$	396/ $\sqrt{3}$	407/ $\sqrt{3}$
Ratio [%]	0.0017	0.0014	0.0009	0.0007	0.0006	0.0006
Phase [mrad]	0.035	0.026	0.012	0.006	0.004	0.004

7.9. Sensitivity to external magnetic fields

External magnetic fields may introduce an e.m.f. in the windings of the transformer. This e.m.f. will be added to the voltage to be measured and thus introduce an error into the reading obtained with the transformer.

The load current drawn in the overhead lines and busbars in the switchyards are a source of external magnetic fields in the field measurements. The strength of this field is moderate, typical values encountered at the position of the active part of the reference transformer NUES 420 are 10 to 30 μT .

Räisänen [27] has analysed the NUES 420 with respect to the influence of external magnetic fields and has concluded that the error introduced in the

readings obtained with the NUES 420 is less than $\pm 0.00002\%$ and ± 0.0002 mrad for an external magnetic field strength of $100\text{ }\mu\text{T}$. This influence is estimated as a type B influence characterised by a difference between upper and lower bounds equal to $2a_i$. Equation (9) is applicable for the estimation of the standard deviation, giving $0.00002/\sqrt{3} = 0.000012\%$ and $0.0002/\sqrt{3} = 0.00012$ mrad respectively.

7.10. Summary of uncertainties for the reference transformer

The individual uncertainties, discussed above for each influence quantity, must be added in a systematic way to obtain the total uncertainty. The method introduced by ISO/TAG 4 [26] is applied.

The standard deviation relevant to each input quantity has been directly estimated from the change in the output quantity y produced by a change in an input quantity x_i in accordance with equation (13). All uncertainties discussed are uncorrelated and the variances can therefore be directly added to obtain the total variance for influences related to the reference transformer.

All contributions have been evaluated as type B contributions.

Table 4. Estimated equivalent standard deviation of uncertainty contributions associated with the reference transformer NUES 420

Quantity considered	ε [%]	δ [mrad]
Annual calibration uncertainty	0.0030	0.035
Annual calibration variation	0.0023	0.026
Capacitive coupling	0	0
Temperature dependence	0.0035	0.022
Mechanical strain	0	0
Ageing	0	0
Burden sensitivity	0.0010	0.020
Magnetic fields	0	0
Total standard deviation	0.0052	0.053

The uncertainty associated with the reference transformer is estimated in accordance with the ISO/TAG 4 method for a coverage factor $k=2$ to be $\pm 0.011\%$ and ± 0.11 mrad respectively.

8. Measuring instruments

Several instruments are used in the *in situ* calibrations of voltage transformers, but not all of them have any direct influence on the results. Actually, only the transformer calibration bridge and the inductive voltage divider have a direct influence. The vector meter is used to determine the burden on the object under test and is therefore of some interest.

8.1. Transformer calibration bridge

8.1.1. General

The transformer calibration bridge TAB 79 is an automatic bridge built by Messwandlerbau GmbH in Germany. The instrument is based on a licence from Physikalisch Technische Bundesanstalt (PTB) in Braunschweig in Germany.

The bridge is designed to sense only the fundamental frequency of the power network voltage and incorporates high selectivity filters to accomplish this. It has numeric displays for direct readout of applied voltage, ratio error and phase displacement. Readout of the results to a computer is also possible via an IEEE 488 data bus. All settings on the bridge can be controlled both manually and by the computer. Readout of actual bridge settings to the computer is also possible via the data bus.

The operating principle of the bridge is based on evaluation of the difference voltage between a reference transformer and the object under test. This principle allows accurate measurements with a minimum expenditure of apparatus and effort.

8.1.2. Operating principle

The secondary winding of the transformer under test is connected to terminals X_U , X_V of the bridge and the secondary winding of the reference transformer to terminals N_U , N_V . This places the secondary windings in opposition to each other via internal connections in the bridge. See figure 16. The voltage $\underline{U}_\Delta$ at point N_V with respect the earth point X_V represents the difference between the secondary voltages.

A "normalised" difference voltage $\underline{U}_D$ is obtained by dividing the power frequency component of the difference voltage $\underline{U}_\Delta$ with a d.c. voltage $|\underline{U}_{ref}|$ proportional to the magnitude of the secondary voltage $\underline{U}_{ref}$ of the reference transformer. This difference voltage represents the vector quantity of the relative difference between the two transformers.

The difference vector $\underline{U}_D$ is decomposed into its components by synchronous sampling. The sampling is timed by an oscillator phase-locked to

Figure 16. Block diagram for transformer calibration bridge

the reference voltage $\underline{U}_{ref}$. The instantaneous value of $\underline{U}_D$ at the instant of zero crossing for the reference voltage is the quadrature component of $\underline{U}_D$. The instantaneous value of $\underline{U}_D$ at the instant of the peak for the reference voltage is the in-phase component of $\underline{U}_D$. The operating principle has been described in detail by the inventors Braun and Köhler [30].

The magnitude of the reference voltage is converted by a true rms A/D converter to a digital value, also presented on a readout.

The operation of the bridge as described above provides a true readout of in-phase and quadrature error components. These are a close approximation to the normally used ratio error and phase displacement concepts. The relation between the two error concepts is given by equation (2).

The above discussion presumes that the error of the reference transformer is zero. In practice this is not so, and the errors of the reference transformer have to be taken into account in the evaluation of the readings provided by the bridge. Relevant corrections are stored in the computer program used in the field calibrations and are automatically added to the readings to produce the true result.

8.1.3. Calibration

Calibration of the bridge is performed twice yearly, once immediately before the measuring season and once immediately after.

The calibration is performed as a simulated ratio measurement where operating voltage and difference voltage are connected directly to the terminals of the bridge as shown in figure 17. The difference voltage is applied as Cartesian components.

The operating voltage is applied on the reference transformer input terminals N_u and N_v . A precisely known fraction of this voltage and with a known phase is applied between the X_v terminal from the object under test and the N_v terminal of the reference transformer to obtain the simulated error voltage. The simulated error voltage is injected at precisely the same point as where the difference voltage is obtained under the normal operating conditions, cf. figure 16.

The ratio component of the simulated difference is obtained from the inductive voltage divider IVD1. The phase displacement voltage is obtained from a passive network consisting of a precision isolation transformer T1, an RC bridge and a second inductive voltage divider IVD2.

All components used in the calibration circuit are verified separately in routine calibrations performed each year.

The uncertainty in the calibration of the transformer calibration bridge for the 2% error range is less than $\pm 0.004\%$ of the ratio equal to ± 4 LSD (Least

Figure 17. Calibration circuit for transformer calibration bridge

Significant Digit in the display of the bridge) for the ratio error and less than ± 0.01 mrad or ± 1 LSD for the phase displacement. The uncertainty of the calibration of ratio error does however depend on the injected phase displacement, and for a phase displacement of less than 5 mrad, the uncertainty of the calibration for the ratio error becomes less than $\pm 0.001\%$ or ± 1 LSD. The other available ranges on the bridge are not used in the field calibrations. The uncertainty of the calibration is further discussed in [31].

The calibration program for the transformer calibration bridge is quite comprehensive and includes scanning of the measuring accuracy for the full range of ratio error and phase displacement respectively for the 2% error range plus a few combinations of them. Further the measurement accuracy for various test voltages, different error ranges and settings of the input divider circuit is determined. In total 45 different calibration points are checked.

8.1.4. Measurement uncertainty

The manufacturer's stated uncertainty for the transformer calibration bridge for the 2% error range is

$$\varepsilon = \pm 0.005\%$$

$$\delta = \pm 0.15 \text{ mrad } (\pm 0.5 \text{ min})$$

The results of the annual calibrations of the bridge show that the specification is always fulfilled and the deviations from the nominal values in the calibration do not even exceed the uncertainty of the calibration.

The environment of the bridge is controlled and in no way inferior to the laboratory environment the bridge is designed and specified for. To enumerate some of the factors taken into consideration, the ambient temperature is held constant by a climate control system, electrical disturbances are avoided since the instrument van is a Faraday cage. Disturbances from the power supply to the bridge are considered negligible since an extensive screening and transient protection are installed. The quality obtained for the mains voltage supply to the instruments is superior to that normally encountered in domestic installations.

In conclusion, the measurement uncertainty of the bridge is at least as good as specified by the manufacturer and can be assumed to correspond to a coverage factor $k=2$. The applicable standard deviation is therefore 0.0025 % and 0.075 mrad respectively.

8.1.5. Sensitivity to harmonics

A precision instrument such as the calibration bridge TAB may exhibit sensitivity to harmonics present on the output voltages from the voltage

transformers. As an example, the influence of harmonics was demonstrated by Richter [34] to have caused a systematic error larger than the estimated measuring uncertainty in the calibration of the in-house reference transformers at PTB in Germany.

For the TAB the most critical influence is expected on the measurement of the difference voltage. The magnitude of the harmonics in the difference voltage may be far larger than that of the fundamental due to non-linear frequency response in the voltage transformers.

Sample measurements in the field have shown that the total harmonic distortion is less than 0.4% on the voltage measured on the output of CVTs or approximately 0.25 V. The reference transformer NUES 420 has an almost linear frequency response below 10 kHz as shown in Chapter 14. A CVT, on the other hand, often has a resonance in the range 200 to 600 Hz with a peak that is two to four times the nominal ratio. The value of the actual difference in harmonic voltage between the CVT and the reference transformer outputs is unknown, but may in accordance with the above be estimated to be less than 0.75V.

An investigation of the sensitivity of the bridge to the presence of harmonics in the difference voltage was performed by supplying the bridge with 100 V, 50 Hz, between N_U and N_V and injecting a difference voltage between X_U and X_V , with harmonic voltages only. See figure 17 for identification of symbols. The presence of a combination of harmonic voltages in the difference voltage proved to be the worst case. With 1.5 V at 150 Hz plus 1.5 V at 250 Hz an influence of less than ± 0.01 % or ± 0.1 mrad could be observed on the TAB for the error range 2%. This case is worse than the estimated worst case in the field where less than 0.75 V is expected. This influence is estimated as a type B influence characterised by a difference between upper and lower bounds equal to $2a_i$. Equation (9) is applicable for the estimation of the standard deviation, giving 0.0058 % and 0.058 mrad respectively.

8.2. Inductive voltage divider

An inductive voltage divider is a transformer with very tightly coupled windings, usually in the form of an auto transformer. Due to the tight coupling, and the resulting low leakage inductance, the equivalent series reactance will be very low. A careful design with controlled capacitive distribution in the windings can easily produce errors less than a few parts per million for the ratio error and less than a few μ rad for the phase displacement at mains frequency. Inductive voltage dividers have been discussed by many authors, for example [32], [33] and [34].

Such an inductive voltage divider is customarily characterised for its maximum operating voltage by the maximum permissible voltage-frequency product, and an upper limit for the voltage.

For use with the mobile measuring system there are two inductive voltage dividers available, one with a maximum operating voltage of 350 V but not more than $2.5f$ V, where f is the operating frequency, and another with a maximum operating voltage of 500V but not more than $6f$ V. At mains frequency the voltage frequency product is the limiting case for both inductive voltage dividers and they can therefore be used up to 125 V and 300 V respectively. Routine calibrations of both of the inductive voltage dividers have demonstrated that they exhibit ratio errors of less than ± 0.00002 % (of full scale) and phase displacements of less than ± 0.001 mrad respectively. This influence is estimated as a type B influence characterised by a difference between upper and lower bounds equal to $2a_i$. Equation (9) is applicable for the estimation of the standard deviation, giving $0.00002/\sqrt{3}=0.000012$ % and $0.001/\sqrt{3}=0.0006$ mrad respectively.

The inductive voltage dividers are used on the input of the transformer calibration bridge to adapt special ratios in the object under test to the ratios available on the reference transformer.

8.3. Vector meter

8.3.1. General

The operating principle of the vector meter is similar to that of the transformer calibration bridge. The main difference is in the input circuits and the presentation of the result. The transformer calibration bridge measures the difference of the two input voltages (or the two currents in the case of current transformers) and presents an error reading. The vector meter, on the other hand, converts all input quantities, be it voltage or current, to a normalised voltage. One input channel is designated the reference channel N. The other input channel is the "measured quantity" designated X and is displayed as a vector fraction $a+jb$ of N. The two input channels are fully independent with transformer isolation on both inputs.

The internal voltage on the N-channel is used to control an internal clock via a phase-locked-loop to obtain synchronisation for the sampling of the voltage on the X-channel. The voltage on the X-channel is filtered to obtain the pure mains frequency signal. By sampling the filtered X-channel voltage at the peak of the reference voltage, the value of the in-phase component of the measurand is

obtained. The sampling at the zero-crossing of the reference voltage provides the out-of-phase, or quadrature, component.

The vector meter is very versatile and, depending on what quantities are measured at the N and X inputs, a number of different parameters can be calculated from the measured values. For example the errors of an instrument transformer, the complex impedance of a load or the complex power consumption of an object may be determined.

In the mobile measuring system the vector meter is used to measure the apparent power and power factor of the load on the voltage transformers at the actual operating voltage. The burden is calculated as the power that would have been obtained at the rated secondary voltage.

The uncertainty in the determination of the burden has no direct influence on the uncertainties in the determination of the errors of the voltage transformers. There is an indirect influence on the measurements made with artificial burden. In these measurements the value of the artificial burden is measured with the vector meter, and an error in the determination of the value of the burden results in an error in the transformer error versus burden curve. The uncertainty is of some interest when the results obtained with the installed burden are compared with those obtained with the variable burden. The uncertainty is however small and is considered to be negligible.

8.3.2. Calibration

The vector meter is calibrated before and after each measuring season. The results of the calibrations performed on the vector meter demonstrates that is always within its specifications. The calibration is performed by injecting current and voltage into the two respective inputs. The source of the test quantities is the power and energy meter calibration facility at SP.

The vector meter is mostly used with a small current transformer of clamp type with a stated uncertainty of $\pm 0.5\%$. A calibration is performed with the current clamp together with the vector meter as a part of the normal vector meter calibration.

