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Present state and prospects of electrical energy measuring techniques at the PTB

Andreas Braun*

1 Introduction

Electrical energy measuring techniques have always ranked among the classical areas of work of the PTB and its predecessor, the Physikalisch-Technische Reichsanstalt (PTR). As in the past, the activities are still mainly focussed on measuring the quantities relevant to the generation, transmission, distribution and consumption of electrical energy.

In the Federal Republic of Germany, electrical energy to the amount of approximately 50 billion euro per year is consumed. Assurance of the uniformity of energy measurement within the framework of legal metrology is one of the central tasks assigned by the Verification Act to the PTB. Fulfilment of this task requires the development and realization of the physical technical units which are to be disseminated – through the testing of standard measuring devices – to the responsible agencies, i.e. the verification authorities of the federal states and the state-approved test centres for electricity meters.

Another important task of the PTB is to keep and further develop the national standards for electrical energy measurement with which the calibration laboratories of industry can compare their standards. This not only guarantees uniformity of the measurements performed by industry but also allows products to be manufactured which are competitive on the world market.

When handling these two tasks it has time and again – both in the days of the PTR and today – been necessary to develop measuring instruments which were not available on the market. In quite a lot of cases, these instruments then were of such great interest to the instrument-manufacturing industry that companies acquired the expertise to produce them in series. This too has enabled the PTB to make a contribution to the competitiveness of industry.

The PTB – and thus also the PTB's "Electrical Energy Measuring Techniques" Department – ensures its own competitiveness by practising

quality management in accordance with ISO 17025 and global metrological integration through international comparisons. These measures will contribute to the traditional confidence the PTB, and before it the PTR, have enjoyed for decades being justified also in future.

The Department is subdivided into the Sections "Instrument Transformers and High-Voltage", "AC/DC Transfer" and "Electricity Meters." Add to this the "Measurement of Non-electrical Quantities" Project which succeeded the former "Instrument Transformers" Laboratory and is closely connected with the Department although it is not formally part of it. Within the scope of this project, measurement procedures are being developed and measuring set-ups installed in close cooperation with the relevant sections.

The tasks of the "Instrument Transformers and High-Voltage" Section comprise the field of current and voltage transformers, instrument transformer test sets and burdens as well as the measurement of high DC and AC voltages, impulse voltages and impulse currents and the calibration of peak voltmeters, partial discharge meters and digital recorders for impulse voltage measurements. The "AC/DC Transfer" Section is responsible for the development of planar thermal converters, the development and calibration of AC-DC voltage and AC-DC current transfer standards and of AC voltage and AC current measuring set-ups. The "Electricity Meters" Section deals with electricity meters, tariff devices, reference meters and energy and power meters.

The work in these fields essentially covers:

- Type approvals of measuring instruments for verification.
- Testing of standard devices within the scope of legal metrology.
- Calibration of measuring instruments within the framework of the DKD and for domestic and foreign manufacturers.

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- Development of measuring methods and setting-up of measuring equipment.
- Consultancy services and assessment of test and calibration centres.
- International cooperation, and collaboration in standardization.

The working methods of the Department are characterized by the interaction between testing/approval/calibration (TAC) on the one hand, and research and development (R&D) on the other. So the necessity of rationalizing the performance of TAC tasks or of enabling it at all has, for example, led to R&D solutions by the development of new measurement procedures and the establishment of measuring set-ups.

The permanent enhancement of the measurement capabilities on its part has made it possible to extend the offer of technical and scientific services in compliance with the requirements of practice.

2 Legal metrology

The activities in the area of legal metrology are regulated by laws and ordinances by which specific tasks are assigned to the PTB:

- Approval of instrument transformers and electricity meters and their auxiliary devices for verification.
- Prior to new developments, consultancy services to manufacturers of such devices.
- Testing of the standards of the verification authorities and the state-approved electricity test centres.
- Cooperation with the verification authorities in the establishment and inspection of test centres.

A significant part of the Department's capacities are absorbed by the performance of these tasks

(see *Latzel, H.G. et al.*). So it is most important to permanently check the scope of these tasks in order that they might be carried out as efficiently as possible. This is achieved, among other things, by:

- Provision of permanently updated information material on the Department's Internet pages (including application forms).
- Reduction of test effort and expense by the inclusion of test results of external bodies (e.g. state-approved test centres).
- Allocation of partial tasks to cooperation partners on a contractual basis (for example the Bavarian State Authority of Weights and Measures).

By far the most important contribution to the rationalization of these activities is the development of measurement procedures and the setting-up of measuring facilities. So the calibrations upon type approval and upon the testing of standard measuring devices today is in great part performed with automated measuring devices which have been designed and realized at the Department or within the "Non-electrical Quantities" Project mentioned above (see *Latzel, H.G. et al., Ramm G. et al., and Schon, K. et al.*).

It is in the field of legal metrology that there is a strong interaction between the requirements of the market, i.e. of the manufacturers, energy suppliers and test centres and the activities of the PTB. A fundamental change which is actively supported by the PTB in close cooperation with the other stakeholders, is taking place in particular as a result of the liberalization of the electric current market.

Recently, the desire to use non-conventional instrument transformers has repeatedly been expressed again also in connection with legal metrology. Since the early seventies, the Depart-



Figure 1:

Four generations of reference meters. On the left: Ferraris, 1925; in the middle: thermal design, 1965; top right: analog-electronic design, 1979; bottom right: digital-electronic design, 1995.

ment has been dealing with this subject – at the beginning also by research activities of its own. So over the years, the Department has, therefore, been able to assist individual companies in boosting the efficiency of devices developed for network protection to meet the requirements of legal metrology. In no single case, however, has a concrete application for type approval been filed. This is due to various causes: so neither the accuracy of measurement required by verification law nor the extension of the time of operation without subsequent verification expected by the customers – at least compared with conventional instrument transformers – were achieved. In the meantime, international standards have been or will soon be published so that it is justified to again deal with this subject (see *Seifert, H. et al.*).

3 Industrial metrology

The essential tasks of industrial metrology are:

- Calibrations of measuring instruments for DKD calibration laboratories.
- Rendering of consultancy services to, and assessment of, these laboratories.
- Calibration of measuring instruments for energy measurements for use outside legal metrology, for example for export or foreign applicants.

In the field of energy measurements, the metrological activities in industrial and legal metrology are quite similar. As the devices are often identical, the measuring set-ups used for calibration are identical, too. The only difference is that in legal metrology the scope of the calibration and the deadlines for recalibration are fixed and that performance of the calibration confirms compliance with specified measurement tolerances (maximum permissible errors) – which semantically is covered by the term “test.” When devices are, however, calibrated for industrial applications or for export, the applicant decides on the scope of the calibration and obtains a calibration certificate with the measurement deviations determined. Also, the calibration certificates issued within the DKD do not contain any statement on the validity.

In summary it can, therefore, be said that as far as technical aspects are concerned, the same statements are valid for industrial metrology and for legal metrology, and this applies to both, the measurement procedures used and the interaction between the need for rationalization and automation and the development of measuring techniques satisfying this need.

4 Research and development

The objectives of the research and development activities in the “Electrical Energy Measuring Techniques” Department are the following:

- Investigation of physical effects for their suitability for practical metrology.
- Development of measuring sensors.
- Use of modern media (for example: Internet) for the transfer of measurement data relevant to invoicing.
- Reduction of the measurement uncertainty by use of new measurement principles.
- Investigation of classical measurement procedures for their suitability for providing essential solutions to problems by modern means (electronics, use of PCs).
- Rationalization of the test and calibration activities by automation of the measuring set-ups.

Separate articles in this publication deal with important recent research results. One focal point is the electrical AC power (see *Ramm, G. et al.*). This central quantity has always played a substantial part at the PTB/PTR so that the best measurement principles available have been applied. For years, this has only been the thermal converter which, designed as planar multiple thermal converter, has occupied a leading position. This will not change in the future either – at least for the frequency range from above 1 kHz to 1 MHz. As a new measurement procedure, digital voltage synthesis with synchronous sampling and evaluation by means of discrete Fourier transformation (DFT) has been added. This allowed the limit of the measurement uncertainty in the technical frequency range (15 Hz to 400 Hz) to be reduced to a minimum of $1 \cdot 10^{-6}$ ($k = 2$).

Another focal point is the determination of the r.m.s. value of AC voltages and AC currents (see *Klonz, M.*). Not only has the PTB made essential contributions in this area by the development of the thermal converters but it also has developed strategies for how these converters can be used to determine voltages between 1 mV and 1000 mV and currents between 1 mA and 20 A with smallest uncertainties of measurement.

Measuring facilities for energy are frequently operated with very high voltages and currents and are, therefore, to be tested not only for accuracy but also for insulation resistance and electromagnetic compatibility. This is why the research and development sectors of the Department also deal with these fields (see *Schon, K., et al.*). The research activities are focussed on voltage dividers for high DC voltages, digital recorders for impulse voltage measurements,

impulse current generation and measurement as well as measurements of partial discharges.

High requirements must be met when the exchange of sensible measurement data from legal metrology is concerned. For this topic, at the Department's suggestion, the SELMA project "Safe electronic exchange of measurement data" has been established within the framework of VERNET – an ideas competition of the BMWi to support German industry in the implementation of safety technologies in open communication networks – and will be handled by a pool of energy suppliers, manufacturers, federal and state authorities (PTB, BSI, AGME) as well as two universities (Münster and Siegen). The project is for the time being limited to electricity and gas meters, it may, however, be generally regarded as trend-setting for the transfer of data subject to legal control. A prerequisite for this are modern, communication-capable energy measuring instruments as they are evaluated to

an increasing extent in the Department within the scope of type approvals. The SELMA project confirms that the competence established in the handling of approvals can give impetus to promising industrial developments.