8.3.3. Measurement uncertainty

The uncertainty in the determination of the power consumption may be evaluated from the specification of the vector meter. For the measurement of the reference quantity, in this case the voltage at the terminals of the voltage transformer, the uncertainty is $\pm 0.2\%$ of reading and ± 3 LSD (Least Significant Digit). All three readouts of the vector meter are $3\frac{1}{2}$ digits. For the measurand, in this case the load current, the uncertainty is $\pm 0.2\%$ of reading and ± 3 LSD in the largest of the quantities a and b . In the evaluation the fractional uncertainty $\pm 0.2\%$ is in both

cases regarded as obtained with procedures as those described by ISO/TAG 4 [26] and the value divided by 2 is used. The specification of digit uncertainty is taken as a maximum estimation and the value divided by $\sqrt{3}$ is used.

The uncertainty in the current ratio and the phase displacement of the current clamp must also be taken into account. The ratio error is specified to $\pm 0.5\%$ and the calibrations have shown that the long term variation is less than $\pm 0.5\%$. A total value of $\pm 0.7\%$ will be used in the analysis. The phase displacement is not specified but the long term variation is within ± 9 mrad ($\pm 0.5^\circ$). The uncertainties are taken as maximum estimations and the values are divided by $\sqrt{3}$ in accordance with equation (9).

Variation width in the measurements can be estimated to be less than ± 1 digit in each of the three measured quantities. This uncertainty is taken as a maximum estimation and the value is divided by $\sqrt{3}$.

Any errors caused by measuring cables and probes are deemed to be negligible.

An estimate of the influence on the calculated power of uncertainties in the above discussed quantities is not straightforward and must be evaluated from the basic equations for the apparent power and the phase angle of the load. ISO/TAG 4 [26] defines that the variance s_y^2 of an output quantity is given by the transfer function G and the variances $s_{x_i}^2$ of the (uncorrelated) input quantities x_i by equation (10)

$$s_y^2 = \sum_{i=1}^v \left(\frac{\partial G}{\partial x_i} \right)^2 s_{x_i}^2 \quad (10)$$

The equation defines the absolute variance S , but in many cases relative variance s can be used.

8.3.3.1. Apparent power

The apparent power as measured with the vector meter and the current clamp can be written as

$$S = U^2 \cdot k \cdot N \cdot \sqrt{a^2 + b^2} \quad (21)$$

where

U is the shown normalised value for the voltage measurement

k is a proportionality factor dependent on the measuring ranges chosen for the two channels

N is the ratio of the current clamp

a and b the vector quantities of the X channel

Taking the partial derivatives of equation (21) with respect to the input variables:

$$\begin{aligned}\frac{\partial \mathcal{S}}{\partial U} &= 2U \cdot k \cdot \sqrt{a^2 + b^2} \\ \frac{\partial \mathcal{S}}{\partial a} &= U^2 \cdot k \frac{a}{\sqrt{a^2 + b^2}} \quad \text{resp} \quad \frac{\partial \mathcal{S}}{\partial b} = U^2 \cdot k \frac{b}{\sqrt{a^2 + b^2}} \\ \frac{\partial \mathcal{S}}{\partial N} &= U^2 \cdot k \cdot \sqrt{a^2 + b^2}\end{aligned}\quad (22)$$

Formal multiplication in the respective equations by ∂U , ∂a , ∂b and ∂N followed by simplification yields the relative form

$$\begin{aligned}\frac{\partial \mathcal{S}}{S} &= \frac{2 \partial U}{U} \\ \frac{\partial \mathcal{S}}{S} &= \partial a \frac{a}{a^2 + b^2} \quad \text{resp} \quad \frac{\partial \mathcal{S}}{S} = \partial b \frac{b}{a^2 + b^2} \\ \frac{\partial \mathcal{S}}{S} &= \frac{\partial N}{N}\end{aligned}\quad (23)$$

In accordance with ISO/TAG 4 [26] the total relative variance for the apparent power can now be written

$$s_s^2 = \left(\frac{\Delta S}{S}\right)^2 = \left(\frac{2\Delta U}{U}\right)^2 + \left(\Delta a \frac{a}{a^2 + b^2}\right)^2 + \left(\Delta b \frac{b}{a^2 + b^2}\right)^2 + \left(\frac{\Delta N}{N}\right)^2 \quad (24)$$

For the variance in the measurands a and b it is noted that

$$\left(\Delta a \frac{a}{a^2 + b^2}\right)^2 + \left(\Delta b \frac{b}{a^2 + b^2}\right)^2 \leq \frac{(\max(|\Delta a|, |\Delta b|))^2}{a^2 + b^2} \leq \left(\frac{\max(|\Delta a|, |\Delta b|)}{\max(|a|, |b|)}\right)^2 \quad (25)$$

Therefore

$$\left(\frac{\Delta S}{S}\right)^2 \leq \left(\frac{2\Delta U}{U}\right)^2 + \left(\frac{\max(|\Delta a|, |\Delta b|)}{\max(|a|, |b|)}\right)^2 + \left(\frac{\Delta N}{N}\right)^2 \quad (26)$$

For the quantities a , b and U the influences of both the specification of the vector meter uncertainty and of the variation width in the measurement have to be considered. The vector meter specification in turn is divided in two components,

one that gives uncertainty as a fraction of reading and one that gives uncertainty in the least significant digit in the readout.

For the evaluation of the relative variance of the digit uncertainty in the specification of the vector meter it is assumed that the indicated value of the voltage U is not less than 60%. The maximum value is 199%. It is also assumed that the larger of a and b is not less than 20 %. Inserting the appropriate values in equation (26) and letting index f indicate the %-of-range uncertainty, d the digit uncertainty and v the variation width, the total variance is obtained

$$\begin{aligned} \left(\frac{\Delta S}{S}\right)^2 \leq & \left(2\frac{0.002}{2}\right)_f^2 + \left(2\frac{\left(\frac{0.003}{0.6}\right)}{\sqrt{3}}\right)_d^2 + \left(2\frac{\left(\frac{0.001}{0.6}\right)}{\sqrt{3}}\right)_v^2 + \\ & + \left(\frac{0.002}{2}\right)_f^2 + \left(\frac{\left(\frac{0.003}{0.2}\right)}{\sqrt{3}}\right)_d^2 + \left(\frac{\left(\frac{0.001}{0.2}\right)}{\sqrt{3}}\right)_v^2 + \left(\frac{0.007}{\sqrt{3}}\right)^2 = 142 \cdot 10^{-6} \end{aligned} \quad (27)$$

With a coverage factor $k=2$ the total uncertainty in the determination of the apparent power is estimated to ± 2.4 %.

8.3.3.2. Phase angle

The phase angle of the burden is obtained as

$$\varphi = \arcsin \frac{b}{\sqrt{a^2 + b^2}} - \gamma \quad (28)$$

where γ is the phase displacement of the current clamp.

Taking the partial derivatives of equation (28) with respect to the input variables:

$$\begin{aligned} \frac{\partial \varphi}{\partial a} &= \frac{-b}{a^2 + b^2} \\ \frac{\partial \varphi}{\partial b} &= \frac{a}{a^2 + b^2} \\ \frac{\partial \varphi}{\partial \gamma} &= -1 \end{aligned} \quad (29)$$

In accordance with ISO/TAG 4 [26] the total variance for the phase angle can now be written

$$S_{\varphi}^2 = (\Delta\varphi)^2 = \left(\frac{\Delta a \cdot b}{a^2 + b^2} \right)^2 + \left(\frac{\Delta b \cdot a}{a^2 + b^2} \right)^2 + (\Delta\gamma)^2 \quad (30)$$

Similarly as for the apparent power it is observed

$$\left(\frac{\Delta a \cdot b}{a^2 + b^2} \right)^2 + \left(\frac{\Delta b \cdot a}{a^2 + b^2} \right)^2 \leq \left(\frac{\max(|\Delta a|, |\Delta b|)}{\max(|a|, |b|)} \right)^2 \quad (31)$$

Therefore

$$(\Delta\varphi)^2 \leq \left(\frac{\max(|\Delta a|, |\Delta b|)}{\max(|a|, |b|)} \right)^2 + (\Delta\gamma)^2 \quad (32)$$

Using the same assumptions for the indicated values of U, /a/ and /b/ as for the apparent power, the total variance is obtained as:

$$(\Delta\varphi)^2 \leq \left(\frac{0.002}{2} \right)_f^2 + \left(\frac{0.003}{\frac{0.2}{\sqrt{3}}} \right)_d^2 + \left(\frac{0.001}{\frac{0.2}{\sqrt{3}}} \right)_v^2 + \left(\frac{0.009}{\sqrt{3}} \right)^2 = 112 \cdot 10^{-6} \quad (33)$$

With a coverage factor k=2 the total uncertainty in the determination of the phase angle is estimated to ± 21 mrad ($\pm 1.2^\circ$).

8.4. Variable burden

A variable burden is used to determine the error of the voltage transformer as a function of the burden. It is composed of a combination of resistors and inductances to achieve the desired apparent power and power factor. The normalised power factors are unity and 0.8, lagging (inductive load). For special purposes two other power factors, 0.6 lagging and 0.8 leading, are also available.

The purpose of the measurement with the variable burden is to determine the expected change in the error of the voltage transformer if the installed burden for the voltage transformer is changed in the future.

The uncertainty in the value of the apparent power of any setting of the variable burden is less than $\pm 3\%$. The (absolute) uncertainty in the power factor

is not specified, but may be estimated to be less than ± 0.02 . The burden imposed on the voltage transformer is however normally measured on-line during the calibration and the uncertainty is determined by the measuring circuit.

8.5. Summary of uncertainties for measuring instruments

The standard deviation for each input quantity has been directly estimated from the change in the output quantity y produced by a change in the input quantity in accordance with equation (13). All uncertainties discussed are uncorrelated and the variances can therefore be directly added to obtain the total variance for influences related to the measuring instruments.

All contributions have been evaluated as type B contributions.

Table 5. Estimated equivalent standard deviation of uncertainties for measuring instruments having a direct influence on the calibration of a voltage transformer

Quantity considered	ε [%]	δ [mrad]
TAB calibration	0.0025	0.075
TAB, influence of harmonics	0.0058	0.058
Inductive voltage divider	0.0000	0.001
Total standard deviation	0.0063	0.095

The uncertainty for the instruments used in the determination of the errors of the voltage transformers is estimated to ± 0.013 % and ± 0.19 mrad respectively with a coverage factor $k=2$.

The uncertainty for the determination of the installed burden is similarly estimated to ± 2.4 % and ± 21 mrad.

9. Measuring cable

9.1. Design

The measuring cable is custom built for its purpose and consists of three conductor pairs with individual braided copper screens. Surrounding all three pairs is an outer screen of braided copper with a cross section of 10 mm². Each conductor pair is twisted to reduce sensitivity to external magnetic fields. The conductor cross section is 1.5 mm² with an insulation designed for an operating voltage of 250 V rms. The insulation between screens is designed for an operating voltage of 150 V rms.

Figure 18. The design of the measuring cable

The inner screens of the cable have a metallic cover of better than 85 %, and the outer screen has a metallic cover of better than 92 %, providing a total metallic cover for the signal conductors of better than 98 %. The electrical screening is therefore considered more than adequate.

The twisting of the cable conductors ensures that a homogenous magnetic field gives rise to an equal and opposite e.m.f. in each bight caused by the twisting. The magnetic fields encountered in substations are mainly caused by the load current in the high voltage busbars and the ensuing magnetic fields are therefore semi-homogenous at the position of the measuring cable. The net induction in the measuring cable will therefore be small.

The cable is light and easy to handle but still has a good withstand for abnormal mechanical and electrical stresses. Any damage to the cable would furthermore be discovered by the 500 V insulation test performed in each substation and would only affect the results from one substation. During the

entire time of operation there has been no damage to the cable insulation and this supports the choice of design for the cable.

Heavy duty multiple prong watertight contacts from LEMO, Switzerland, are used for all measuring cable connections. The contact surfaces are gold-plated to ensure that contact resistance is negligible.

The longest single cable is around 60 meters, and when longer runs are required, several cables are used. Commonly required length in a substation is 150 meters although there have been cases where 350 meters have been necessary.

9.2. Coupling impedance

Current in the screen of a cable or in adjacent conductors in a cable may cause interference in a signal conductor pair in the cable by mutual coupling, and cause measuring errors. This effect was investigated by running a current in the screen or the adjacent conductors and measuring the influence voltage in the signal conductor pair.

The quotient of interference voltage to interfering current per unit length of the cable is often called the coupling impedance of the cable. Cf. page 19 in [35].

9.2.1. Between conductor pairs

Interference between conductor pairs may be at hand when the measurement of the error of a voltage transformer is performed with the variable burden connected via one of the conductor pairs in the cable. With a maximum burden of 150 VA at $110\text{V}/\sqrt{3}$, the current is less than 3 A.

A test was performed in the laboratory by injecting a current of 4 A, 50 Hz in one conductor pair of the measuring cable, while measuring the open loop voltage for the other conductor pair with a high sensitivity oscilloscope. The open loop configuration is valid since the input of the transformer calibration bridge has a high impedance, 400 kohm. The influence was measured for 50 and 410 m length of the cable and was in both cases found to be less than 0.1 mV peak.

Related to the normal operating voltage of 63.5 V, the measured interference voltage gives an interference less than $\pm 0.0002\%$. The test does not provide information on the phase and the influence must therefore be considered present both in ratio and in phase displacement.

The coupling impedance is in this case less than $0.5 \mu\text{ohm/m}$. The result expressed as interference voltage is however directly applicable for the estimation of uncertainty and will be used. This influence is estimated as a type B

influence characterised by a difference between upper and lower bounds equal to $2a_i$. Equation (9) is applicable for the estimation of the standard deviation, giving $0.0002/\sqrt{3}=0.00012\%$ and $0.002/\sqrt{3}=0.0012\text{ mrad}$ respectively.

9.2.2. Between outer screen and conductor pair

The outer screen of the measuring cable is normally earthed at both ends. A current will flow in the screen due to different earth potentials of the two earthing points and may cause interference in the signal conductor. The current as measured in several substations never exceeds 2 A.

A current of 10 A, 50 Hz, was injected in the outer screen of the measuring cable in order to investigate this effect. The open loop voltage in one signal conductor pair was measured for both 50 m and 410 m length of the cable. The interference voltage was less than 0.1 mV peak for the 50 m length and less than 0.35 mV peak for 410 m length. The coupling impedance is therefore less than $0.2\text{ }\mu\text{ohm/m}$.

Related to the normal operating voltage of 63.5 V, this interference voltage is less than $\pm 0.0004\%$ in ratio or $\pm 0.004\text{ mrad}$ in phase. This influence is estimated as a type B influence characterised by a difference between upper and lower bounds equal to $2a_i$. Equation (9) is applicable for the estimation of the standard deviation giving $0.0004/\sqrt{3}<0.0003\%$ and $0.004/\sqrt{3}<0.003\text{ mrad}$ respectively.

9.3. External magnetic fields

The external magnetic fields encountered in a switchyard may reach levels of the order of 5 to 50 μT at ground level. The magnetic field under fault conditions may of course reach much higher levels, but this is of no interest in this discussion. This case was investigated by placing a cable carrying an a.c. current $I = 200\text{ A}$ at a distance $a = 0.5\text{ m}$ from the measuring cable for length of 6m. The magnetic field in the experimental set-up can be approximately calculated by means of the formula for the field around an infinitely long conductor

$$\begin{aligned} B &= \mu \mu_0 H \\ H &= \frac{I}{2\pi a} \end{aligned} \tag{34}$$

For the present case the magnetic field strength at the measuring cable was calculated to 80 μT .

The open loop voltage in the measuring cable was measured to be less than 0.6 mV, which was also the background noise level at zero current.

Another test was performed by winding a current carrying conductor on a cable drum with 56 m of measuring cable. Running 800 A in one turn gave an

interference voltage of less than 0.2 mV in the open loop configuration for the signal conductor. Without calculations it can be shown that this case is much more severe than any that can occur in practice. The current in the busbars in the substation can be estimated as less than 1000 A at the time calibrations are performed. The busbars are located 6 m or more away from the measuring cable and will give a magnetic field less intense and less divergent than the one obtained in the test.

In conclusion the interference voltage caused by magnetic fields for any conceivable configuration of busbars and measuring cable position will be less than 0.6 mV. Related to operating voltage of 63.5V, this voltage gives an influence of less than $\pm 0.001\%$ in ratio or 0.01 mrad in phase. This influence is estimated as a type B influence characterised by a difference between upper and lower bounds equal to $2a_i$. Equation (9) is applicable for the estimation of the standard deviation, giving $0.001/\sqrt{3}=0.0006\%$ and $0.01/\sqrt{3}=0.006$ mrad respectively.

9.4. Effect of capacitive currents

The measuring cable has a distributed capacitance δC_1 of (153 ± 6) pF/m between conductor and the screen. The distributed capacitance between the two signal conductors is $\delta C_2=(19 \pm 2)$ pF/m. These capacitances have been calculated from measurements of the capacitance between conductors and between conductor and screen. The cable also has a distributed resistance $\delta R = 0.011$ ohm/m in each signal conductor.

To analyse the influence of the capacitive currents on the measurements a simple two-conductor arrangement as in figure 19 and the voltage drop in one conductor is first analysed.

Figure 19. Equivalent circuit for capacitive currents in an infinitesimal section dx of a cable at distance x from the source

The equivalent circuit shows an infinitesimal part dx of a cable with capacitance δC and resistance δR , each per unit length. The capacitive current per unit length in δC is $\delta i = -U_0 j \omega \delta C$. The inductance of the cable has been disregarded since

the resistive voltage drop dominates at power frequency. The total voltage drop ΔU is furthermore assumed to be negligible compared to U_0 .

The voltage drop dU across δR may now be written:

$$dU = i_x \cdot \delta R dx$$

where

$$i_x = \int_0^x \delta i dx = \delta i \int_0^x dx = x \delta i$$
(35)

Finally the total voltage drop U in the conductor is:

$$\Delta U = \int_0^L dU = \int_0^L \delta R i_x dx = \int_0^L \delta R x \delta i dx = -\frac{1}{2} U_0 j \omega \delta C \delta R L^2$$
(36)

The actual cable is more complex with two parallel signal conductors and a screen encircling both conductors. The combined influence of the two cables involved in the measurements, namely the one to the reference transformer and the one to the CVT, must also be taken into account.

Figure 20. Capacitive currents identified in the actual measuring cable

The distributed capacitive currents in the measuring cable are represented by i_1 through i_4 .

Beginning with the cable between the TAB and the CVT it is found that the current i_1 causes a voltage drop in the phase conductor L1 and in the neutral conductor N that can both be written

$$-U_0 j \omega \delta C_2 \delta R b^2/2$$

The current i_2 causes a voltage drop in L1 that is

$$-U_0 j \omega \delta C_1 \delta R b^2/2$$

This capacitive current i_2 is returned to the CVT winding via the earth. In the cable between the reference transformer and the TAB the current i_3 causes a voltage drop in the phase conductor and in the neutral conductor N that can both be written

$$-U_0 j \omega \delta C_2 \delta R a^2 / 2$$

The current i_4 causes a voltage drop in L1 that is

$$-U_0 j \omega \delta C_1 \delta R a^2 / 2 - U_0 j \omega \delta C_1 \delta R ab$$

This capacitive current i_4 is supplied by the CVT. The first term relates to the voltage drop in the cable to the left of the TAB in figure 20, the other term relates to the voltage drop in the cable to the right. The current i_4 is returned to the CVT via the earth.

The voltage drops identified above are all additive with the exception of the one caused by i_3 . The total error voltage ΔU introduced by the capacitive currents is therefore the sum of the individual voltages for the phase conductor L1, CVT neutral N and reference transformer neutral respectively:

$$\begin{aligned} U_{L1} &= -U_0 j \omega \delta R \left\{ \frac{1}{2} (\delta C_1 + \delta C_2) b^2 + \frac{1}{2} (\delta C_1 - \delta C_2) a^2 + \delta C_1 ab \right\} \\ U_{CN} &= -U_0 j \omega \delta R \frac{\delta C_2}{2} b^2 \\ U_{RN} &= U_0 j \omega \delta R \delta C_2 \frac{a^2}{2} \end{aligned} \quad (37)$$

The total error voltage ΔU is obtained by adding the contributions defined by the above equations

$$\Delta U = -U_0 j \omega \delta R \left\{ \left(\frac{\delta C_1}{2} + \delta C_2 \right) b^2 + \left(\frac{\delta C_1}{2} - \delta C_2 \right) a^2 + \delta C_1 ab \right\} \quad (38)$$

This is evaluated for a maximum case of the distance a from the instrument van to the reference transformer equal to 100 m, and the distance b between the instrument van and the CVT equal to 400 m to:

$$\Delta U = -U_0 \cdot j \cdot 75.9 \cdot 10^{-6}$$

The maximum phase displacement caused by the capacitive currents in the measuring cable is therefore estimated to be less than ± 0.076 mrad. The contribution in ratio is estimated to zero. This influence is estimated as a type B influence characterised by a difference between upper and lower bounds equal to $2a_i$. Equation (9) is applicable for the estimation of the standard deviation, giving $0/\sqrt{3}=0$ % and $0.076/\sqrt{3}=0.044$ mrad respectively.

The individual currents can also be calculated and are useful for reference in the field. The currents at the measuring bridge TAB are:

$$\begin{aligned} I_{L1} &= I_4 = -U_0 j\omega \delta C_1 a \\ I_N &= 0 \end{aligned} \quad (39)$$

Evaluating this for the same cable lengths as above and with $U_0=63.5$ V

$$I_{L1}=0.3 \text{ mA}$$

At the CVT the following is obtained

$$\begin{aligned} I_{L1} &= I_1 + I_2 - I_3 + I_4 = -U_0 j\omega \{ \delta C_1(a+b) + \delta C_2(b-a) \} \\ I_N &= I_2 = -U_0 j\omega \delta C_1 a \end{aligned} \quad (40)$$

Evaluating this for the same cable lengths as above and with $U_0=63.5$ V

$$I_{L1}=1.6 \text{ mA}$$

$$I_N=0.3 \text{ mA}$$

Measurements made at several substations have given values approximately equal to the calculated. The measurements therefore validate the calculated influence on the measurements.

9.5. Series resistance of the measuring cable

The series resistance of the cable is measured to 0.011 ohm/m for each signal conductor. For a cable length of 400 m the total resistance of the twisted pair is therefore 8.8 ohm. This resistance acts as a voltage divider in conjunction with the input impedance of the TAB to produce an error. The input impedance is 400 kohm and the calculated voltage drop is ± 0.0022 %. The phase angle of the TAB impedance is not known and the error must therefore be assumed to be present both in the ratio and in the phase displacement components. This influence is estimated as a type B influence characterised by a difference between upper and

lower bounds equal to $2a_i$. Equation (9) is applicable for the estimation of the standard deviation, giving $0.0022/\sqrt{3}=0.0013\%$ and $0.022/\sqrt{3}=0.013\text{ mrad}$ respectively.

9.6. Voltage probes

Voltage probes with integral 10 A fuses with 100 kA breaking capacity are used for all connections between the signal cables and the object under test. The probe leads are unscreened and have a length of 1.5 m. The fuses ensure the safety of the personnel by interrupting short circuit currents caused either by incorrect connections or by failure in any part of the equipment. The fuses are an important aspect of the total safety philosophy employed in the measurements.

9.6.1. Probe series resistance

Repeated measurements on the probes have revealed that end-to-end resistance of a probe after long use does not exceed 0.4 ohm. In comparison the voltage circuit to the transformer calibration bridge can have a total resistance of approximately 9 ohm, most of which derives from the measuring cable. The estimated maximum additional influence from the resistance of the probe is estimated to $\pm 0.0001\%$ in the ratio error or $\pm 0.001\text{ mrad}$ in the phase displacement. This influence is estimated as a type B influence characterised by a difference between upper and lower bounds equal to $2a_i$. Equation (9) is applicable for the estimation of the standard deviation, giving $0.0001/\sqrt{3}=0.00006\%$ and $0.001/\sqrt{3}=0.0006\text{ mrad}$ respectively.

9.6.2. Capacitive influence

The connecting leads from the probes to the special measuring cable are unscreened for a total length of 2 m. A capacitive influence from the high voltage busbars to the measuring circuit is therefore present. The effect is however shunted by the low impedance of the voltage transformer secondary circuit.

The influence is estimated by means of a discussion of the corresponding electrostatic case. The charge Q in an electrode is the integral of the electric flux over the surface of the electrodes and the electric flux is the electric field multiplied by the permittivity of the medium. In the present case, the electrodes are the high voltage busbars and the probe leads.

$$Q = \iint D dS$$

$$D = \varepsilon E$$
(41)

The electric field E in a substation is normally not more than 10 kV/m at ground level. Disregarding the distorting effect on the field by the presence of the probe leads and assuming an effective surface area A of less than 2 m² for the probe leads, the charge is calculated to be

$$Q = \varepsilon_0 EA \approx 8.8 \cdot 10^{-12} \cdot 10^4 \cdot 2 = 176 \cdot 10^{-9} \text{ C}$$

The capacitive current is obtained by multiplying with the angular frequency ω of the busbar voltage.

$$I = \omega Q \approx 314 \cdot 176 \cdot 10^{-9} \approx 55 \cdot 10^{-6} \text{ A}$$

The output impedance of the test objects, the voltage transformers, can be estimated from the observed changes in ratio error and phase displacement with the burden. The maximum change in ratio error and phase displacement from zero burden to 150 VA at a power factor of 0.8 is 2% and 10 mrad (34 min) respectively. It can from this be deduced that the highest output series resistance of a CVT is 0.6 ohm in series with a reactive impedance of 0.1 ohm. The stated maximum changes are valid for all CVTs except 18 very old units built before 1960. The voltage drop caused by the capacitive current can therefore be estimated as less than ± 0.00006 % in the ratio and less than ± 0.0033 mrad in phase displacement. This influence is estimated as a type B influence characterised by a difference between upper and lower bounds equal to $2a_i$. Equation (9) is applicable for the estimation of the standard deviation, giving $0.00006/\sqrt{3}=0.000035$ % and $0.0033/\sqrt{3}=0.0019$ mrad respectively.

9.6.3. Induction in probe leads

The probe connecting leads are not always twisted and there may be a certain influence between the voltage circuit to the measuring bridge and the cable pair connecting the burden to the object under test. Testing this for a worst case configuration with the cable pairs running adjacent to each other at a distance of 50 mm and a load current of 4 A in one pair gave an interference voltage of less than 1 mV but with a background noise level of the same magnitude. The separation between conductors in each pair was 100 mm. Related to the normal operating voltage of 63.5 V, the interference level is estimated as less than 0.002 % in ratio or 0.02 mrad in phase displacement. This estimate is of the type $2a_i$ and equation (9) is applicable for the estimation of the standard deviation, giving $0.002/\sqrt{3}=0.0012$ % and $0.02/\sqrt{3}=0.012$ mrad respectively.

9.7. Summary of uncertainties associated with the measuring cable

The standard deviation for each input quantity has been directly estimated from the change in the output quantity y produced by a change in the input quantity in accordance with equation (13). All uncertainties discussed are uncorrelated and the variances can therefore be directly added to obtain the total variance for influences related to the measuring cables.

All contributions have been evaluated as type B contributions.

Table 6. Estimated equivalent standard deviation of uncertainties associated with the measuring cable

Quantity considered	ε [%]	δ [mrad]
Coupling impedance between twisted pairs	0.0001	0.001
Coupling impedance between signal pair and outer screen	0.0003	0.003
Induction in measuring cable from external magnetic fields	0.0006	0.006
Capacitive currents in measuring cable	0	0.044
Series resistance of measuring cable	0.0013	0.013
Resistance of voltage probe	0.0001	0.001
Capacitive coupling to voltage probe leads	0.0004	0.002
Induction in voltage probe leads loop	0.0012	0.012
Total standard deviation	0.0019	0.048

The total measuring uncertainty associated with effects in the measuring cable is ± 0.0038 % in ratio and ± 0.096 mrad in phase displacement for a coverage factor $k=2$.

10. Site specific effects

Generally the connection point for the reference transformer will be at a distance from the tested object. The load current in the high voltage busbars will cause a voltage drop in the busbar series impedance that will be manifest as a measuring error in the determination of ratio error and phase displacement of the voltage transformer.

Wave travel time could conceivably cause an additional error. The size of any substation is however much less than the wave length at power frequency and the effect is negligible.

So-called line traps may be inserted between the CVT and the substation to block power line carrier signals. The voltage drop caused by the load current through the power frequency impedance of the coils of the line traps is also a source of measuring errors.