The success of these research and development activities is favoured by the fact that the same electrotechnical qualification is required for handling the tasks (testing and calibration of electrical devices) and for finding solutions (electric/electronic measuring procedures). This is why the employees entrusted with TAC and R&D activities as colleagues are in direct contact with one another and, as they have the same technical background, can optimally bring their plans and ideas into accord.

Also, the heads of the organizational units of the Department have the same professional qualification so that – in addition to their organizational management functions – they can act as contact persons and coordinators for both, the TAC and the R&D sector. This also ensures that within the organizational structure which will in future be more project-oriented they will be able to effectively control the cooperation between the TAC and R&D projects.

5 National and international cooperation

The integration of the Department into national, regional and international activities has many aspects. Focal points are:

- Cooperation in legal metrology bodies (together with the verification authorities, state-approved test centres, manufacturers of measuring instruments subject to legal control, electricity suppliers, OIML).
- Cooperation in the Deutscher Kalibrierdienst.
- Cooperation in standardization (DKE, CENELEC, IEC).
- International comparisons (EUROMET, CCEM).
- Consultancy services to foreign state institutes and instrument manufacturers for the extension of their measurement capabilities.

These activities require considerable commitment which, as experience gained has shown will be called for also in future, as precisely these links are necessary to perform need-oriented work, i.e. work with due regard to practice. Here, too, however, the possibilities of rationalization as offered by modern means (video conferences and measurement comparisons via Internet) are already used and the development of information technology will in future further increase their effectiveness.

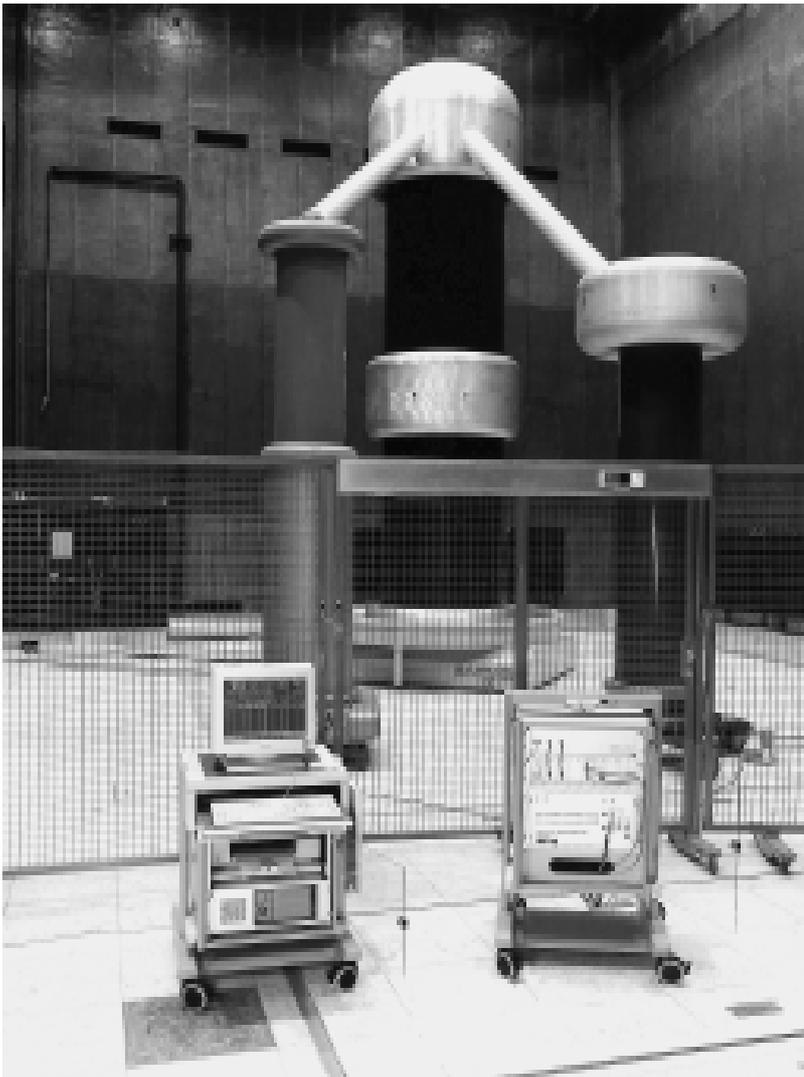


Figure 2:

Test of a high-voltage standard instrument transformer. In the foreground: the self-calibrating transformer measuring system developed at the PTB.

6 Outlook

The future development will have to cope with both, declining resources (personnel and equipment) and unchanging or even increasing requirements. This challenge can be met only if several measures are combined. Among these are:

- Organizational changes to flexibilize the assignment of the employees, i.e. establishment of projects of limited duration to solve special development tasks.
- Use of the latest commercial measuring equipment for data acquisition and processing to enable the employees to concentrate their development capabilities on the development of measuring sensors and their adjustment to the measuring instruments and the development of the required measurement programs (software development).
- Formation of working groups for several measuring instruments, including testing, approval and calibration.
- Thorough analysis of what services can be reduced or outsourced by cooperation with other agencies to allow important new tasks to be taken over.

At PTB/PTR, electrical energy measuring techniques have a long tradition which is associated with names like H. Schering, R. Vieweg, W. Hohle, E. Zinn, H.-J. Schrader, W. Claussnitzer and R. Friedl. In the past hundred years, the focal points of the work have not, however, considerably changed. Now as before, the services sector with type approval, testing and calibration is up against the research and development sector dealing with the development of measurement procedures and the setting-up of measuring facilities. What has fundamentally changed is the technology used which has led to personal computers being universally used in measurement procedures and measuring facilities. Not only has this resulted in more accurate measurement results being obtained, but the time required could be considerably reduced. As a result, an extended spectrum of services could be offered to the electricity suppliers and the verification authorities and the manufacturers of measuring instruments despite their increased requirements. It is the central task of the Electrical Energy Measuring Techniques Department of the PTB to ensure this also in future.

Approval, testing and calibration of equipment for electric energy measurements

Hans-Georg Latzel¹, Martin Kahmann², Helmut Seifert³,
Andreas Suchy⁴

1 Introduction

To support consumer protection, the Federal German Verification Act prescribes that only approved and verified measuring instruments may be used for invoicing electric energy [1]. "Approved" here means that a measuring instrument type must comply with the legal requirements [2], and the PTB tests on the application of the manufacturer whether this compliance is achieved. After type approval has been granted, electricity meters and instrument transformers are verified in one of the approximately 150 state-approved test centres for electricity measuring instruments and only then are they installed in the electricity supply system. The standard measuring devices used at the test centres for verification must be tested at regular intervals at the PTB for compliance with the requirements of the PTB Testing Instructions [3, 4]. The measuring facilities required for this purpose are also used for the metrological inspection of instrument types within the scope of acceptance tests and for comparison with national and international standards. In addition, they are used to calibrate measuring instruments of customers outside the area subject to legal control.

2 Approvals

For electricity meters and instrument transformers, an informal application for acceptance for verification, including a description of the construction and the technical data of the equipment, can be filed with the PTB. Approval is granted after successful checking of the documents and, where appropriate, testing of a specimen. Within the scope certified in the approval, the applicant is entitled to manufacture devices in series and to have them verified by a state-approved test centre. Just like the verification offices, these institutions which deal exclusively with the areas of gas, heat, water and electricity perform sovereign tasks and are controlled by the supervising verification authority of the respective federal state.

2.1 Electricity meters

2.1.1 Requirements

In its "Electric energy Measuring Techniques" Department, the PTB grants at the moment type approvals for verification for electricity meters of the following instrument categories: motor-operated electricity meters ("induction meters"), electronic electricity meters and supplementary devices for electricity meters. For these instrument categories, the standard requirements for construction stipulated by verification law have been published as the so-called PTB Requirements 20.1 [5]. For electricity meters, the requirements mainly make reference to industrial standards. For motor-operated meters, these are EN 60521 (for active power) and DIN VDE 0418 part 2 (for reactive power). In the case of electronic electricity meters, a differentiation according to class accuracies is to be made between EN 60687 (for active power, classes 0,2S and 0,5S) and EN 61036 (for active power, classes 1 and 2) on the one hand, and EN 61268 (for reactive power, classes 2 and 3) on the other. For supplementary devices, only part of the requirements have been explicitly fixed in the PTB Requirements 20.1, while the standard requirements for construction are mainly found in the PTB Requirements 50.6 and 50.7 [6, 7]. These requirements apply also to supplementary devices for gas, water and heat measuring devices which fall within the province of other PTB Divisions.

As implementation regulation for the verification of approved electricity meters and supplementary devices, i.e. for the official routine test, the verification authorities and state-approved test centres have to use Volume 6 of the PTB Testing Instructions [3]. This volume is at present composed of parts A (induction meters), B (electronic electricity meters), C (DC meters) and D (supplementary devices). Part E with specifications for the equipment of the test laboratories is under preparation.

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2.1.2 Development of the demand for conformity testing of electricity meters and supplementary devices

For decades, the demand for PTB approvals and test certificates for electricity meters and supplementary devices has shown ups and downs as the need for certain instrument techniques frequently follows the changes in the general conditions. The users then utter their demand for appropriate measuring techniques more or less at the same time and as a result the development activities and the filing of applications for approval on the part of the instrument manufacturers also show a certain parallelism, leading to the irregular work load of the approval authority. Examples of this from the past few years are, among others, the conversion of the line voltage from 220 V to 230 V (around 1989), the coming into effect of a new federal electricity tariff system (around 1990), the publication of VDEW specifications for electronic meters (around 1997) and the liberalization of the electricity market (since 1998).

Due to industrial concentration processes in both, the measuring instruments industry and the public supplies sector, i.e. of those buying measuring instruments, the ups and downs have, however, flattened since the mid-nineties. Large and established meter manufacturers have merged into other companies and numerous companies of the utility sector merged as a reaction to the changed competitive situation on the liberalized electricity market. As a result, the diversity of the demand for measuring instruments and, consequently, the more or less synchronous need of the manufacturers for approvals for many different variants have decreased.

The total amount of applications for conformity tests for electricity meters and supplementary devices has not, however, decreased but increased. This is above all due to two market tendencies:

Innovation dynamics: The increasing capacity of electronic circuits as well as the change from analog to the considerably more flexible, software-controlled digital technology leads to ever shorter development cycles for improved or completely new products also as regards electronic meters. As a result of this innovation dynamics, the number of applications filed with the PTB is increasing, and new challenges are to be met as regards the qualification of the approval personnel. The progress achieved in information technology, which is at the origin of the increased number of applications, must be made use of to adjust the approval processes without increasing the costs

inappropriately. Here, the “E-Government Initiative” of the Federal Government serves as valuable guidance in the field of electricity meter approvals. Essential information and check lists which are available on the Department’s Internet pages (www.ptb.de/de/org/2/23/234), have had a noticeable rationalization effect both for the applicants and for the PTB Sections.

Globalization of trade: The requests for approval and for conformity tests have noticeably increased on the international level as well. So services have been rendered to applicants from Austria, Denmark, Finland, France, Hungary, Morocco, Nepal, Poland, Romania, Slovenia, Sweden and Turkey. In many cases, the firms do not apply for the PTB certificate to get access to the German market but because metrological certificates of the PTB still facilitate the export of measuring instruments into many countries of the world. The European Measuring Instruments Directive (MID) will have a considerable influence on the approval procedures, as besides type approval, which has so far been mandatory, some other procedures will provide access to the market whose effects on the activity of the PTB are not yet clearly seen (see section 5).

2.1.3 Tendencies of the technical development

More than 95 percent of all electricity meters used in Germany for invoicing are induction meters. In more than a hundred years, their technique has been perfected so that the number of approval procedures for new or modified instrument types may be neglected as against those for electronic devices. As a consequence, the present operative approval business almost exclusively concerns devices with a market share below 5 percent. In view of the drop in prices and operating costs due to the increased reliability of electronic devices and, compared with induction meters, the larger spectrum of functions, it can, however, be expected that the importance of electronic meters will in future augment considerably, also as regards their use. At present, the efforts of the developers of electronic electricity meters and supplementary devices are focussed in particular on the reduction of the production costs (simplification and standardization of sub-assemblies and software), development of smaller physical sizes (e.g. “DIN rail meters”), improvement and extension of communication capabilities (interface implementations for service and installation bus systems, protocol standardizations etc.). For software-controlled devices, a general trend towards the centralization of functions can be observed. With the costs for data communication decreasing, the meters and supplementary de-

vices increasingly perform functions which cannot be centralized, i.e. they serve above all for the remote sensing of measurement values, whereas all other process steps of the formation of measurement results for invoicing are performed centrally.

The PTB recognized these development tendencies at a very early stage and thus could take them into account. So the international standards have been developed with the active collaboration of the PTB, and technical solutions have been elaborated in cooperation with manufacturers and users. This ensures that also in future the experience the PTB has gained in the handling of type approvals will benefit the developers of new device generations and thus have a positive impact on the technical progress.

2.2 Instrument transformers for electricity meters

2.2.1 Requirements for instrument transformers as used for invoicing

Instrument transformers are measuring transducers which transform voltage or current within specified error limits and transmit the relevant data to metering systems. Upon application of a manufacturer, the PTB grants type approvals for the following high-voltage, medium-voltage and low-voltage instrument types: inductive current transformers, inductive or capacitive voltage transformers and combined current and voltage transformers. Granting of a type approval for national verification is based on the Verification Ordinance and its Appendices and on the PTB Requirements [8]. The latter are accepted rules of technology which have been adopted by the Plenary Assembly for Verification Matters (representatives from industry, verification authorities and the PTB). Further details regarding mechanical transformer constructions, metrological characteristics and

the marking of the measuring instrument are described in the harmonized European Standards EN 60044-1 foll. [9 to 12] published by the DIN. Essential information about instrument transformers is also available on the Internet (www.ptb.de/org/2/23/234).

A new development in the field of type approvals relates to the non-conventionally operating transformers whose principle is dealt with in a separate article [13]. For this instrument type, too, requirements have been laid down which have been published as DIN, EN or IEC standards.

As for electricity meters, the PTB has also published regulations for the verification of instrument transformers for invoicing: the PTB Testing Instructions "Instrument Transformers" which provide guidance for the verification authorities and state-approved test centres [4].

2.2.2 National type approval for instrument transformers in the context of the economic development in Europe

Due to the cost pressure the manufacturers feel as a result of the liberalization of the electricity market, established devices are modified to adjust the price/performance ratio to the market, as an increase in competition is also expected from European contenders producing comparable qualities at lower wage levels. Due to these changes in the general conditions, the applications vary strongly for some instrument types. Another possibility of counteracting the ever increasing costs and thus the permanent drop in the sales figures are mergers of companies or cooperations regulated by contract between manufacturers of different products who agree to mutually exchange their products.

About one third of the applications comes from abroad as, for example, from Austria, Belgium, the Czech Republic, Italy, the Netherlands, Poland, Spain and Switzerland. Applicants from these countries frequently ask the PTB to what extent the results obtained in high-power or accredited test laboratories are recognized within the scope of the type approval procedure. As bilateral agreements do not exist, decisions are to be taken as the case arises. Measurement results of renowned laboratories and also investigations



Figure 1:

Measuring instruments subject to approval: from the left: inductive medium-voltage transformer, supplementary device for electricity meters, communication-interfaced electricity meter, inductive medium-voltage current transformer.

by the manufacturer himself, are desirable, as they provide the confidence in the product to be approved which is necessary for the evaluation. The communication of test results from accredited foreign laboratories reduces the test efforts of the PTB, provided traceability to the national standard of the Federal Republic of Germany is provided, for example by intercomparisons.

Others like to make use of the PTB's reputation as a globally known metrology institute to get access to global markets; this becomes obvious when applicants want to get an approval for high operating voltages and high currents though these are not subject to mandatory verification [2].

The national type approval procedure will probably be applied also after the European Measuring Instruments Directive (MID) has been introduced, as the MID draft does not provide any regulations for instrument transformers.

2.2.3 State of the art and tendencies

Today's medium and high-voltage instrument transformers, for which approvals are applied for to the PTB, are insulated with oil-impregnated paper, protective gas (SF₆) or cast resin. There are no fundamental new developments in the field of conventional transformers, but increased activities to optimize materials and procedures. Automatic or semi-automatic production is forced up in particular in the range of low and medium voltage. This allows the production costs for instrument transformers to be considerably reduced while the quality remains unchanged. Further efforts are made to cut the costs for verification; fully automatic test stands complement the automatically operated production line.

In the field of electric energy measuring techniques there is a development potential for electronic instrument transformers. Literature refers to different measurement principles whose realization in commercial measuring instruments does not depend on technical expertise but rather on the demand of the energy market. The future will show if the approach of electronic acquisition and digital processing up to conceivable online structures can also be realized for invoicing (for instrument transformers, examples exist already in the area of protection). This topic is dealt with in another contribution [13].

As in the case of electricity meters (see 2.1.3), the PTB also collaborates in drawing up future standards for instrument transformers and brings its technical competence to bear in the development of new devices. At the same time, the testing technique required for the new devices is developed so that type approvals can be immediately handled for the latest technolo-

gy as well.

3 Testing

After type approval has been granted, every single electricity meter or instrument transformer for invoicing is to be verified at a state-approved test centre for electricity measuring instruments. Upon verification, first the external characteristics and the inscriptions are compared with the information given in the approval certificate (conformity test). Then the metrological tests are performed in accordance with the PTB Testing Instructions (accuracy test). If the requirements are met and the error limits complied with, verification is documented by application of the principal verification mark. The facilities of the test centre required for the metrological tests must comply with the requirements specified in the PTB Testing Instructions.

3.1 Meter test

In Germany state-approved test centres for electricity use substandard meters to verify electricity meters. Whether these devices are suitable for this purpose is checked by the PTB's "Power and Energy, Pattern Approval" Team. Before they are used for the first time or after they have been opened or repaired, all substandard meters used in Germany for legal metrology purposes must be checked for accuracy. To ensure permanent control, the test centres check the meters every three months on their own responsibility and record the results. Checks of this kind are mainly performed with comparators. In contrast to test certificates for substandard meters, the validity of test certificates for comparators, which are also checked at the PTB's "Electricity Meters" Section, is limited in time. The period of validity depends on the extent to which the device has changed with respect to the previous test; it generally varies between three and five years. Comparators are inspected by the test centres against chemical standard elements or with electronic DC voltage references. These devices are also checked by the PTB.

3.1.1 Substandard meters

In the past decade, decisive changes have taken place in test equipment technology. The measurement uncertainties specified by the manufacturers have been improved from $\pm 0,1\%$ to $\pm 0,02\%$. Today, most manufacturers use digital measurement procedures and offer a large number of options, such as harmonics analysis, phase angle and phase frequency measurement as well as a great number of measuring modes (three and four wire active volt-ampere consumption as well as different measuring modes for three and four wire reactive volt-ampere

consumption).

All substandard meters are provided with at least one output which emits pulses proportional to the power applied. These pulses are used for external, and sometimes also for internal, error calculators determining the measurement deviations of the test units upon verification. It is, therefore, of utmost interest to determine the measurement deviations of the standard meters at the meter pulse output. In this case too a comparison measurement between a reference device with known measurement deviations and one or several test units is carried out.