10.1. Load carrying bus

The load current in the bus is composed of an in-phase component, the active current I_A , and of a quadrature component, the reactive current I_R . The total current in the bus causes a voltage drop across the series impedance of the bus. The impedance is composed of the series resistance R and of the inductance L and the voltage drop may be written as

$$U = (I_A + jI_R)(R + j\omega L) = I_A R - I_R \omega L + j(I_A \omega L + I_R R)$$

$$\begin{aligned} \operatorname{Re}(U) &\leq |I_A R| + |I_R \omega L| \\ \operatorname{Im}(U) &\leq |I_A \omega L| + |I_R R| \end{aligned} \tag{42}$$

The real part of the equation represents the in-phase error and the imaginary part represents the quadrature error. These are in the following used as approximations for the contribution in ratio error and phase displacement respectively.

In a large 400 kV substation with 600 m of bus runs between the reference transformer and the object under test, it could be estimated that no more than 400 m of the bus carries a load current. The power flow between the two points will in general not be uni-directional and the total influence can be estimated as not worse than 200 m of bus with the maximum current. There is an ambiguity in the direction of the error that can not be resolved since the direction of the power flow is not recorded. This error must therefore be treated as an uncertainty. The distances tend to be shorter in substations for lower voltages and it is assumed

Table 7. Voltage drop in substation busbars due to the load current in the busbars estimated for different system voltages.

	400 kV	220 kV	130 kV
Re(U) [V]	9	7	5
Im(U) [V]	63	47	31

that the longest equivalent bus length with maximum current will be 150 m at 220 kV and 100 m at 130 kV. The maximum current is assumed to have the same value regardless of system voltage.

A typical bus impedance can be estimated for the case of the twin SAL 910 conductor. This is a 910 mm² all aluminium conductor. The resistance in twin SAL 910 bus is estimated as 15 mohm per km and the inductance is estimated as 1mH per km. The complex impedance is therefore (0.015 + j0.314) ohm/km at 50 Hz.

Estimating the maximum active load current within a substation as no more than 1000 A and the reactive load current as no more than 100 A at the time calibrations are performed, it is found that the maximum voltage drop in substations with different system voltage is as given in table 7.

The relative error caused by this voltage drop is obtained by dividing with the phase-to-earth voltage of the high voltage bus.

This influence is estimated as a type B influence characterised by a difference between upper and lower bounds equal to $2a_i$. Equation (9) is

Table 8. Standard deviation for load current effects for different system voltages

System voltage [kV/ $\sqrt{3}$]	Contribution in ratio		Phase displacement	
	Max. error [±%]	Std. dev. [%]	Max. error [±mrad]	Std dev. [mrad]
400	0.0039	0.0023	0.273	0.158
220	0.0055	0.0032	0.370	0.214
130	0.0067	0.0039	0.426	0.246

applicable and the relative standard deviation is therefore obtained by dividing the maximum relative error by $\sqrt{3}$.

10.2. Wave travel time

Power frequency would normally be considered a stationary case, at least for a geometry that has the size of a substation. In the present context, very high requirements are posed on the accuracy of the measurements and the claim that this case can indeed be regarded as a stationary case should be substantiated. This is done here by analysing the case of an open-ended line with transmission line theory.

Figure 21. Schematic representation of open-ended line

According to transmission line theory, a voltage wave arriving at the open end of the line will be reflected with conservation of the polarity. Adding this reflected wave to the incoming wave, the generator end voltage U_i and the open end voltage U_e can be written as:

$$\begin{aligned} U_i &= U_0 \cos \omega t + U_0 \cos \omega(t - 2\alpha) = 2U_0 \cos \omega(t - \alpha) \cos \omega\alpha \\ U_e &= 2U_0 \cos \omega(t - \alpha) \end{aligned} \quad (43)$$

The result shows that for this idealised case there is no phase difference between the two ends of the line. There is however a small amplitude difference that can be estimated by calculating the difference in voltage between the two ends of the line:

$$\begin{aligned} \frac{U_e - U_i}{U_0} &= 2 \cos \omega(t - \alpha) \cos \omega\alpha - 2 \cos \omega(t - \alpha) = \\ &= 2 \cos \omega(t - \alpha) (\cos \omega\alpha - 1) \end{aligned} \quad (44)$$

Series expansion of the term within parentheses gives

$$\cos \omega\alpha - 1 = \left(1 - \frac{\omega^2 \alpha^2}{2} + \frac{\omega^4 \alpha^4}{24} - \dots \right) \approx -\frac{\omega^2 \alpha^2}{2} \quad (45)$$

The voltages on the two ends of the transmission line are equal within $\omega^2\alpha^2/2$ p.u. for the in-phase component. The voltages at the two ends of the line are in phase and the quadrature component is zero. The in-phase component is approximately equal to the ratio error and the quadrature component is approximately equal to the phase displacement.

The measuring cable and an open bus end are adequately represented by this model. At power frequency (50 Hz) on a bus length of 600 m and assuming the wave velocity to be the speed of light, it is found that the ratio error contribution is $\omega^2\alpha^2/2 = 0.2 \cdot 10^{-6}$. The same result is obtained for a measuring cable length of 400 m with a wave velocity of 0.65 of the speed of light. The ratio error contribution is negligible in both cases.

10.3. Power line carrier components

Power line carrier (PLC) systems are used on the 220 and 400 kV power networks for communication purposes. On incoming lines to a substation there are normally two CVTs used as coupling capacitances for PLC communication systems. Of the total population of CVTs approximately half are used for PLC circuits. A simplified circuit diagram for the power frequency equivalent of a typical PLC installation is given in figure 22.

The insertion of a high frequency blocking circuit in the earth connection of the capacitive divider of the CVT could presumably affect the accuracy of the CVT at power frequency. The two drain coils in the low voltage tap of the CVT have an inductance of 21 mH and 0.23 to 2.12 mH respectively. In the worst case the resulting inductance in the low voltage tap of the CVT is 1.9 mH which at a power frequency current of 0.5 A gives a voltage drop of 0.3V. This voltage in relation to the intermediate voltage level of approximately $20/\sqrt{3}$ kV gives an error of 0.0026% and 0.0 mrad. Investigation of a few typical CVT installations revealed a difference less than 0.005% in the voltage ratio and less than 0.03 mrad in the phase displacement between having the drain coils short-circuited and not. This influence is estimated as a type B influence characterised by a difference between upper and lower bounds equal to $2a_i$. Equation (9) is applicable for the estimation of the of the standard deviation, giving $0.005/\sqrt{3}=0.0029\%$ and $0.03/\sqrt{3}=0.017$ mrad respectively.

The line trap in the high voltage line is used to isolate the busbars in the substation from the PLC signals on the line. The inductance of the line trap coil is typically 0.5 mH. The maximum line current encountered during the period that the *in situ* calibration is performed can be estimated to no more than 500 A active current and 50 A reactive current, resulting in a voltage drop of 79 V in phase and 7.9 V in quadrature. Referred to the operating voltage on the 220 kV

Figure 22. Power line carrier coupling impedances

and 400 kV networks, a maximum influence of $\pm 0.0062\%$ and ± 0.62 mrad at 220 kV and $\pm 0.0034\%$ and ± 0.34 mrad at 400 kV is obtained. This influence is estimated as a type B influence characterised by a difference between upper and lower bounds equal to $2a_i$. Equation (9) is applicable for the estimation of the standard deviation and the relative standard deviation is 0.0036% and 0.36 mrad for 220 kV and 0.002% and 0.2 mrad for 400 kV.

10.4. Summary of uncertainties associated with site specific effects

The standard deviation for each input quantity has been directly estimated from the change in the output quantity y produced by a change in the input quantity in accordance with equation (13). All uncertainties discussed are uncorrelated and the variances can therefore be directly added to obtain the total variance for influences related to the site specific effects.

All contributions have been evaluated as type B contributions.

Table 9. Total estimated equivalent standard deviation associated with site specific effects for different system voltage

Quantity considered	400 kV		220 kV		130 kV	
	ε [%]	δ [mrad]	ε [%]	δ [mrad]	ε [%]	δ [mrad]
Load carrying bus	0.0023	0.158	0.0032	0.214	0.0039	0.246
Wave travel time	0	0	0	0	0	0
CVT drain coils	0.0029	0.017	0.0029	0.017	0	0
Line trap	0.0020	0.200	0.0036	0.360	0.0000	0.000
Total standard deviation	0.0042	0.255	0.0056	0.419	0.0039	0.246

With a coverage factor $k=2$, the total measuring uncertainty associated with site specific effects is ± 0.0084 % in ratio and ± 0.51 mrad in phase displacement for a 400 kV substation.

11. Evaluation of total measurement uncertainty

The uncertainties in the calibration of voltage transformers have been discussed as pertains to the reference transformer, the measuring instruments, the measuring cable and the site specific effects. The observed variation width in the measurements and the difference between polar and Cartesian representation of errors should also be considered.

The uncertainties shall be added in accordance with the provisions of ISO/TAG 4 [26] and the resulting standard deviation shall be multiplied by 2 to obtain the total uncertainty. It is however practical to distinguish between two groups of uncertainties, the uncertainties associated with the measuring system and those associated with the measuring situation (the site specific effects).

11.1. Measuring system uncertainty

The uncertainties of the measuring system are summed from the results obtained previously and for the difference between polar and Cartesian representation of errors. The latter is estimated as per equation (2) and the contribution is $\pm 0.0041\%$ and ± 0.054 mrad. This influence is estimated as a type B influence characterised by a difference between upper and lower bounds equal to $2a_j$.

Equation (9) is applicable for the standard deviation giving 0.0024% and 0.031 mrad respectively.

Table 10. Estimated equivalent standard deviation for measuring system uncertainty

Quantity considered	ε [%]	δ [mrad]
Reference transformer	0.0052	0.053
Measuring instruments	0.0063	0.095
Measuring cable	0.0019	0.048
Cartesian to polar conversion	0.0024	0.031
Total standard deviation	0.0087	0.123

The total uncertainty of the measuring system itself for a coverage factor $k=2$, is thus estimated to $\pm 0.017\%$ and ± 0.25 mrad (± 0.9 minutes).

11.2. Site specific effects

The site specific effects in the substation are substantially the additional errors caused by the load current in the high voltage busbars and in certain cases also in the coils of line traps for PLC systems. The applicable standard deviation for this effect is different for different system voltages as tabulated in table 9.

11.3. Observed variation width

The applicable standard deviation for the variation width of the ratio error measurement can be estimated from the recorded values of the standard deviation in each measurement. Each recorded value of ratio error and phase displacement is obtained as the mean value of 10 measurements separated by approximately one second in time. The variation that may be present due to variations in the object under test is not considered, the calibration is valid at the time of the calibration and any long term instability in the object under test must be evaluated by other means. The standard deviation s_{ε_i} for the 10 measurements of the ratio error is recorded and is available for over 5000 recorded points. The mean value of s_{ε_i} is 0.0008 % (of the ratio) with a standard deviation of 0.0033% (of the ratio). Taking the mean value of s_{ε_i} plus two standard deviations, 0.0074% (of the ratio) as the applicable standard deviation of the distribution of the variation width is conservative, but will be used. In accordance with ISO/TAG 4 [26] and equation (6), the standard deviation s_{ε} of the variation width of the ratio error shall be adopted as $s_{\varepsilon}=0.0074/\sqrt{10}=0.0024\%$, where 10 is the number of measurements. The standard deviation of the phase displacement is not recorded, but experience has shown a normal variation clearly less than ± 0.12 mrad (± 0.4 min). The standard deviation of the variation width in the phase displacement is thus estimated as per equation (9) to be ± 0.069 mrad.

11.4. Total uncertainty

The total uncertainty is evaluated from the above three components measuring system, site specific effects and variation width. The influence of the distance effects is different for different system voltages and the uncertainty must be evaluated for each voltage level separately. All contributions have been evaluated as type B contributions except the variation width, which has been evaluated as a type A contribution.

Table 11. Estimated equivalent standard deviation for total measuring uncertainty for different system voltages

Quantity considered	400 kV		220 kV		130 kV	
	ε [%]	δ [mrad]	ε [%]	δ [mrad]	ε [%]	δ [mrad]
Measuring system	0.0087	0.123	0.0087	0.123	0.0087	0.123
Site specific effects	0.0042	0.255	0.0056	0.419	0.0039	0.246
Variation width	0.0024	0.069	0.0024	0.069	0.0024	0.069
Total standard deviation	0.0100	0.291	0.0106	0.442	0.0098	0.284

For a coverage factor $k=2$, the resulting total measuring uncertainty is twice the total estimated equivalent standard deviation.

Table 12. Summary of total measuring uncertainty for a coverage factor $k=2$

System voltage [kV]	Ratio error [%]	Phase displacement [mrad]	Phase displacement [minutes]
400	0.020	0.64	2.2
220	0.022	0.89	3.1
130	0.020	0.57	2.0

As an overall figure for the uncertainty of the measuring system and including all site specific effects for any of the system voltages considered, it is suitable to cite $\pm 0.022\%$ for the uncertainty in the voltage ratio and ± 0.9 mrad for the phase displacement.

12. The capacitor voltage transformer

12.1. History

An early precursor of the CVT was the potential device utilising the capacitive tap of transformer bushings to obtain a signal that could be used for indication and protection purposes. The limited capacitance and stability of capacitance precluded the development of this system into a voltage transformer with sufficient accuracy for metering purposes.

With the installation of large high voltage networks came also a need for reliable communication systems between substations and operations centres. Power Line Carrier (PLC) systems were developed as a solution to this problem. A PLC system utilises the high voltage conductors to transmit modulated medium frequency (often in the range 20 - 200 kHz) signals on the network. The signals are coupled into the conductors by means of coupling capacitors. These coupling capacitors have a fairly large capacitance to couple the PLC signals sufficiently well and are therefore suitable as capacitive dividers for capacitor voltage transformers. As early as in the 1930's a low-side capacitor was added to the PLC capacitor to obtain a voltage divider useful at least to drive indicating devices and protection relays [³⁶]. Somewhat later an intermediate transformer was added to increase the output power of the device and to reduce output voltage to the level normally used in secondary voltage circuits. A resonating inductor placed in the secondary circuit of the transformer could be used to enhance accuracy and output power. In the period following World War II, transmission voltages were increased in response to increasing demand for electric energy supply. A need for metering on very high voltage systems followed. The cost for conventional transformers increases sharply with the operating voltage, and gave an incentive to improve the existing potential devices. Moving the inductor to the high voltage side of the intermediate transformer proved to be the major improvement needed to provide the potential device with the stability and accuracy required for use in metering service. This device was the first example of the modern CVT.