Modern substandard meters have at least one interface so that they can be read and controlled by a computer. The test quantities simultaneously available at the reference device and at the test units can also be controlled by computer. This allows test sequences to be performed automatically.

The points for testing at the PTB are selected taking the requirements of legal metrology into account. Due to this fact and the large diversity of the meters used for invoicing, the number of potential test points is very great. For event meters, there are up to 160 test points at different voltages, currents, power factors and measuring modes which are automatically checked in succession.

In the course of the test, at least one test unit and the PTB reference device are fed from a three-phase electronic supply unit (Figure 2) which is composed of three current and three voltage amplifiers triggered by a generator. For

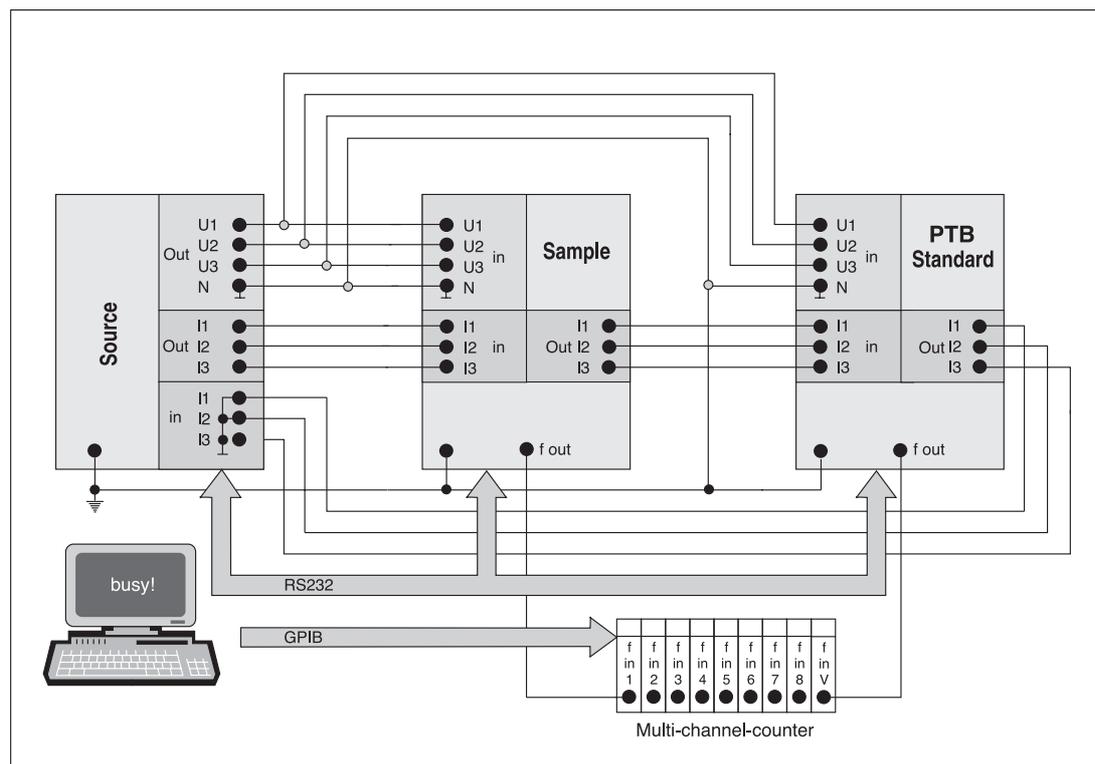
legal metrology, tests are performed almost exclusively at 50 Hz. Exceptions are tests at $16\frac{2}{3}$ Hz which are performed at some test centres verifying energy meters for railway traction current. The adjustment of current and voltage amplitudes, phase angles and frequency is computer-controlled. Then all devices are set to the current and voltage ranges, which are optimal for the load level adjusted, and to the measuring mode. The test program now calculates the number of pulses required to guarantee sufficient resolution of the measurement results. The output pulses of the standard meter are compared with those of the test units via a gate circuit. From several measurement values, mean values and standard deviations are formed.

The measuring facility is in a position to generate and measure voltages from 30 V to 500 V as well as currents from 3 mA to 125 A at frequencies between 15 Hz and 70 Hz.

3.1.2 Comparators

The comparators have also been further developed: in the past, they were single-phase devices, whereas they have now three phases and offer the same options (measuring modes, harmonics analysis etc.) as substandard meters. Their measurement uncertainty lies within $\pm 0,01\%$. They are provided with a DC voltage input for 1,018 75 V to which a standard cell or an electronic voltage standard is connected for self-checking. Modern comparators can also use other voltages. The exactly known magnitude of the voltage is entered, and the devices calculate

Figure 2:
Principle of the test circuit for testing or calibrating substandard meters: three-phase supply unit (source), test unit and standard measuring instrument, multi-channel meter for determination of the output pulses of test units and standard measuring instrument as well as PC with interfaces.



the deviations from the internally measured voltage values. The devices then show their intrinsic errors for all components to which DC voltage can be applied as well. Current or voltage transformers and low-resistance input modules are not taken into account.

The measurement deviations of the power measurements are determined by comparison of measurements with devices whose deviations are known. These are determined at regular intervals by comparison with the national standard of the PTB.

3.2 Instrument transformer test

In addition to the facility for the generation of the desired current and/or voltage, a measuring set-up for the verification of instrument transformers for invoicing comprises a standard instrument transformer, an instrument transformer test set and a standard burden. The standard instrument transformer serves as a reference, i.e. the difference between standard instrument transformer and instrument transformer is the measure for assessing the accuracy. The difference is determined with an instrument transformer test set, a kind of balance for AC currents and voltages, and the standard burden is used to simulate the loading of the instrument transformer by the electricity meters connected in series and the supply leads. These devices are checked at regular intervals at the PTB for compliance with the requirements [4].

3.2.1 Instrument transformer test sets

Figure 3 shows the principle of the test circuit for measuring the accuracy of current transformers. The standard current transformer T_N and the current transformer to be measured T_X are connected in series in primary circuit and supplied by the current source with the desired test current I_p . In secondary circuit, the current transformers are so connected with the inputs N (“standard”) and X (“device under test”) of the instrument transformer test set that the latter determines the complex difference between I_x and I_N . The burden Z_x is the value set with the standard burden for loading the instrument transformer.

Figure 4 shows the principle of the test circuit for the accuracy measurement of voltage transformers. The standard voltage transformer T_N and the voltage transformer T_X are parallel connected in primary circuit and supplied by the voltage source with the desired test voltage U_p . In secondary circuit, the voltage transformers are connected with the relevant burdens Z_N and Z_X as well as with the instrument transformer test set which determines the complex difference between the secondary voltages.

For testing of instrument transformer test sets, the operating conditions prevailing in the test circuits according to Figures 3 and 4 are simulated by an electronic standard device (calibrator). On the X side, a current or voltage is supplied the magnitude of which differs from the respective N value by a preselectable percentage (ratio error ϵ_x) and leads or lags by a preselectable angle (phase displacement δ_x). These standard devices have been developed at the PTB [14, 15]. The present design is computer-controlled so that the test which formerly required much work could be considerably rationalized.

3.2.2 Burdens for instrument transformers

Standard burdens for current and voltage transformers used for verification in state-approved test centres for electricity measuring instruments must be checked at the PTB for compliance with the requirements before they are put into operation and after that every five years. The measurement deviations related to the respective impedance must not exceed ± 3 per-

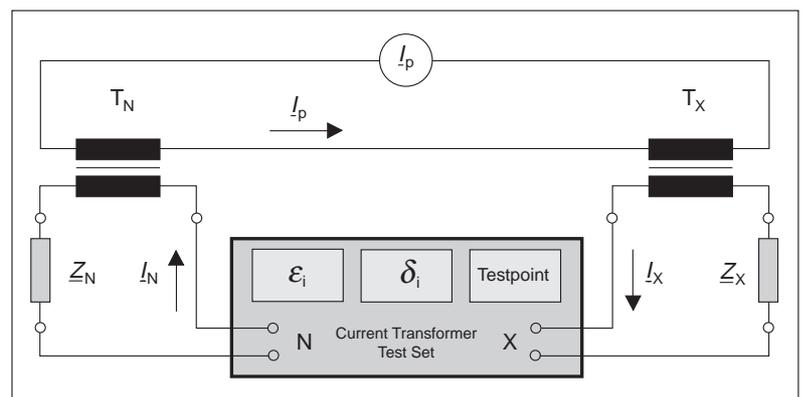


Figure 3: Principle of the test circuit for measuring the accuracy of current transformers.

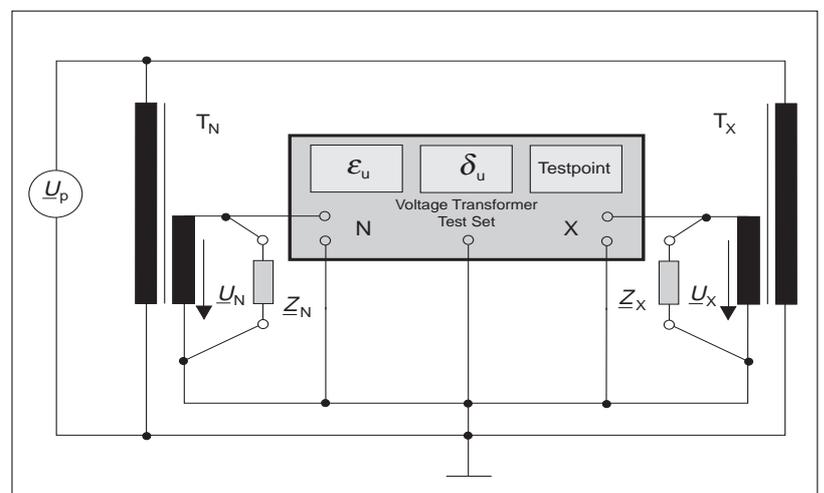


Figure 4: Principle of the test circuit for measuring the accuracy of voltage transformers.

cent. For checking, an impedance measuring facility of four-wire design is used which has also been developed at the PTB [16]. After digitizing of the measured values of voltage and current by discrete Fourier transformation, the amplitudes of the associated fundamentals and the included phase displacement are determined. The resulting complex quotient is the impedance searched.