Since the cost of a high voltage CVT is less than that of an inductive transformer and since the coupling capacitors are needed in the substations anyhow, the development of the CVT presented a possible double gain, saving both the cost of an additional piece of equipment and on using a cheaper type [³⁷], [³⁸].

In Sweden a close co-operation between ASEA [³⁹] and the Swedish State Power Board led to an early introduction of the CVT both for protection and for metering purposes. This fact is also mirrored in the fact that the Swedish

Standards Committee officially recognised the CVT as early as 1957 [40]. Official recognition of the CVT in IEC standards did not come until 1969.

12.2. Design and characteristics

The CVT consists of three major components, a capacitive divider, a compensating reactance and an intermediate transformer. The two latter together are called the electromagnetic unit. See figure 23. The capacitive divider, C1 and C2, shall supply the power for the electromagnetic unit and to the burden. The purpose of the compensating reactance L is to cancel the equivalent series reactance of the high voltage capacitor at power frequency. With a well-tuned reactance a CVT yields an output that is nearly independent of the burden.

The optimisation of a CVT is a complex matter including consideration not only of the high voltage capacitance and the intermediate voltage level, which to a large extent determine the accuracy attainable, but also the magnetisation in the core with respect both to cost and to the risk for ferro-resonance due to core saturation. Introduction of damping circuits Z is often used to control ferro-resonance and to ameliorate transient response [38]. The unavoidable winding resistances and parasite capacitances of the transformer and the compensating reactance in the electromagnetic unit have been disregarded in figure 23, but the operation of the CVT is sufficiently well characterised for the present discussion by this simplified circuit.

Figure 23. Equivalent circuit for a CVT showing the capacitive divider and the electromagnetic unit. The latter comprises the compensating reactance L, the intermediate transformer and the damping circuit Z

An inductive voltage transformer is not expected to undergo any serious change in transfer characteristics with time since its voltage ratio is tightly coupled with the turns ratio of the transformer. In the CVT, on the other hand, the ratio error and phase displacement can be influenced by a number of parameters, and control of these parameters is essential in CVT design [15] , [38]. Changes in the

transformer in the electromagnetic unit are not a concern but changes in the compensating reactance and in the capacitive divider must be reckoned with. Some designs for ferro-resonance control and transient response control use components that may be susceptible to changes that affect the overall accuracy of the device.

The components of the divider stack may change on a reversible basis due to temperature effects. The choice of dielectric in the capacitors governs the influence of temperature on the capacitance ratio. Originally capacitors were manufactured with oil impregnated paper as insulating medium. The oil-paper dielectric has an appreciable sensitivity to temperature, the total capacitance change over the range -40°C to 20°C is on the order of 3%. The change in the ratio of the capacitive divider is ideally zero, but imperfect tracking of the temperature coefficients and/or the temperature tracking of the high and low voltage arms of the capacitive divider may lead to a non-negligible change of the divider ratio. Today mixed dielectrics with oil, paper and plastic films are used. A judicious choice of materials and of the thickness of the different insulating materials, will produce a compound dielectric with practically constant permittivity for a very wide temperature range. The change in capacitance of a well-designed capacitor can be less than 0.5% for the temperature range -40°C to 20°C . The use of these materials has made it possible to design stable CVTs with accuracy class 0.2.

The total internal capacitive current of the stack must be large enough to make the influence of external leakage currents negligible. In order to meet the requirements, the CVT is normally designed to draw a capacitive current that is of the order of 0.5 A. Even so, heavy pollution and/or rain have been known to cause problems on stacks with more than one porcelain housing.

The presence of nearby energised and/or earthed objects may change the capacitive current in the capacitor stack and cause measuring errors. The capacitance of the stack must be much larger than the stray capacitances to nearby objects and the higher the desired precision of the CVT is, the higher the capacitance must be.

Irreversible effects on the capacitance may be caused by degrading of the insulation medium, change in capacitor plate area by for example wrinkling of the capacitor foil or by change in the distance between capacitor plates. These effects are gradual and may not be immediately apparent. Each stack is a series connection of many elements, as many as 300 is quite common at 400 kV system voltage, and even a total failure of one element may not be immediately apparent. A precise determination of the ratio error and phase displacement will often be required to detect such failures.

The compensating reactance is mostly designed as an iron core inductor with one or more gaps to avoid saturation and to linearise the characteristic. Mechanical deformation of the core and spacers can change the inductance and cause a detuning of the CVT. Detuning will result in increased phase and ratio errors as well as in an increased sensitivity to changes in the burden.

The non-linear magnetisation characteristics of the transformer in the electromagnetic unit can, in conjunction with the capacitances C_1 and C_2 , lead to the appearance of stable odd-order subharmonic oscillations. This phenomenon is called ferro-resonance. Subharmonics of any order can also appear as transient oscillations. These oscillations can interfere with protective relay operation and are of concern both for the designer of the CVT and for the designer of the protective relays. Proper design of the damping element Z will produce a CVT with negligible tendency for subharmonic oscillations. Ferro-resonance is prone to appear at the removal of a secondary short-circuit. One of the type tests required in IEC 186 [2] for CVTs is a ferro-resonance test comprising the removal of a short circuit from the secondary terminals and verifying that any ferro-resonance is not sustained. Many different solutions for the damping element exist, the simplest being a resistor with a high power consumption. Switched designs where the damping element is only switched under conditions when ferro-resonance is present or imminent, are also often found.

The transient response of the CVT is of some concern. The LC circuit in the intermediate voltage part is a resonant circuit with a fairly high Q -value that may cause a ringing in response to a step function on the high voltage side. Such a step can occur if a primary short-circuit is removed, i.e. a cleared earth fault. The damping introduced by damping circuits is therefore essential and has been discussed by many authors, for example Battistelli, Mangoni and Gertsch [⁴¹], Kumar and Ertem [⁴²] and Wong and Humpage [⁴³].

The equivalent circuit in figure 23 indicates that frequency deviations may have an influence on the error of the CVT due to the series LC resonance circuit. The magnitude of the influence depends on the overall Q -value of the circuit and therefore depends also on the design of the transient damping impedance Z . The analysis of the CVT is discussed at some length in [38]. Examples of obtained results for a class 0.2 CVT are shown in [⁴⁴] for several operating conditions of the CVT.

The change in the error of a well-tuned CVT due to increased burden, is an increase in the ratio error and a small decrease in the phase displacement, provided that the burden is close to power factor 0.8 inductive [38], [39].

The CVT is a complex device with a non-trivial response to transient conditions, and design of protective relays must take into account the

characteristics of the CVT. The cost benefit of using a CVT instead of an inductive voltage transformer does however make it attractive to use, and the introduction of CVTs of class 0.2 has also made it suitable to use them for metering purposes.

13. Results obtained in the field calibrations

13.1. General

During the years 1990 through 1993 approximately 50% of all the voltage transformers on the 130 kV to 400 kV networks in Sweden have been calibrated with the mobile calibration system. A small number of voltage transformers on the Norwegian National Grid have also been included in the calibrations insofar as they are used on inter-ties to Sweden. The present survey is based on the evaluation of the results from 549 capacitor voltage transformers in 54 substations. The results on 24 inductive voltage transformers also included in the *in situ* calibrations are not included in this evaluation. In each visited substation all voltage transformers have been calibrated and the body of data accumulated is therefore regarded as representative of the population of voltage transformers on the network.

The large body of data available from the field work makes it possible to evaluate both the apparent drift rate of the measuring errors and the failure rate for CVTs. Drift rate can be directly evaluated for 315 CVTs where sufficient information on both factory calibration and on adjustment winding status is available. For others, only an approximate evaluation can be made. The definition of failure used in this context will be based on regarding excessive errors, rather than any signs of external damage, as indicative of a failure.

Although the population of CVTs is large, some caution must be exercised in evaluation of for example drift rates for sub-populations such as different brands of CVTs. Too small populations may exhibit a large scatter in the results and consequently giving a large uncertainty in the conclusions drawn from the material.

Several different brands of CVTs are installed on the Swedish networks, but it has been chosen not to identify the different brands by name in the thesis. This is done ensure that the necessary impartiality of a scientific work is not compromised.

The major part of the network has been in operation for several decades, with some substations having equipment dating back to the mid-nineteen fifties. A slow process of replacing old equipment in existing substations plus a gradual increase of the system capacity does however mean that there is also a fair amount of newer equipment installed.

Control and metering equipment used to be electromechanical relays and Ferraris type meters, having an appreciable power consumption. The rated burden of the voltage transformers was chosen to 150 VA in the early days to accommodate this type of equipment. The process of replacing old control and

metering equipment with modern, results in a drastic reduction of the installed burden on the voltage transformers, in many cases to a level of only a few VA. As a result, a large portion of the installed CVTs have an output capacity that is unnecessarily high in relation to the burden installed.

Several different accuracy classes have been in common use in the past. In the beginning of the period of installation of CVTs the accuracy class 0.6, with an error diagram that has a rhomboid shape in accordance with the Swedish standard SEN 2703 [40], was the most common. The rhomboid shape was chosen to obtain a constant maximum power error for power and energy measurements regardless of the combination of maximum voltage and current transformer errors. In the earliest installations there are a few cases where no information is available on the accuracy class of the installed voltage transformers, but it is assumed for the purpose of analysis of the calibration results that no accuracy class worse than 0.6 has been used for the metering winding. The accuracy class 0.5 in accordance with IEC 186 has in later years replaced class 0.6. There is a very clear trend that accuracy requirements have increased with time with accuracy class 0.6 having been in general use up to approximately 1977. From 1978 accuracy class 0.2 in accordance with IEC 186 has been predominant.

Figure 24. Error limits for a class 0.6 voltage transformer according to SEN 2703 and classes 0.2 and 0.5 according to IEC186

A summary of the distribution of accuracy classes for the different operating voltages is given in table 13. The main emphasis in the calibrations is clearly shown to be on the 220 and 400 kV networks. The number of high accuracy voltage transformers (i.e. class 0.2) is close to half of the population and slightly lower than the number of ordinary accuracy voltage transformers (i.e. classes 0.5

Table 13. Capacitor voltage transformers per accuracy class and system voltage

System voltage	130 kV	220 kV	275 kV	400 kV	Total
Class 0.2	9	118	3	109	239
Class 0.5	3	30	3	51	87
Class 0.6	6	80	3	113	202
Others		12		9	21
Total	18	240	9	282	549

and 0.6). The group "Others" refers to a small number of old CVTs that lack information on the designated accuracy class, and which in the following evaluations have been assumed to have an accuracy class of 0.6.

The distribution of accuracy class with the year of manufacture as shown by the bar graph in figure 25 gives a clear view of the changeover to class 0.2 occurring around 1978. A number of CVTs manufactured approximately in the period 1955 to 1965 do not have their year of manufacture marked on the nameplates. These have been arbitrarily assigned to 1960.

Figure 25. Number of calibrated voltage transformers shown per year of manufacture

The majority, 381 units, of the transformers were of brand A, 75 units of brand B, 10 of brand C, 12 units of brand D, 9 units brand E and the balance, 62

units, being mostly very old units of varying Swedish manufacture. Only brands A and B will be discussed separately in the following. In addition to the CVTs there are also 24 inductive voltage transformers used on the 130 to 220 kV networks. They have however been excluded from the present evaluation since the number of inductive transformers is low and since it has also proved difficult to obtain information on the factory calibration results for these units.

The brand A CVTs have been consistently designed to permit adjustment of the ratio in the field by means of adjustment windings accessible in a terminal box on the electromagnetic unit. The connection of the adjustment windings is uniquely identified by the jumper positions in the terminal box. This feature is at the same time both a boon and a disadvantage. The boon is that an old unit with an accuracy class of, for example 0.6, may easily be readjusted in the field to provide an error less than 0.2% at installed burden. The disadvantage is the corollary, it is necessary to open the terminal box and note jumper positions, in order to ascertain if the CVT has been readjusted since the factory calibration. A comparison between the original factory calibration and the field calibration can only be made for non-adjustable CVTs and for those adjustable CVTs for which the jumper positions are known. Of 381 adjustable units of brand A, 104 units of classes 0.5 and 0.6 plus one unit of class 0.2 have been readjusted during the course of the *in situ* calibrations providing information on the jumper positions. It is also highly probable that the brand A 0.2 class CVTs have not been previously readjusted in the field, signifying that the jumper positions can be regarded as known also for this group. No such conclusion can be inferred for classes 0.5 and 0.6, on the contrary these were usually finally adjusted when they were erected on site in the substation. There are 132 CVTs of brand A of class 0.2 giving a total of 237 CVTs for which the connection of the adjustment windings can be considered to be known. The number of CVTs that are not field adjustable is 106 so that there are 343 CVTs for which the results of the calibration *in situ* may be directly compared to the factory calibration. Factory calibration reports have been obtained for all but 28 CVTs resulting in 315 CVTs being available for comparisons.

Evaluation of the stability of the CVTs is best made as a comparison with factory calibration data to obtain the exact change that has occurred for each CVT. This method will however exclude a number of CVTs from the evaluation. It is therefore of interest to make an evaluation of the errors obtained for all CVTs to test if the results for this larger population is consistent with the results obtained in the comparison with factory calibration data. It is for this evaluation suitable to assume that the ratio error is equal to the class index at zero burden. This view of the results will also be used to evaluate the influence of extraneous

factors such as ambient temperature in the substation, the solar irradiation or the phase position of the CVT.

It should be noted that all voltage transformers in each substation have been calibrated, i.e. transformers used only for protection purposes are also included in the study. All voltage transformers used for protection purposes in the Swedish National Grid are dual purpose voltage transformers in the sense of IEC 186 and have an assigned accuracy class both for metering and for protective purposes.

13.2. Errors at installed burden

The error at installed burden is measured in the voltage make-up box in the switchyard. The connection between the voltage make-up box and the CVT is normally a three-wire connection, but two-wire connections are also quite common. The current drawn by the burden will cause a voltage drop on the connecting cable, a voltage drop that is an added measuring error. The results are therefore not truly representative of the CVT, but are a compromise between the wish to identify the error of the measurement of power or energy, valid in the control house, and the wish to measure the error of the CVT itself. Measurement at the terminal box of the CVT is not permitted for safety reasons.

The burden current in the cable between the voltage make-up box and the control house will cause a further error in the measurement of power and energy in the substation. This effect has not been a point of study in the present examination, which concerns the CVT itself. The calibration team has however estimated that the ratio error valid in the control house is displaced in the negative direction with respect to the one measured in the voltage make-up box, by an amount normally in the range of 0 to 0.2% of the ratio.

The mean ratio error at installed burden for the class 0.2 CVTs was 0.13% with a standard deviation of 0.15%. The mean phase displacement was 0.42 mrad with a standard deviation of 0.58 mrad. These CVTs have with one exception not been adjusted in the field and the measured errors can be assumed to mirror the true errors for the population. The results for the class 0.2 CVTs are shown in figure 26, where the smaller rectangle encloses the mean value plus one standard deviation in each direction. It will be shown later that the installed burdens are very low and for most CVTs below the range defined in IEC 186. The ratio error obtained at a low burden should be close to the positive class limit, just as observed here. The phase displacement is small and within the class 0.2 limits for all CVTs.

The frequency diagram for the ratio error in figure 27 shows that the distribution is reasonably symmetrical around the mean ratio error, but that there

Figure 26. Ratio and phase error at installed burden for all class 0.2 CVTs.

is a small number of units with large errors. The symmetry of the distribution lends further credibility to the interpretation that the rather high mean value for the ratio error is due to the low burdens.

The mean ratio error for class 0.5/0.6 CVTs was 0.5% with a standard deviation of 1.0% of the ratio. The phase displacement was 0.8 mrad with a standard deviation of 2.7 mrad. The results are shown in figure 28, where the rectangle encloses the mean value plus one standard deviation in each direction.

This group of CVTs has probably been adjusted in the field and it can not with certainty be assumed that the ratio error at low burden should be close to the

Figure 27. Relative frequency distribution for the ratio error at installed burden for CVTs of class 0.2.

Figure 28. Ratio and phase error at installed burden shown for all class 0.5/0.6 CVTs except two units with phase displacement in excess of 15 mrad and two units with ratio errors in excess of 5%.

upper class limit. Several units with large errors are clearly visible both in figure 28 and in the frequency distribution of errors in figure 29. It is probable that these units are damaged.

The major part of the population of CVTs has a low and therefore non-standard burden. A determination of the number of CVTs that are within their class limits at installed burden has been dispensed with as being of little value. The author regards an evaluation of the stability of the CVTs, based on the ratio error at zero burden, as more pertinent and such an evaluation will be made in the

Figure 29. Relative frequency distribution for the ratio error at installed burden for CVTs of class 0.5/0.6.

following. The frequency distributions for the ratio error show that the ratio error for each group is cluster around the upper class limit, as would be expected at low burden.

13.3. Evaluation of voltage transformer stability

The further study of the results obtained in the *in situ* calibrations is based on results obtained for zero burden because the available cables between the voltage transformer and the voltage makeup box in the switchyard do not always permit a true four-terminal measurement to be made for the measurements with variable burden. In the case that a four-terminal connection to the CVT cannot be made, the voltage drop on the conductor between the voltage make-up box and the CVT due to the current consumed by the variable burden will be added to the output voltage of the CVT, causing a measuring error. The readings obtained for burdens other than nil may consequently exhibit excessive sensitivity to changes in the burden. The values obtained at zero burden are however not influenced by this and can be directly compared to results obtained in the factory.

13.3.1. Comparison with factory calibration

A comparison of the field calibration results with the original factory calibration can be made for all CVTs that are not adjustable and for all that are adjustable and for which the connection of the adjustment windings is known. A total of 343 CVTs fulfilled this criterion, but 28 had to be excluded due to lack of factory calibration results, giving a total base of 315 units. 17 of the excluded units were manufactured in 1971 and earlier.

Of the 315 CVTs included in this examination, 87 are adjustable and have been adjusted during the course of the field calibrations, 122 class 0.2 CVTs are adjustable but have with a high probability not been adjusted since the factory calibration. The 106 CVTs in the balance are not field adjustable. The adjustments mentioned have been carried out in response to observed excessively large ratio errors. The cause of an excessively large ratio error may be a too low burden on the CVT, changes in the CVT itself or both. IEC 186 [2] defines the burden range for a voltage transformer as 25 to 100 % of the rated burden. A CVT with an error outside class limits at very low burden is therefore not *a priori* damaged but may still be within its original limits. Comparison with factory calibration results are often necessary to determine which.

13.3.1.1. Overview

The change in ratio error and phase displacement between the result *in situ* and the factory calibration is shown in figure 30 for all 315 CVTs included in the examination. Ideally, all results should cluster in the diagram on co-ordinates 0,0

but in reality there will be a spread due not only to changes in the CVTs themselves, but also to uncertainties in the field calibration and in the factory calibration.

Figure 30. Change in ratio error and phase displacement for all CVTs (315 units) for which a comparison between original factory calibration and field calibration is meaningful

The measuring uncertainty for the factory calibration is unknown, but a reasonable assumption is $\pm 0.05\%$ for the ratio error and ± 0.9 mrad (± 3 minutes) for the phase displacement. The uncertainty limits for the *in situ* calibration and for the total uncertainty of the estimated factory calibration uncertainty and the *in situ* calibration uncertainty are shown as boxes in figure 31. The uncertainty box should be thought to be positioned with the measured value in the centre. Figure 31 shows the central area of figure 30, and together the two plots show that most of the CVTs cluster around zero change for the ratio error, but also that there is a small number of units with very large errors. The units with very large ratio errors are suspected of a failure in the capacitors comprising the voltage divider. It has unfortunately not proved possible to obtain any of these units for examination and the reasons for the large changes in ratio error must so far remain conjecture.

The change in the phase displacement is well within the class 0.2 limit of 3 mrad (10 minutes) for all but one of the CVTs. The change is furthermore with four exceptions on the same order as the total uncertainty (± 1.3 mrad) of the factory calibration (± 0.9 mrad) and the field calibration (± 0.9 mrad). The change in phase displacement is negligible for the entire population and no further analysis will be made.

Figure 31. Change in ratio error and phase displacement for all CVTs (315 units) for which a comparison between original factory calibration and field calibration is meaningful, but where units with errors in excess of 1 % and 2 mrad have been excluded. Uncertainty boxes refer to SP uncertainty and to estimated total uncertainty respectively.

The observed changes in the ratio error can be evaluated by means of a parameter Normalised Ratio Error Change defined as the quotient of the ratio error change to the accuracy class. The difference between class 0.5/0.6 and the more modern class 0.2 CVTs is quite marked. The Normalised Ratio Error Change given in table 14 is lower by a factor of 4 for class 0.2 CVTs than for others.

The difference in the ratio error change between the groups is of course even larger. The mean change for each group is obtained by multiplying the Normalised Ratio Error Change with the class index. For class 0.2 CVTs the mean ratio error change is only 0.03% whereas classes 0.5 and 0.6 CVTs have a

Table 14. The Normalised Ratio Error Change (ratio error change/class index) for CVTs for which a comparison has been made against the factory calibrations

Population	Number of CVTs	Normalised Ratio Error Change	
		Mean value	Standard dev.
All	315	0.26	1.3
Class 0.5/0.6	89	0.54	2.1
Class 0.2	226	0.14	0.7

mean change of 0.3%, i.e. a difference by a factor of 10. Approximately the same difference is seen also for the standard deviation. It must here be noted that the class 0.5/0.6 population is not a random sample since they have all been adjusted in response to an excessively large ratio error. It follows that this group is expected to contain a disproportionate number of CVTs that have drifted in ratio. Stable CVTs of these classes have more seldom been adjusted and the expected ratio error for these cannot be estimated since the connection of the adjustment windings is unknown.

13.3.1.2. Mean change per year of manufacture

An interesting question is if there is a correlation between the age of the CVT and the observed change. A difference may be expected between CVTs of class 0.2 and those of class 0.5/0.6 and they are therefore analysed separately. The observed ratio error changes are plotted in figures 32 and 33.

Figure 32. Observed change in ratio error per age group for all class 0.2 CVTs, based on 226 units.

The individual values for the ratio error changes are plotted together with a curve showing the yearly mean values and a trend line. The trend line is the least squares fit of a straight line to the observed ratio error changes. The trend, or the apparent drift rate, is with 95% confidence estimated to $(0.000 \pm 0.005)\%$ per year of age for the class 0.2 CVTs shown in figure 32. The mean change for this population is $+0.03\%$ of the ratio, with a standard deviation of 0.14% of the ratio.

The plot for the accuracy classes 0.5 and 0.6 in figure 33 shows with 95% confidence level a trend of $(0.06 \pm 0.08)\%$ per year of age. The plot shows the ratio error as a function of the year of manufacture, whereas the trend is expressed in drift per year of age, giving the positive sign for the trend. The

yearly mean values fluctuate around the trend line, but exhibits the same general trend. The mean change for the population is $+0.3\%$ of the ratio with a standard deviation of 1.1% . Not shown on the plot, but included in the calculation of mean values and trend line, are also 5 points ranging from 2.5% to 7% ratio error in 1973 and 1974 and one point at -1.6% in 1975. Excluding the 6 points not shown on the plot, a trend of $(0.040 \pm 0.014)\%/year$ is obtained and the mean change for the remaining population reduces to 0.08%

Figure 33. Observed change in ratio error per age group for CVTs with accuracy class 0.5 and 0.6, based on 89 units. All but three were manufactured by ASEA. Six points with very large errors are not shown on the plot but have been included in the calculation of trend line and age group mean values.

The results for the two populations show that there is a significant difference in both apparent drift rate and mean change for the ratio error. The class 0.5 and 0.6 CVTs have an appreciably higher drift rate and mean change than the class 0.2 CVTs have. It is however probable that the group of class 0.5/0.6 CVTs included in this examination represent a negative sample of the population and the result may not be a true reflection of the characteristics of the group as a whole.

13.3.1.3. Comparison between brands

A comparison between class 0.2 CVTs of brand A and brand B is shown in figure 34 and figure 35. The intention of the comparison is to illustrate the difference, if any, between brands. Other brands are represented in such small numbers as to make any meaningful interpretation impossible and are therefore not discussed.

Figure 34. Observed change in ratio error per age group for class 0.2 CVTs of brand A. The population consists of 123 CVTs.

The trend for the brand A class 0.2 CVTs shown in figure 34 is with 95% confidence level $(0.012 \pm 0.006)\%$ per year. The mean change for the population is -0.02% of the ratio with a standard deviation of 0.11% .

Figure 35. Observed change in ratio error per age group for 75 CVTs of brand B, all class 0.2

The trend of the change in the brand B types is with 95% confidence $(0.019 \pm 0.011)\%$ per year. The mean change is $+0.1\%$ of the ratio with a standard deviation of 0.15% . All CVTs (75 units) included here have an accuracy class of 0.2.

The trend per year is less than one tenth of the accuracy class for both brand A and for brand B CVTs. The dispersion in the data is however rather large and the result is not entirely consistent with the result for the slightly larger

group shown in figure 32 where a negligible drift rate was obtained. It must therefore be concluded that breaking down the data on brand level increases the uncertainty in the result too much and that drift rates for class 0.2 CVTs should be considered only for the entire population.

13.3.1.4. Change related to capacitor design

The classical design of capacitors for CVTs used only mineral oil and paper for the insulation. Modern compound designs employ plastic film as a third component in the insulation medium to obtain an enhanced temperature stability.

Brand A changed over to compound dielectrics approximately 1978 and brand B in 1985. It can be safely assumed that all CVTs installed in Sweden utilised the compound dielectrics from the same time as brand B did.

Figure 36. Observed change in ratio error per age group for all CVTs from 1985 and onwards based on 84 CVTs. It is assumed that all CVTs in this group are made with capacitors with a compound dielectric that has a good temperature stability.

The slope of the trend line is with a confidence level of 95% $(-0.012 \pm 0.013)\%/ \text{year}$. The mean change for the population is fairly small, $+0.02\%$ of the ratio with a standard deviation of 0.13% of the ratio. The results for this population do therefore not differ decisively from the entire group of class 0.2 CVTs and no certain conclusion can be drawn regarding any difference in stability between the class 0.2 CVTs presumed to have a compound dielectric and the whole group including those that have the traditional oil-paper dielectric.

13.3.1.5. Discussion of the rate of change

No large phase displacement changes have been observed for the population of CVTs that have been compared to factory calibrations. The data presented does show that changes in phase displacement are small and can be neglected.

For the ratio error there is an observable trend that the mean ratio error change increases with the age of the CVT for classes 0.5 and 0.6, even if concession is made to the fact that only one third of this population could be included in the determination of the drift rate. The drift rate for the ratio error of class 0.2 CVTs is however negligible. More than one hypothesis can be advanced to account for the changes observed for the class 0.5/0.6 population.

- There is a systematic drift of the ratio due to ageing of the dielectric.
- The difference in thermal ambient causes a systematic change in the difference between the ratio measured in the factory and that measured in the field. An uneven temperature distribution on a CVT may show up as a ratio error due to the different temperatures of the parts of the divider stack. The temperature coefficient of old CVTs was much larger than it is today, aggravating the problem.
- Ageing of components of the damping circuit in the CVT increases its impedance resulting in an increased positive ratio error.
- Damage to the capacitor rolls in the high voltage arm of the capacitive voltage divider leading to increased capacitance in the high voltage arm.
- Damage to the capacitor rolls in the low voltage arm of the capacitive voltage divider leading to decreased or increased capacitance depending on the design and on which roll that is damaged.

The information available so far from the *in situ* calibrations does not permit a definite determination of which of the above, if any, that is responsible for the observed changes. The author regards it as a fact that several of the CVTs with very large errors have damaged capacitor rolls in the high voltage arm of the capacitive divider. At least one type of CVT included in the evaluation has a damping circuit consisting of a resistor drawing a power of several 100 W. This resistor is placed inside the electromagnetic unit, which is in direct contact with the low voltage arm of the capacitor divider. At normal indoor operating conditions the electromagnetic unit of this CVT is expected to have a temperature rise of approximately 20°C above ambient. A thermographic measurement in the field of 20 CVTs of this type revealed a temperature rise ranging from 2 to 7°C. It is suspected that the temperature distribution in the capacitor stack under field conditions deviates appreciably from the one obtained under laboratory conditions. The capacitors used in this type have oil-paper dielectrics and a relatively large sensitivity to the temperature difference between the parts of the capacitor divider is probable.