3.2.3 Standard current and voltage transformers

Standard instrument transformers are designed for as many transformations as possible so that – if possible – all available instrument transformer types can be directly compared with them. They must comply with clearly smaller error limits than instrument transformers, i.e. $\pm 0,02$ percent for the ratio error and $\pm 0,03$ crad or $\pm 1,0'$ for the phase displacement.

After performance of the initial test, the standard instrument transformers of the state-approved test centres for electricity measuring instruments must be re-measured at the PTB at least every sixteen years (five years for stan-

dards with electronic components). They are checked by direct comparison with standard transformers of the next higher hierarchy level. The measurement circuits used are in accord with the principles shown in Figures 3 and 4 where \underline{Z}_x stands for the operating burden with which the standard transformer is loaded at the test centre during the verification of instrument transformers. Just as the metrological quality of the PTB standard instrument transformers must even be higher than that of the standards of the test centres, the instrument transformer test sets used at the PTB for the testing of standard transformers must have even smaller measurement uncertainties than those demanded for the instrument transformer test sets of the test centres. The development of appropriate facilities has been a traditional task of the PTB which had already been performed by the PTR [17 to 21]. After the electromechanical and the electronic generations, the third device generation is now being used; all its operations such as, for example, digital data processing by discrete Fourier transformation, including self-calibration, are PC-controlled [22, 23].



Figure 5:

Electric energy measuring instruments calibrated at the PTB are intended for customers in many countries of the world. (Irrespective of the number of customers and devices, each country is marked by one dot only; period: 1998 to 2001.)

4 Calibrations

The measuring set-ups the PTB operates for tests in the area of legal metrology are also used for industrial metrology. This collective term denotes commissions, for example from manufacturers of energy measuring instruments, calibration laboratories of the Deutscher Kalibrierdienst (DKD), research institutions, foreign energy supply companies or foreign state institutes. Kind and scope of the measurements can be specified by the customer or are determined in agreement with him within the scope of advisory services extended. Figure 5 shows for which countries the devices – substandard meters, power comparators, power meters, standard instrument transformers, standard burdens, instrument transformer test sets (see figure 6) – calibrated between 1998 and 2001 were intended. During that period, the commissions amounted to approx. 155 000 EURO per year. While the metrological investigations – except for specific customer requirements, for example with respect to measuring frequencies and measurement points – do not differ from those to be carried out for testing in the area subject to legal control, no statement on the compliance with requirements is made at the end of the measurements. The calibration certificate shows the deviations from the rated values and the measurement uncertainty of these deviations.

5 Outlook

At present, the proposal for a Directive of the European Parliament and the Council on Measuring Instruments (MID) is being discussed, which for the whole area of the European Community defines the framework for uniform procedures for placing specific measuring instruments, including electricity meters on the market. According to this Directive, the individual countries are not bound to regulate this area by law, but, if they want to do so, they must follow the procedure prescribed by the MID. The test of whether a measuring instrument complies with the requirements of the MID is performed by “Notified Bodies” of the individual member states; these may be either national metrology institutes or accredited private institutions. Depending on the kind of measuring instrument and the requirement of the applicant, there will be different ways of proving conformity; the procedures so far applied, i.e. design review and type testing, will also be possible in future. According to the MID, initial verification at a state-approved test centre for electricity meters as has so far been required in Germany for measuring instruments with national type approval can be dispensed with if the manufacturer has established a qua-



Figure 6:

The “balance” for instrument transformers – an automatic instrument transformer test set.

lity management system recognized by a Notified Body.

An estimate of the effects the introduction of the MID will have on the size of commissions for approvals and tests at the “Electric energy Measuring Techniques” Department is at present still affected by a very high uncertainty, especially since some details of the MID draft have still to be agreed upon. As the MID regulates only placing on the market, but not the control in subsequent operation, each member state decides itself on the kind of market surveillance. The answer to the question of whether the state-approved test centres for electricity measuring instruments should take over tasks here and how these can be funded, will also affect the number of testing devices to be held ready and thus the scope of the tests to be performed at the “Electric Energy Measuring Techniques” Department.

As to the technical development, the assumption is that information technology will take hold also for invoicing. In future, the boundary between “meters” and “instrument transformers” might become blurred if “intelligent” current and voltage sensors generate the required information locally and further evaluation is performed in computers at the consumer’s or supplier’s. Which level of reliability, including the measuring stability, will be required and what price the customers will be prepared to pay for it will also depend on the energy price itself.

It is an important aspect of the spatial separation of acquisition and processing of measurement values that the transfer of sensible data from legal metrology is to be protected from inadmissible influences. To investigate this topic, the SELMA project “Safe electronic exchange of measurement data” has been initiated by the PTB. The large number of participants in this project – energy suppliers, manufacturers, fed-

eral and state authorities as well as universities – guarantees that all concerns will be taken into account for future solutions. The PTB therefore attaches great importance to this project.

Also in future, the PTB will have to match the measuring equipment required for testing and/or calibration of standard devices of the state-approved test centres or calibration laboratories to the prevailing state of the art. This will be made possible by the experience so far gained in this field [14–16, 21–23].

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PTB Standard Measuring Devices for Electric AC Power

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Waldemar Guilherme Kürten Ihlenfeld⁴

Introduction

The unit of electric power is derived from the units volt and ohm which are known with very low uncertainties. The measurement of the electric AC power additionally requires an AC/DC transfer to ensure traceability to DC quantities. The first part of this article deals with a measuring system for the electric active power, which uses thermal converters for the AC/DC transfer and has been in operation for about 20 years. A new calibration system for the stable generation and precise measurement of the electric active, reactive and apparent power using digital synthesis and sampling methods will be presented in the second part. Here the AC/DC transfer is achieved by calculating the rms value of the AC quantities from sampling values.

Calibration system for electric active power using multijunction thermal converters

For the precise measurement of active AC power, measuring procedures are used which trace back these AC quantities to equivalent direct current quantities. In a measuring set-up suggested by Schuster [1] in 1980, thermal converters are used as AC/DC transfer elements. Especially designed multijunction thermal converters yield very small AC/DC transfer differences [2].

The basic set-up of the PTB thermal converter based measuring device for electric power is shown in Figure 1. The AC power source of the system possesses separate current and voltage circuits which are phase-locked with each other. Measuring devices to be calibrated are connected to the system as usual, i. e., voltage paths connected in parallel and current paths in series.

Any kind of highly stable power source may be used as power supply to the measuring system. The system is connected via a two-stage voltage transformer and a current transformer with electronic error compensation. Rated input voltages are 120 V and 240 V, rated input currents 1 A and 5 A. The frequency ranges from 45 Hz to 65 Hz. Measurements can be conducted at any phase angle between voltage and current signals.

The secondary current output of the current transformer is converted, via a precisely known current measuring resistor and an inverter, into

the voltages $+U_i$ and $-U_i$. These signals are, with the help of summation and difference amplifiers, geometrically combined with the output voltage $+U_u$ of the voltage transformer to form the summation signal $U_u + U_i$ and the difference signal $U_u - U_i$, which in turn are supplied to two AC/DC voltage transfer elements (multijunction thermal converters).

A block diagram of the AC/DC transfer for active power measurements is shown in Figure 2. To simplify matters, a single-junction thermal converter is represented instead of the multijunction thermal converter actually used. First of all the system determines the output voltages of the thermal converters $U_{th\ sum}$ and $U_{th\ diff}$ when the converters are fed with the AC quantities $U_u + U_i$ and $U_u - U_i$. These output voltages

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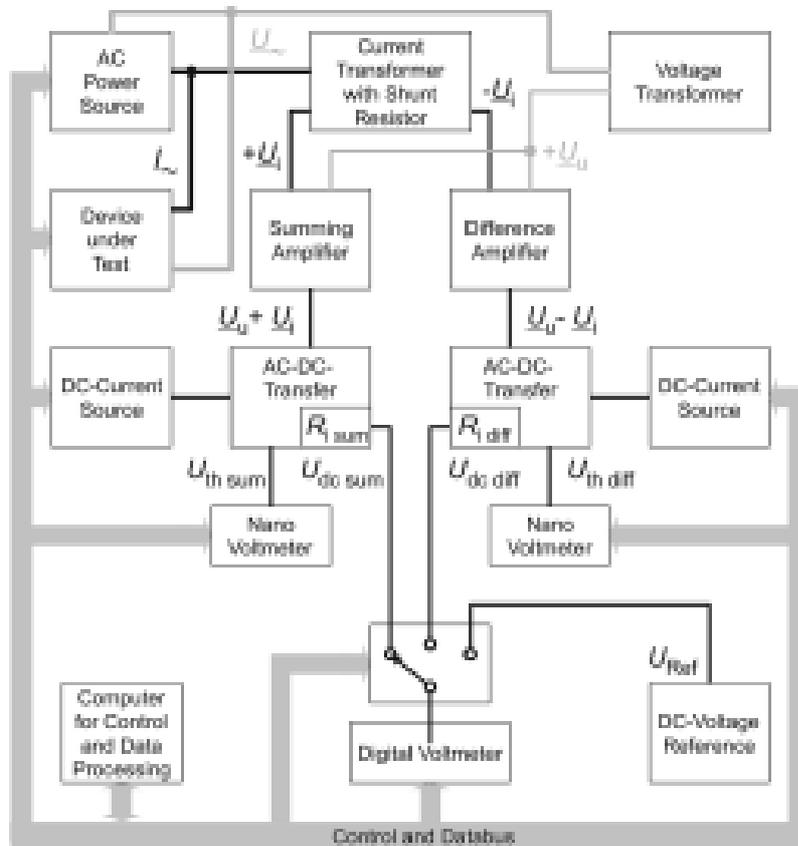


Figure 1: PTB calibration system for electric active power using thermal converters for AC/DC transfer.

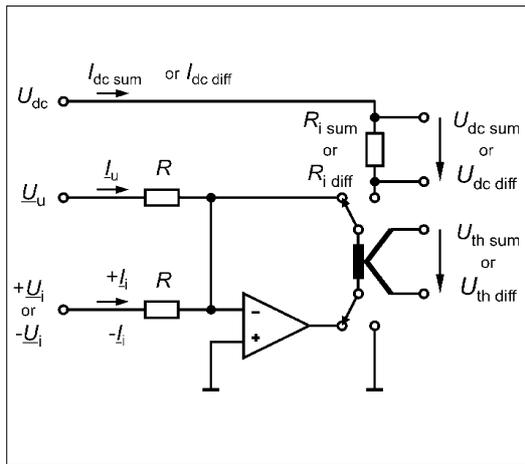


Figure 2:
Block diagram for the AC/DC transfer for active power measurements.

lie within the millivolt range; they are measured with special, high-resolution nanovoltmeters.

Subsequently, the inputs of the thermal converters are switched over to DC sources, which are adjusted until the equivalent DC currents $I_{dc\ sum}$ and $I_{dc\ diff}$ lead to the same output voltages of the thermal converters as the AC quantities. These equivalent DC currents are determined with standard resistors $R_{i\ sum}$ and $R_{i\ diff}$ and their ensuing voltages $U_{dc\ sum}$ and $U_{dc\ diff}$. All these measurement steps are computer-controlled, as with the data acquisition of the instrument under calibration.

Similar to the measurement of rms values of voltages and currents with thermal converters, for the determination of the active power, this measuring system takes advantage of the quadratic relationship between the output voltage and current through the thermal converters' heating resistor. In principle, the summation and difference signals are squared and the difference is calculated from the two squares as:

$$(\underline{U}_u + \underline{U}_i)^2 - (\underline{U}_u - \underline{U}_i)^2 = 4 \cdot \underline{U}_u \cdot \underline{U}_i \quad (1)$$

Thus a product of voltages is obtained, which is proportional to the electric active power. This "thermal" measuring procedure has been applied at the PTB since about 1980 for the calibration of precision measuring devices for the electric active power and has taken part in international comparisons. For the active power at 120 V and 240 V and at 1 A and 5 A, the expanded relative uncertainty is $20 \cdot 10^{-6}$ ($k = 2$, related to the apparent power). The system may also be applied for the measurement of AC voltages and AC currents [1]. In case of sine signals, this allows the apparent power and together with the active power, also the reactive power to be calculated.

Calibration system for the electric active, reactive and apparent power using digital synthesis and sampling procedures

Almost twenty years after Schuster's publication [1], a novel procedure for the stable generation and the concurrent precise measurement of the electric active, reactive and apparent power was presented at the PTB [3]. It is based on digitally synthesized AC voltages, on the rms value of one AC voltage resulting from the synchronous sampling of two AC signals with only a single sampling voltmeter and on the determination of their complex AC voltage ratio by means of the discrete Fourier transform (DFT).

The working principle is illustrated in Figure 3. The double AC voltage source generates two sinusoidal voltages \underline{U}_a and \underline{U}_b with the frequency f from the clock signal provided by the sampling voltmeter with the frequency f_{clock} . The digital synthesis allows the phase angle γ between these voltages to be set. Series-connected voltage and transconductance amplifiers apply the derived quantities \underline{U} and \underline{I} to the voltage and the power path \underline{Z}_u and \underline{Z}_i , respectively, of the test sample. A calibrated rms voltmeter determines the rms value U_{DVM} of the AC voltage \underline{U} on the voltage path of the device under test and thereby traces it back to the SI quantity "DC voltage" and to the unit of volt, whereby the voltage transformer UW with the transformation ratio K_u reduces this voltage to \underline{U}_1 . The current \underline{I} through the current path of the device under test is transformed via the combination of the two-stage current transformer IW with the transformation ratio K_i and the AC current measuring resistor \underline{Z} into the voltage \underline{U}_2 . This measuring resistor \underline{Z} for which not only the equivalent resistance but also the time constant have to be known with very high accuracy, ensures traceability to the SI quantity "DC resistance" and to the unit of ohm.

A signal, derived from frequency f , with frequency f/m , connects first \underline{U}_1 and then \underline{U}_2 through the signal switch with the input of the sampling voltmeter which records several sampled values of \underline{U}_1 and \underline{U}_2 over an adjustable number of periods. Via the clock provided by the sampling voltmeter the measuring system briefly referred to as "Salisa" (Sequential alternating synchronous sampling procedure) ensures the phase-locked coupling of the measurement frequency f with the sampling frequency of the voltmeter, which is an essential prerequisite for subsequent calculations. By way of discrete Fourier transform, a program calculates the complex voltage ratio

$$\frac{\underline{U}_2}{\underline{U}_1} = A + j \cdot B \quad (2)$$

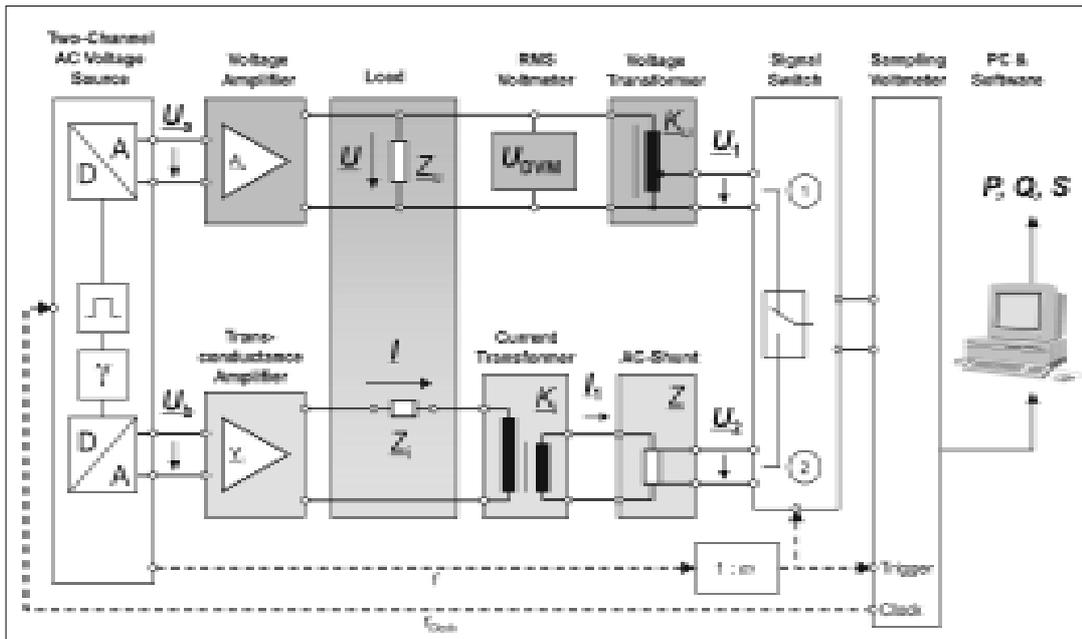


Figure 3:
PTB calibration system
for electric active, reac-
tive and apparent power
using digital synthesis
and sampling procedu-
res.

from these values, determines DC components, harmonic distortions and the relative stability of the voltages sampled. Moreover, the disturbances caused by the signal switch in the switching phase are eliminated, and the equality of channels 1 and 2 is controlled or corrected by self-calibration.

The determination of the active power P , the reactive power Q and the apparent power S requires the rms values of the voltage \underline{U} applied to the test meter and/or of the current \underline{I} which is likewise sinusoidal as well as the phase shift φ between these quantities. The rms value of the voltage is determined by the rms voltmeter:

$$U_{\text{eff}} = \frac{U}{\sqrt{2}} = U_{\text{DVM}}. \quad (3)$$

Via the relations

$$\underline{U} = \underline{U}_1 \cdot \underline{K}_u \quad \text{and} \quad \underline{I} = \underline{I}_1 \cdot \underline{K}_i = \frac{\underline{U}_2}{Z} \cdot \underline{K}_i \quad (4)$$

as can be deduced from Figure 3, \underline{I} can be determined from the result of the DFT (coefficients A and B) as well as from the complex characteristics of the AC measuring resistor (Z), of the current transformer (\underline{K}_i) and of the voltage transformer (\underline{K}_u):

$$\underline{I} = \underline{U} \cdot \frac{1}{Z} \cdot \frac{\underline{K}_i}{\underline{K}_u} \cdot (A + j \cdot B). \quad (5)$$

This equation provides the rms value I_{eff} of the current \underline{I} as well as the phase shift φ between the voltage \underline{U} and \underline{I} , which finally allows the calculation of the apparent, active and reactive power (for details, see [3, 4]):

$$S = U_{\text{eff}} \cdot I_{\text{eff}}, \quad P = S \cdot \cos \varphi, \quad Q = S \cdot \sin \varphi. \quad (6)$$

The first prototype operating on this principle was set up for a voltage of 120 V and a cur-

rent of 5 A (equivalent to a power of 600 VA) at a frequency of 62,5 Hz. Model equations were established for the calculation of the measurement uncertainty allowing for all uncertainty contributions of the complex quantities Z , \underline{K}_i and \underline{K}_u as well as the influence of U_{DVM} and the uncertainty of the coefficients A and B [3, 4]. The calculations yielded an expanded relative uncertainty of $5 \cdot 10^{-6}$ ($k = 2$, related to the apparent power) for the active, reactive and apparent power. This value holds for all power factors and phase angles φ , respectively, between current and voltage.