The results obtained indicate for class 0.2 an average drift of $(0.000 \pm 0.005)\%$ per year. For class 0.5 and 0.6 the average drift is estimated to $(0.040 \pm 0.014)\%$ per year if six units with very large errors are excluded from the population. Excluding units with very large errors from the population is reasonable since a very large error will be apparent even without calibration and the damaged CVT will be discovered by routine maintenance inspection.

For a large population of CVTs the obtained drift rates can be used to predict suitable intervals for re-calibrations. Setting as a tentative criterion that the drift for the population may not be larger than half the class index, it follows that class 0.5 and 0.6 CVTs should be re-calibrated every 7 years. The average drift rate for class 0.2 CVTs would indicate that no re-calibration is required. This does however not take into account the rather large spread in results seen in the calibrations and it may in this case be better to base a tentative interval on the 0.005%/year uncertainty in the drift rate, giving an interval of 20 years.

13.3.2. Ratio error measured at zero burden

An accurate evaluation of the stability of voltage transformers must be based on a comparison with results obtained earlier, for example the factory calibration for the transformer. While the determination of the drift rate is more accurate in this case, a number of CVTs will be excluded from the determination due to lack of sufficiently precise information. All CVTs can however be included in an analysis, if it is assumed that they were originally adjusted to produce a certain ratio error at zero burden.

Most voltage transformers will have been initially adjusted to produce a ratio error close to the upper class limit at zero burden. It is also possible that they could have been initially adjusted to produce zero ratio error at 25% of the rated burden, but this case is disregarded as it is uncommon among the CVTs in

Table 15. Voltage transformer errors at zero burden as measured before any adjustments had been carried out

	all		class 0.2		Class 0.5/0.6	
	mean	std dev.	mean	std dev.	mean	std dev.
Ratio error [%]	0.47	0.8	0.19	0.15	0.7	1.0
Normalised error [p.u.]	1.1	1.4	1.0	0.7	1.1	1.7
Phase displacement [mrad]	0.6	1.4	0.36	0.6	0.8	1.8

Sweden for which factory calibration reports are available. The spread in factory calibration at zero burden seems to be from 0.10% to 0.25% for class 0.2 CVTs and from 0.45% to 0.7% for class 0.6 CVTs in the cases where such calibration reports are available. The mean value seems to be approximately 0.9 times the class index.

Defining a "Normalised Error" as the quotient of the actual ratio error at zero burden to the accuracy class index, a quantity is obtained that should be expected to have the value 0.9 for the initial factory calibration. A change in the Normalised Error would indicate that there is a consequent change in the voltage ratio of the CVTs in the population. The standard deviation gives a measure of the spread in the data and is indicative of the amount of random drift in the voltage ratio.

The mean values shown in table 15 do not definitely indicate a consequent drift in either positive or negative direction. The standard deviation of the Normalised Error is 1.7 for the old types with accuracy class 0.5 and 0.6, giving evidence of a fairly large random drift even though the mean value of the Normalised Error is 1.1 only gives a slight evidence of a systematic drift. Assuming that original calibration gave a Normalised Error of 0.9, the drift of the ratio error can be calculated to less than 0.1% of the ratio for the whole population of class 0.5/0.6 CVTs. This result is in contrast to the result obtained by comparison with factory calibration for the same class 0.5/0.6 CVTs and underlines the previous observation that the group used in the comparison with the factory calibration probably represented a negative sample of the population.

The standard deviation of the Normalised Error for class 0.2 transformers is 0.74, which is better but still considerable. Of the class 0.2 CVTs only one has been adjusted whereas approximately one third of the CVTs of classes 0.5 and 0.6 have been adjusted. The result obtained for class 0.2 CVTs is entirely consistent with the analysis in the preceding section. The mean value of the ratio error recorded in the factory calibration at zero burden was 0.17% and the mean change was +0.03%. Their sum 0.20% coincides very well with the 0.19% mean ratio error found in the *in situ* calibrations for the entire population.

The results give a slight indication of a positive drift in the population of class 0.5/0.6 CVTs. The results obtained for the CVTs with accuracy class 0.2 are consistent with the results obtained for the slightly smaller population of class 0.2 CVTs for which a comparison with factory calibrations has been carried out. The standard deviation is quite large for all populations and the random drift must be regarded as substantial.

13.4. External influences on the CVT ratio

Several external factors may influence the ratio of a CVT. To investigate this for the CVTs included in the *in situ* calibrations, the author has chosen to evaluate the correlation between the ratio error and the respective influence factors for the results obtained at zero burden. The population of class 0.5/0.6 CVTs has been excluded from the evaluation since these often have unknown connection of the adjustment windings due to having been previously adjusted in the field. The scatter observed for this group is large and may mask the effects investigated. The class 0.2 CVTs have not been adjusted in the field and the ratio error should be close to the class limit of 0.2%. This group also has a small scatter in the results.

13.4.1. Influence of position of the CVT on the ratio error

Mid-phase position for a CVT implies different parasitic capacitances to earth and to live objects than for outer-phase positions. The capacitor divider of the CVT is to some extent sensitive to the influence of such parasitic capacitances, even though manufacturers strive to mitigate this by using a capacitor stack with a sufficiently large capacitance.

It is expected that the influence is moderate to small, and the large dispersion of the results for CVTs with other accuracy class than 0.2 implies that a comparison should be made only for class 0.2.

Table 16. Correlation between mean ratio error and phase position based on 239 class 0.2 CVTs

Position	Ratio error		Phase displacement	
	mean [%]	std. deviation [%]	mean [mrad]	std. deviation [mrad]
Outer phase	0.19	0.14	0.36	0.57
Mid-phase	0.19	0.16	0.35	0.55
All phases	0.19	0.15	0.36	0.56

The differences between mid-phase and outer phase position as shown in table 16 are negligible. Even the standard deviation for the different populations is almost identical and no significant correlation between the position of the CVT and the ratio error can be found.

Figure 37. Correlation between the ambient temperature *in situ* and the recorded ratio error for 239 class 0.2 CVTs

13.4.2. Correlation between ambient temperature and ratio error

The capacitive divider of a CVT is inherently temperature dependent and the design of the divider determines how well stabilised the ratio will be. For the same reason as in the preceding section, this study is limited to the class 0.2 CVTs. Figure 37 plots the recorded errors against the ambient temperature and a trend line for the temperature dependence is shown. The slope of the trend line is with a 95% confidence $(-0.004 \pm 0.003)\%/^{\circ}\text{C}$. The data obtained from this population thus indicates a barely significant negative temperature dependence.

13.4.3. Correlation between the solar irradiation and the ratio error

Intense sunlight will heat the capacitor stack in the CVT. Uneven heating of the stack may lead to ratio errors dependent on the radiated solar power. The insolation, i.e. the irradiated solar power per unit area, has been measured in most cases and results are available for 146 CVTs of class 0.2. A plot of the ratio error versus the irradiated solar power per square meter is given in figure 38. The observed trend for the ratio is $(-0.02 \pm 0.07)\%/kW$ and a correlation between the insolation and the ratio error can therefore not be established.

13.5. CVT failure rate

13.5.1. Evaluation of the failure rate

A failure of a CVT is normally understood to imply gross damage to the unit clearly evidenced as externally visible damage or measuring errors so large as to be immediately apparent. The author's experience with the *in situ* calibrations has shown that fairly large errors, even up to a few percent of the ratio, can remain unnoticed for a long time due to lack of suitable references for voltage measurement in a substation. Such a large error can be regarded as an unnoticed partial failure of the CVT.

The present investigation based on large-scale *in situ* calibration of CVTs provides a unique possibility to identify the partial CVT failures manifesting as excessively large measuring errors. There is no generally accepted definition of when a change in the ratio error should be considered as a (partial) failure of a CVT and it will be necessary to define, at least tentatively, suitable criteria for the identification of failures.

Figure 38. Correlation between the insolation and the ratio error for 146 class 0.2 CVTs .

For CVTs where comparison can be made with a factory calibration, a failure will here be defined as a change larger than that caused by the loss of one capacitor roll in the capacitor stack or a change in the ratio larger than the class index. The exact number of capacitor rolls in the different CVTs is not known, but is for the types used in Sweden normally in the range 0.7 to 0.9 rolls per kV system voltage. A criterion for the maximum ratio change that is not considered as a failure can therefore be formulated as $(\frac{100}{0.8 \cdot \text{Rated voltage}}) \%$ or the class index, whichever is the smallest. The rated voltage is to be given as the rated system voltage in kV. In the evaluation of the CVTs, 45 out of 315 CVTs have failed according to this definition.

A less well-defined criterion must be used for CVTs for which a comparison with the factory calibration is not possible. Defining that all units exhibiting an estimated ratio error change larger than the class index as being defective is reasonable and will be used here. As discussed in the preceding section, the ratio error at zero burden is expected to fall close to the class limit. A CVT will consequently be considered to have failed if the ratio error measured at zero burden is not from zero to twice the class index. In the evaluation of the CVTs, 47 out of 234 CVTs have failed according to this definition.

The present database with 549 CVTs is too small to provide a definite basis for an evaluation of the failure rate as a function of the age of the CVTs as evidenced by figure 39, which shows that the failure rate per age group varies widely between years, and that even the five year average shows large fluctuations. The database is however quite large enough to provide a good estimate of the overall failure rate, provided that the failure rate is assumed to be constant. The inverse of the failure rate is sometimes used and is designated as the MTBF - Mean Time Between Failure.

Assuming that the failure rate λ is constant over time, an exponential distribution is obtained, Bazovsky [45]. The probability R that a CVT survives until time t is

$$R = 1 - e^{-\lambda t} \quad (46)$$

For a large population with n units there will be r failed units after time t , where r is given by

$$r = nR = n(1 - e^{-\lambda t}). \quad (47)$$

Solving for λ gives

$$\lambda = -\frac{1}{t} \ln\left(1 - \frac{r}{n}\right) \approx \frac{r}{nt} \quad (48)$$

The failure rate for the entire population can be estimated by using the approximation in equation (48) to obtain

$$\bar{\lambda} = \frac{\sum r_i}{\sum t_i * n_i} \quad (49)$$

where

r_i is number of failed units per year

t_i is the number of hours since the year of manufacture

n_i is the number of units for each year of manufacture

Evaluating equation (49) for 92 observed failures during a total operating time of 86 million hours, the overall failure rate is obtained to be

$$\lambda = 1.1 \text{ ppm/hour.}$$

This result corresponds to a Mean Time Between Failure (MTBF) of 104 years.

Figure 39. Failure rate per age group for all calibrated CVTs. The unbroken line indicates a failure rate per age group for all calibrated CVTs. The dashed line indicates a failure rate per age group for all calibrated CVTs except 1983. The dotted line indicates a failure rate per age group for all calibrated CVTs except 1983 and 1984. The dash-dot line indicates a failure rate per age group for all calibrated CVTs except 1983, 1984, and 1985. The open circles indicate the number of installed CVTs.

The moving average shown in figure 39 exhibits a slight trend suggesting an increased failure rate for newer equipment. The number of CVTs installed in, for example the period from 1985, is moderate and the trend is not regarded as significant.

A certain difference between different brands can be seen in the evaluation in figure 40. The evaluated failure rate is 0.81 ppm/hour (ppm - parts per million) for 381 CVTs of brand A, 3.2 ppm/hour for 75 CVTs of brand B and 1.6 ppm/hour for 93 CVTs of other manufacture. The reason for the fairly high failure rate for the brand B types is obscure, but there seems to be a consistent problem in the large delivery for 1983, where a large positive drift is seen for a majority of the units, cf. figure 35. Excluding all 22 units manufactured in 1983 a failure rate of 0.98 ppm/hour is obtained for the remaining 56 CVTs of brand B manufacture. This failure rate is on par with the total population and supports the conjecture of a problem with the delivery for 1983.

The stability of class 0.2 CVTs is evaluated in figure 41 for the total population of these CVTs. The early peak in the diagram is due to a few failed CVTs in a small initial population. The bad results of the 1983 brand B CVTs affect this evaluation quite distinctly, the failure rate for the population is estimated to 1.6 ppm/hour. If the 1983 brand B group is disregarded, the failure rate is reduced to 1.1 ppm/hour, which is the same value as for all CVTs. It is important in comparing the results for class 0.2 CVTs with the whole population of CVTs to recall that the criteria for failure are more stringent for the class 0.2 CVTs and that the failure rate of class 0.5/0.6 CVTs would be higher if the same criteria were applied.

Figure 41. Failure rate for 239 class 0.2 CVTs

13.5.2. Failure rate as basis for estimation of re-calibration intervals

The estimation of the re-calibration interval depends on the acceptable number of failures in a substation before a calibration must be carried out. As an example a substation with a total of 11 CVTs, three incoming lines with three CVTs each and two buses with one CVT each, may be examined to obtain the statistical time interval before one CVT has failed. Evaluating equation (47) for these parameters and for a failure rate $\lambda=1.1\text{ppm/hour}$, we obtain

$$\begin{aligned} e^{-\lambda t} &= \frac{10}{11} \\ -\lambda t &= \ln \frac{10}{11} \\ t &= -\frac{1}{\lambda} \ln \frac{10}{11} = 87 \cdot 10^3 h = 9.9 \text{ years} \end{aligned} \quad (50)$$

For the given assumptions and the established failure rate, the recalibration interval is found to be ten years for the total population. The calculation does not take into account the different characteristics of class 0.2 CVTs versus the class 0.5/0.6 CVTs and some caution should be exercised in applying the data.

13.6. Installed burden

The installed burdens in the substations in the Swedish National Grid have decreased with time as a result of on-going modernisation of protection and metering systems. At present the mean value for the installed burden is 20 VA with a standard deviation of 13 VA. The majority of the CVTs are designed in to comply with the requirements of IEC 186 [2] for an installed burden ranging

Figure 42. Value of the installed burden and its phase angle for 570 voltage transformers

Figure 43. Histogram of the distribution of the magnitude of the burden measured for 570 voltage transformers.

from 37.5 to 150 VA. The installed burden is, with one standard deviation, in the range from 7 to 33 VA. The minimum value recorded is only 0.1 VA whereas the maximum is 74 VA. See figure 42. A consequence of the low value of the installed burden is that the ratio error can be expected to be close to the positive class limit.