International comparisons

International comparisons are supposed to show whether the measurement values and measurement uncertainties determined by different methods have been calculated correctly by the participating institutes. With the help of international comparisons systematic or other, previously undetected, uncertainty effects may be discovered. In the area of electric power measurement, several such comparisons have taken place in the last five years. The most complex, world-wide comparison was carried out between 1996 and 1999. 15 institutes from all regions of metrological significance participated under the auspices of the National Institute of Standards and Technology (NIST) [5]. It was a comparison of the active power at 120 V and 5 A at five different power factors (1 and 0,5 and 0, respectively, inductive and capacitive) at frequencies in the range of 50 Hz to 60 Hz. The complete results of this CCEM comparison will be published soon; Figure 4 exemplarily shows the measurement results obtained at power factor 1. Depicted are the deviations of the meas-

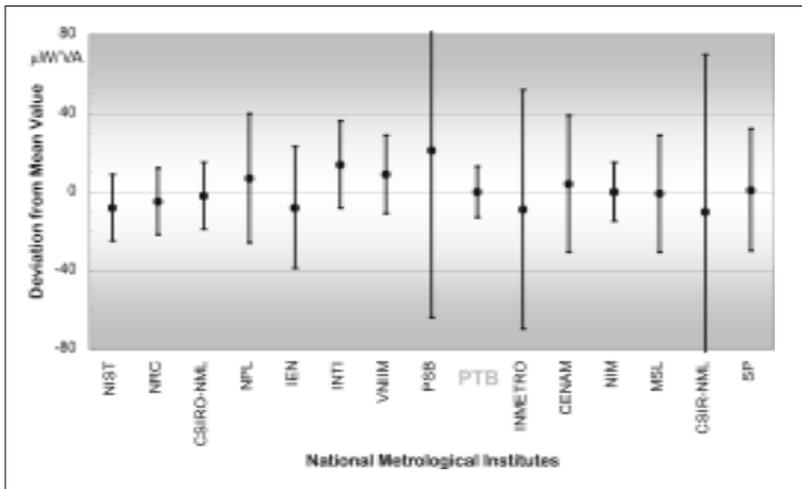


Figure 4:

Results of the CCEM comparison for electric active power at a voltage of 120 V, a current of 5 A, a power factor of 1 and a measurement frequency of 53 Hz. The weighted mean of all participants' data is the reference line. Plotted are the deviations of the measurement values of the participating institutes from the mean value with their expanded uncertainties ($k = 2$).

urement results of the individual participants from the mean value representing the weighted average of all participants' data at power factor 1. The long-term drift of the reference standard in the time period from 1996 to 1999 has been approximated by a polynomial and eliminated by computation. Due to this and to the short-time stability of the reference standard, which influences measurements spread over weeks of individual participants, the best possible uncertainties of the participants have in part been considerably increased. The expanded standard uncertainty of the value determined by the PTB increases to approx. $12,5 \cdot 10^{-6}$ ($k = 2$, see Figure 4) due to the uncertainty of the PTB equipment of $2,5 \cdot 10^{-6}$ ($k = 1$), to the standard deviation of the measurements at the PTB of approx. $4 \cdot 10^{-6}$ and the uncertainty contribution of approx. $4 \cdot 10^{-6}$ ($k = 1$) caused by the computational elimination of the long-term drift. Although the reference conditions were not optimum because of the insufficient stability of the reference standard, Figure 4 shows two things: on the one hand the PTB measurement value is the one with the lowest uncertainty and on the other hand, it is precisely the same as the international mean value. This practically confirms the excellent properties of the sampling procedure as well as the model equations, devised for calculating the measurement uncertainty.

Within the scope of a EUROMET comparison with 17 countries participating, comparison measurements were carried out in Europe between 1997 and 2001 using practically the same measuring points and a very similar transfer device. In this comparison, the Physikalisch-Technische Bundesanstalt acted as the pilot laborato-

ry. The results are at present being evaluated. Further regional comparison measurements of the electric power were performed in the Asia-Pacific area and on the American continent. All these regional comparisons are linked by the global CCEM comparison which serves to ascertain and document the degree of equivalence.

Precise rms value determination for low-frequency AC voltages from sampled values

The prototype presented above uses a rms voltmeter (Figure 3) for measuring and assuring traceability of the voltage \underline{U} applied to the test meter. Parallel to the voltmeter the voltage transformer UW is connected whose output voltage \underline{U}_1 is sampled. The rms voltmeter can be dispensed with when the rms value of \underline{U}_1 , via the transformation ratio of the voltage transformer, is determined from the sampled values. First of all it has, however, to be clarified which influence quantities are relevant and by which uncertainty the calculation of the rms value from sampled values is affected by them.

The experimental set-up shown in Figure 5, which includes components of the prototype (see Figure 3), was chosen to resolve this question. The AC voltage source synthesizes a voltage $U_{DAC}(t)$ whose frequency is synchronized with the clock frequency f_{clock} of the sampling voltmeter. f_{clock} is divided by the divider by a constant m , and with the resulting frequency f_{RAM} the digital code for each step of the sinusoidal signal $u_{DAC}(t)$ to be synthesized is generated. The low-pass filter with the cutoff frequency f_c eliminates high-frequency components with many times the fundamental frequency (with the period T_0) caused by the digital synthesis. Within this period T_0 , the sampling voltmeter is triggered with the sampling frequency f , and within the period of time T_i , the filtered signal $u(t)$ is sampled and integrated and the mean value U_v (sampled value) of the instantaneous signal $u(t)$ is taken over T_i . N sampled values U_v are recorded over M periods and transmitted to the connected computer which then determines the rms value according to the equation shown, taking into consideration the cutoff frequency f_{cv} of the low-pass filter in the input circuit of the voltmeter.

A phase-locked coupling between source and sampling voltmeter is ensured as, a constraint of the system, only one common clock is used. This phase-locked synchronisation, in combination with the full number of sampled periods, are two preconditions for a precise determination of the spectrum of the signal to be measured. Under these conditions and if the sampling theorem [6] is strictly complied with, the spectral lines of the signal coincide with the spectral lines of their discrete Fourier transform,

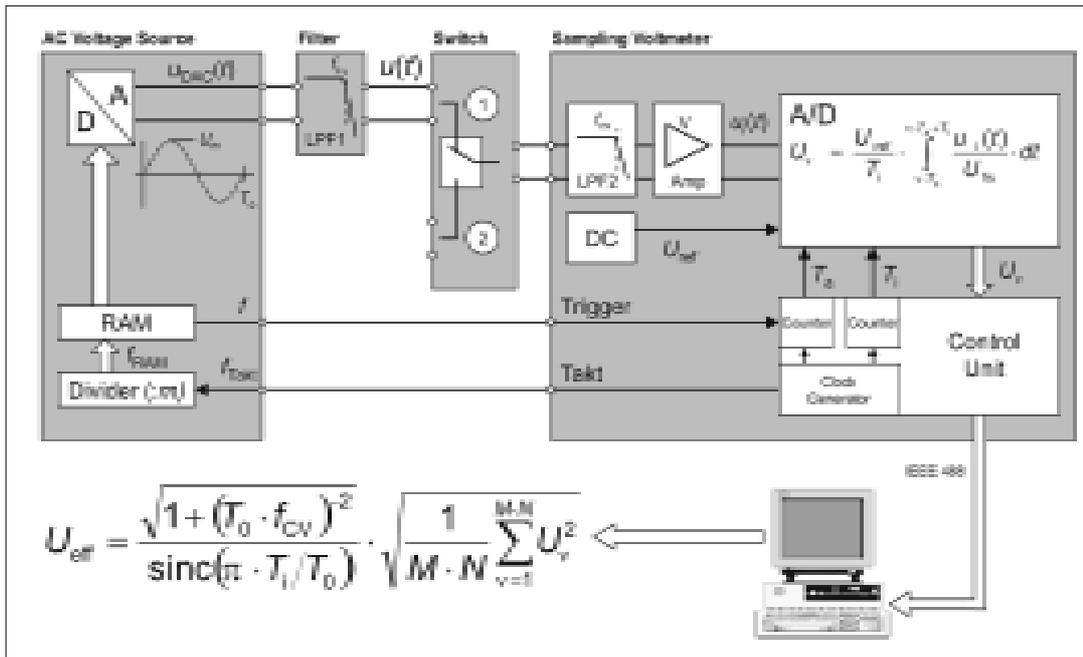


Figure 5: Circuit configuration and model equation for precise rms value determination for AC voltages from sampled values; sinc x is the (sin x)/x function.

which actually makes it possible to precisely determine the rms value from sampled values.

Detailed mathematical models for both the digital voltage source and the sampling voltmeter were set up in the form of model equations [6] reflecting the practical physical characteristics of such elements. The results show that with this system, rms values of sinusoidal voltages around 5 V (typical output voltage of the voltage transformer UW in Figure 3) at frequencies between 15 Hz and 500 Hz can be determined with an expanded uncertainty of less than $1 \cdot 10^{-6}$ ($k = 2$). The measurement results are traced back to the SI quantity “DC voltage” via the DC reference of the sampling voltmeter.