The phase angle of the installed burden is 13° with a standard deviation of 18° . The phase angle of the actual burdens should be compared to the standardised 37° (power factor 0.8 inductive) used in all testing of voltage transformers. The actual phase angle is, with one standard deviation, in the range -5° to 31° , i.e. the phase angle prescribed by IEC falls outside this range. The phase angle 13° corresponds to a power factor of 0.92.

The discretisation seen in the phase angles in figure 42 close to zero stem from the fact that phase angle was recorded as power factor with a resolution of 0.01.

The number of voltage transformers for which the phase angle of the installed burden is negative (i.e. capacitive or leading) amounts to 17% of the population.

The present IEC practice of testing voltage transformers is to use a burden of 25 to 100 % of rated burden, where the rated burden has a power factor of 0.8. The findings presented here do however not support this practice, indeed figure 43 indicates that it would be more appropriate to define the burden range as 0 to 100% of the rated burden

The frequency distribution of phase angles in figure 44 show that the phase angle of the burden clusters around 13° (the mean value of the phase angle), or a power factor of 0.97. Final testing at a power factor of unity instead of 0.8 lagging would therefore be more appropriate for the range of phase angles encountered in practice.

Figure 44. Histogram of the distribution of the phase angle of the burden measured for 570 voltage transformers.

14. System behaviour for harmonics and transients

The measuring system is not intended for use at other frequencies than 50 Hz power frequency but the influence on the measuring system due to transients and harmonics should be considered. Possible damage due to large transients on the network should also be considered.

The frequency response at low voltage has been measured for the reference voltage transformer NUES 420 at one ratio. Other ratios are obtained by changing the ratio of the intermediate transformer, which is at low voltage. No significant difference in frequency response is therefore foreseen.

Figure 45. Frequency response of the reference transformer NUES 420

As seen on the diagram, the frequency response is quite good up to several kHz. The lack of high resonance peaks indicates that the transient response should be good.

The excitation of the transformer core of the NUES 420 has been chosen to approximately 0.7 Tesla at a system voltage of 400 kV. This choice ensures that there is no event on the high voltage system that will cause the core to saturate. Problems with ferro-resonance due to a combination of capacitance of an opening breaker and non-linear magnetisation of the transformer core as discussed in [7] can therefore be disregarded.

The transformer calibration bridge TAB filters the input very efficiently in order to measure only the power frequency component of the test voltage. Harmonics and transients have very little influence on the results.

During breaker and disconnector operations in a switchyard there will be very large transients present both as conducted interference on the high voltage conductors and as radiated electromagnetic waves. No measurements are conducted under these conditions, indeed personnel are not permitted to be

present in the switchyard during operations, and a possible influence on measurement results need not be discussed. A permanent damage to the equipment due to the transients is conceivable, but considerable effort has been extended to make the instrument van a good environment for the sensitive equipment. Experience has also verified this, during the time of operation there have been no instances where transients have been suspected to damage any instrument.

15. Safety

Work in a high voltage substation is inherently dangerous and the safety aspects must be carefully considered before any work is undertaken. Protective measures must be implemented both as safe operating procedures and by using equipment that is as "fool-proof" as is reasonably possible. Some of the more important measures implemented in the Swedish *in situ* calibrations are enumerated below.

The short-circuit current available at the low voltage terminals of a standard CVT is considerable, often in excess of 100A, and the possibility, and effect of, improper connections being made must be considered. All voltage measurement connections are therefore made with special voltage probes with heavy duty internal fuses. The fuses used have a breaking capacity of 100 kA at 600 V and a nominal operating current of 10 A. Gold plated contact surfaces in the probes ensure low contact resistance over a long time. The fuses protect both personnel and equipment from the effect of inadvertent short-circuits.

All personnel are removed to a safe area during any breaker or disconnector operations in the switchyard. This is a redundant safety rule that is always enforced by the operator of the Swedish National Grid.

Other enforced safety rules control the line-of-command chain very rigidly to avoid any ambiguity as to who orders any operations on the high voltage circuit. In fact, if the assigned commanding person is not present, no further work can be performed on the high voltage circuit. Work on the low voltage side, such as the calibrations, can however be continued.

A very detailed operations write-up is made prior to the visit to the substation and is followed point by point during the calibration work. This is not the straitjacket it would seem, it forces everybody to proceed in small but safe steps, even if something unexpected occurs. It is important to remember that most mistakes happen during investigations of something unexpected that has happened. The *in situ* calibrations have been in operation during approximately 200 working weeks, and during this time there have been no incidents related to safety.

16. Problems experienced

Running such a large operation as the *in situ* calibrations discussed here cannot be expected to be entirely devoid of problems. Most of the problems encountered have fortunately been of minor nature and have been solved as a matter of course. A few items are however outstanding and are discussed here.

The first year of operation - 1989 - included two major problems. The first one concerned interference on the measuring circuit caused by an unknown connection between analogue and digital earths in the transformer calibration bridge TAB. The digital earth connected via the computer to mains earth and an earth loop was formed extending from the CVT earth point via the measuring cable to the earth point of the instrument van. Current on the high voltage busbars induced a small current in the measuring circuit that was added as an error to the signal. Errors up to approximately 1% and 10 mrad were subsequently identified in a pattern that could be traced to the influence of an interference voltage of approximately 0.6 V, common to all three phases in one bay. The pattern resembles the one discussed by Hillhouse and Leep [13]. The interference was unfortunately not discovered until after half of the season had passed. Introduction of an optical fibre in the computer communication circuit proved to be an efficient remedy. It was possible to use numerical methods to recover the correct values of ratio error and phase displacement with an estimated uncertainty of $\pm 0.2\%$ and ± 2 mrad.

The reference transformer consists of a cascade connection of a high voltage transformer with a ratio of 1:1000 and a low voltage intermediate transformer with several taps to obtain the different total ratios available. The low voltage intermediate transformer proved to be housed in an indoor type vessel with insufficient sealing of the cover. The laboratory calibration of the NUES 420 after the measuring season yielded curious results that finally proved to be caused by large amounts of water inside the intermediate transformer. The fact that errors less than 0.1% resulted from this calamity attests to the sturdy design of the transformer. The damage was however of such nature that it was deemed to be prudent to replace the intermediate transformer by an entirely new one, this time in a hermetically sealed vessel.

These two problems did combine to preclude any accurate calibration values to be obtained for the first season and none of the values obtained then have been used in the present study.

A major earth fault occurred in the reference transformer bushing in 1992. The transformer vessel and the bushing are both insulated by SF₆ and the earth fault occurred along the surface of the internal support insulator in the bushing flange. The cause for the earth fault has not been decisively determined, but the

most probable cause is the presence of particles in an area subjected to high electric field stress. The support insulator was found to be mounted with the conical part downwards, thus rendering the particle traps of the insulator more or less useless. The bushing was rebuilt and the support insulator was inverted to obtain a better operation of the particle traps. There were no adverse effects on the transformer proper and calibration showed no significant change in ratio error and phase displacement afterwards. There is no reason to suspect that there was any problem with the measurements immediately prior to the earth fault and a repeat measurement carried out the following year on CVTs calibrated immediately prior to the earth fault showed no more than normal change in the values.

17. Conclusions

The measuring system for *in situ* calibration of voltage transformers on the Swedish National Grid is intended to be used to calibrate all capacitor voltage transformers (CVTs) used on the power networks with system voltages from 130 kV up to 400 kV. The CVTs are in many cases used in systems for metering of electric energy. It is important to verify the *in situ* measuring system meticulously in view of the large cost for using the system, the important decisions regarding replacement of old CVTs and the large economic value of the metered energy monitored by these CVTs. It is paramount to guarantee the integrity of the results of the calibrations.

The verification of the measuring system includes all aspects of the system including the reference transformer, measuring instruments, measuring cable and the influence of effects in the substation itself. Using procedures established by ISO TAG 4 for evaluation of the combined effect of all influences it has been shown that the total uncertainty in a calibration *in situ* is less than $\pm 0.022\%$ for the ratio and ± 0.9 mrad (± 3.1 min) for the phase displacement. The measuring system contributes to this with $\pm 0.017\%$ of the ratio and ± 0.25 mrad (± 0.9 min) for the phase displacement.

The calibrations have shown that the installed burden in Swedish substations is very low, and for the majority of CVTs outside the range defined in IEC 186. For this reason calibration results obtained at installed burden have been given, but no evaluation of the compliance of the CVTs with the respective class limits at installed burden has been performed.

Evaluation of the results obtained in the calibrations has been made for results obtained at zero burden to avoid the effect of voltage drops due to load currents on the cables between the voltage make-up box and the CVT. Two groups of CVTs have been evaluated separately, namely those with 0.2 and those with classes 0.5 and 0.6. Only the ratio error of the CVTs exhibits any appreciable change, the measured phase displacement is with four exceptions within the respective class limits and the evaluation has therefore been limited to the ratio error.

CVTs with accuracy class 0.2 have been evaluated with respect to their change in ratio error between the original factory calibration and the *in situ* calibration. This evaluation was possible for 226 out of 239 CVTs and showed that the observed mean drift rate for class 0.2 CVTs is negligible. The mean value of the ratio error for the whole group had a negligible difference as compared to the factory calibration. The random drift is however still not negligible and an evaluation, based on regarding an excessive ratio error change as a failure, indicated a failure rate of 1.6 ppm/hour. Excessive ratio error change

for this group of CVTs has been defined as a change exceeding 0.2% of the ratio. Disregarding a group of 22 CVTs manufactured in 1983, which seem to have a common problem, the failure rate reduced to 1.1 ppm/hour. An evaluation of a suitable interval between calibrations based on the spread in the drift rate gave 20 years as a suitable interval whereas an evaluation based on the failure rate showed 10 years to be a more appropriate interval.

CVTs with accuracy classes 0.5 and 0.6 have been evaluated with respect to their change in ratio error between the factory calibration and the *in situ* calibration for one third of the population. The evaluation for the rest of the population was based on assuming that the original ratio error was equal to the class index and the comparison was made against the ratio error measured before any adjustments were made. These results are not compatible and it is possible that the results from the comparison with the factory calibration may be misleading, since this is made for the part of the population showing excessively large ratio errors.

The drift rate was evaluated only for the smaller group of CVTs compared with factory calibrations since the class 0.5/0.6 CVTs in general were adjusted on site at erection and records of the connection of the adjustment windings are not available. The drift rate for this group was found to be $(0.040 \pm 0.014)\%$ /year of age. The mean change was 0.08%. Six units with very large errors have been excluded to obtain these figures.

The mean Normalised Ratio Error at zero burden for the population of class 0.5/0.6 CVTs is 1.1, which indicates that the ratio error for the group in its entirety has increased by 0.1% of the ratio. The Normalised Ratio Error is understood as the ratio error divided by the class index.

Estimating a suitable interval between calibrations from the estimated drift rate a recommendation of 7 years is obtained. The average drift for the whole population therefore seems to be moderate, but available data does not permit a more specific evaluation.

The failure rate has not been estimated separately for the class 0.5/0.6 CVTs, but the failure rate for the population of all CVTs regardless of accuracy class is 1.1 ppm/hour and since the failure rate estimated for class 0.2 is higher it follows that the failure rate for class 0.5/0.6 is at least not higher than 1.1 ppm/hour. On the basis of the failure rate, a suitable interval between calibrations was estimated to be 10 years. It must though be stressed that different failure criteria have been applied to the different accuracy classes. A failure of a class 0.5/0.6 CVT has been defined as a ratio error change larger than the class index, except for CVTs on the 400 kV network where instead a 0.3%

failure criterion has been applied. A substantially different result is expected if the criterion of 0.2% used for class 0.2 would be applied.

With respect to the wish to use class 0.5/0.6 CVTs for metering purposes it would be advisable to have a short interval between calibrations and it seems to be a reasonable compromise to suggest 5 years for this group until more knowledge is available.

The correlation between several environmental parameters and the ratio error has been investigated. The position of the CVT, i.e. mid-phase or outer phase, the ambient temperature during the calibration and the solar irradiation all showed no significant correlation with the ratio error.

The value of the installed burden is low with a mean value of 20 VA and a standard deviation of 13 VA. The range of the installed burden has been 0.1 VA to 74 VA. The CVTs calibrated have almost invariably a rated burden of 150 VA and the installed burden does, with one standard deviation, not fall in the 25% to 100% range of rated burden prescribed by IEC 186. The ratio error at installed burden should therefore be expected to be close to the positive class limit and this observation has also been verified by the results. The phase angle of the burden has been found to be 13° with a standard deviation of 18° . The standardised power factor 0.8 inductive, phase angle 37° , does therefore not fall within the range observed. It is suggested that the present IEC 186 practice should be changed so that the burden range for a voltage transformer should be 0-100% of the rated burden and that the power factor should be unity.

The present project, which has enabled the author to write this thesis, is at the moment in a continuous phase and calibrations proceed routinely each summer period with the calibration of some 150 CVTs per year. The strife to ensure the quality and accuracy of the measurements is however never routine and the effort to ameliorate the measurements is continuous. The results obtained have already come to good use in the preparation of an official report suggesting rules and regulations to be employed for the free market for energy in Sweden. The report sets, among many other details, the basic recommendations for intervals between calibrations of CVTs used for energy metering.

The continuation of the *in situ* calibrations is important. Repeated calibrations of the same CVT makes it possible to track the change of the ratio of the CVT more definitely than hitherto and to distinguish the true long-term drift from short-term instability. The coming free market for energy will require reliable and indisputable measurement of transmitted energy for billing, a need that will require repeated calibrations of the voltage transformers at intervals based on the observed drift and failure rates. An accurate knowledge of the

changes in the ratio of CVTs over time is also important for decisions on replacement both of individual CVTs and of groups of CVTs.

A future study of the correlation between lightning intensity, ground resistivity and CVT failure rate is desirable since it may shed some light on the mechanisms of CVT failure. The work will be fairly extensive, involving both examination of available records on the lightning and soil characteristics for the different regions, but also detailed examinations of several failed CVTs to determine the mechanism of the failure. A study in this area would require certain funding for the research, even though it is hoped that much can be done within the framework of mutual interests of utilities and manufacturers.

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