For confirmation of this theory additional experimental investigations have been carried out. So the voltage $u(t)$ was sampled and simultaneously converted into a DC voltage via a high-quality thermal converter [2]. At frequencies around 50 Hz, which are of special importance to the measurement of power, the results agreed within less than $1 \cdot 10^{-6}$, that is within their expanded uncertainty. Apart from the thermal converters, this sampling system thus offers a second, independent method for traceability of AC to DC quantities, which is decidedly superior as regards the measuring speed.

New digital standard for electric AC power

In international comparisons lowest possible measurement uncertainties can be realized only with a limited number of measuring points. The preferred measurement conditions for electric AC power (120 V, 5 A, 50/60 Hz, five different power factors) have already been explained. In everyday practice, however, further measure-

ment ranges are asked for. According to the positive experience gained with the prototype set up and the associated findings as to how the rms value can be calculated with high precision from the values sampled, a new digital standard for the electric AC power was designed. It had to have more measurement ranges than the prototype, be also applicable at a frequency of $16 \frac{2}{3}$ Hz and no rms voltmeter should be required for the measurement of the rms value of the voltage at the test meter.

Figure 6 shows the new digital standard for use at the PTB. Its components are accommo-



Figure 6: New digital PTB standard for electric AC power with a working range of 1 VA to 3600 VA.

dated in three mobile units. The left unit serves to operate and control the measurement sequence. The voltages and currents required for the measurement are generated, amplified and measured in the central unit. The transconductance amplifier is placed at the top, below it are the digital voltmeter used as sampling voltmeter and the double AC voltage source, and right at the bottom is the voltage amplifier. In the third unit, on the right-hand side, the conditioning of the generated voltage and of the current to the device under test takes place, as well as the conversion of the quantities for measurement by the sampling voltmeter. Right at the top the transformer for the generation of different currents is situated, below it is the two-stage current transformer with the series-connected AC measuring resistor. In the middle of the unit on the right a power meter is situated which is used as test object and whose output voltage is measured by the digital voltmeter placed above it. At the bottom is the transformer for the generation of different voltages and the voltage transformer.

The components voltage transformer, two-stage current transformer and AC measuring resistor are most important for achieving low uncertainty [3, 4]. They are not available on the market but have been completely devised, set up and calibrated at the PTB with the lowest possible expanded uncertainties around $1 \cdot 10^{-6}$ ($k = 2$). The sampling voltmeter used is commercially available. The double AC voltage source, which has to show a relative short-time stability of the amplitudes of less than $0,5 \cdot 10^{-6}$, and a phase jitter of less than $0,5 \mu\text{rad}$ with harmonic distortions below 0,01 % as well as the fast, low-resistance signal switch are also proprietary developments of the PTB.

In contrast to the prototype, in addition to 120 V and 5 A, the rated voltages of 60 V and 240 V as well as currents from 0,1 A to 10 A can be selected, which can be varied in the working range of 40 % up to 120 % (i. e. from 25 V to 300 V and from 0,04 A to 12 A corresponding to 1 VA to 3600 VA). Furthermore, the measurement frequency at voltages up to 100 V maximum can be reduced to approx. 16 Hz.

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The development of multijunction thermal converters for precise measurement of the rms value of AC voltage and AC current

Manfred Klonz¹

Introduction

In the past few decades, the great development efforts made by the measuring instrumentation industry has led to a considerable increase in the accuracy of power meters, AC voltmeters and AC ammeters. Calibration of these devices with the desired low uncertainties requires that the PTB's standards and measuring set-ups be permanently further developed. While power meters are traditionally used at line frequency, voltmeters cover a frequency range from a few Hz to 1 MHz and ammeters a frequency range from 10 Hz to 100 kHz. The development of multijunction thermal converters for the transfer of AC voltage and AC current to the equivalent DC quantities now allows the PTB to achieve measurement uncertainties for this frequency range which lie between $2 \cdot 10^{-6}$ at 1 kHz and $25 \cdot 10^{-6}$ at 1 MHz ($k = 2$). With these low uncertainties, the calibration laboratories in the Deutscher Kalibrierdienst (German Calibration Service) have a considerable competitive advantage worldwide.

The highest requirements with respect to the measurement uncertainty are to be met at the PTB for the development of standard measuring devices for the measurand "power at line frequency." Accurate measurement of the active power implies multiplication of the instantaneous values of current and voltage and their subsequent integration. The thermal procedure applied at the PTB since the end of the seventies, uses multijunction thermal converters for multiplication which are later also employed to transfer AC to DC power [1]. For the rms value of the AC voltage measured, a measurement uncertainty of smaller than $1 \cdot 10^{-6}$ is required.

Recent investigations of the sampling procedure using a digital voltmeter for precise power measurements show that a standard measurement uncertainty of less than $2,5 \cdot 10^{-6}$ is obtained at line frequency [1]. Comparisons of sampling and thermal procedures for measurement of the rms value of the AC voltage between 10 Hz and 100 Hz indicate an agreement of $1 \cdot 10^{-6}$ [2]. The uncertainty analysis for the sampling procedure reveals that at line frequency, the uncertainties of the individual influence

quantities lie even below $1 \cdot 10^{-6}$ [3]. As they further decrease towards lower frequencies, such a low uncertainty may also be reckoned within the range below 10 Hz to the mHz range.

AC-DC transfer

Thermal converters allow the rms value of AC voltage and AC current to be traced back to DC quantities which traditionally are known with low uncertainty. Thermal converters work on the equivalent heating power principle (Joule heat) of DC and AC current in a resistor. The Joule heat of the electric current leads to a temperature increase in a thin resistive wire (heater) which is very sensitively measured with thermocouples. Figure 1 shows the principle of a single-junction thermal converter.

For AC-DC transfer, the DC quantity is adjusted to the same output voltage of the thermocouples as the AC quantity (Figure 2).

The three-dimensional multijunction thermal converter of the PTB

At the PTB, work on AC-DC transfer started in the early eighties with the development of the three-dimensional multijunction thermal converter [1].

A twisted bifilar resistive wire used as heater (Figure 3) is supported by a series array composed of 56 to 120 thermocouples which allows the temperature difference between heater and base plate to be measured so sensitively that DC-AC transfer is possible with a relative resolution of less than 10^{-7} . At frequencies between 10 Hz and 100 kHz, AC-DC transfer differences

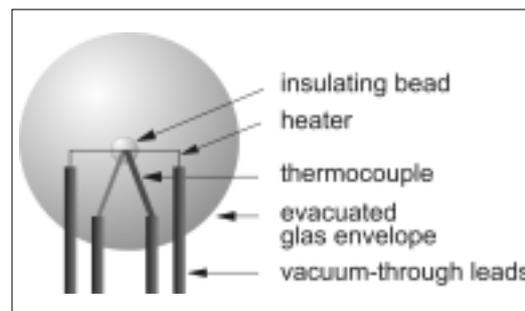


Figure 1:
Block diagram of a single-junction thermal converter

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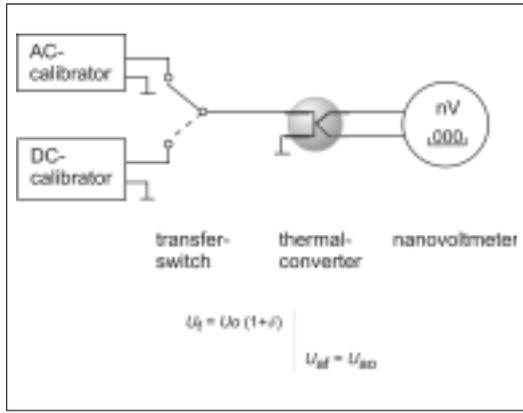


Figure 2: Principle of the transfer of an AC voltage U_i to a DC voltage U_0 with thermal converters

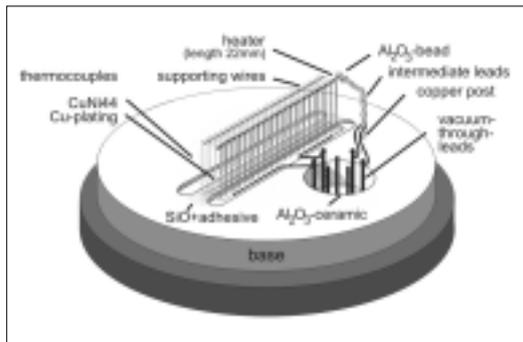


Figure 3: Three-dimensional multijunction thermal converter.

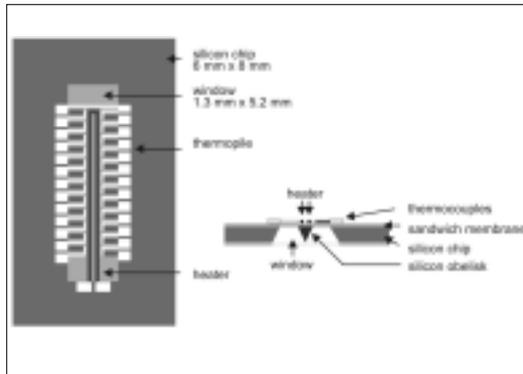


Figure 4: Planar multijunction thermal converter.

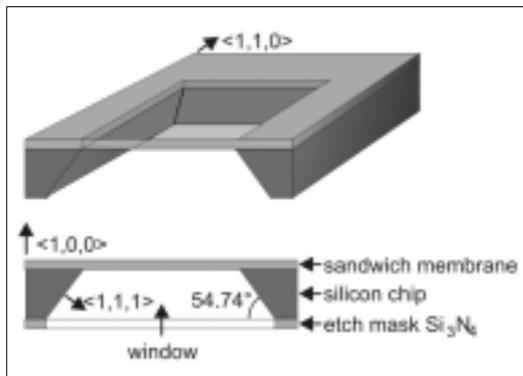


Figure 5: Anisotropic etching of the window in the silicon chip. During etching in warm caustic potash solution (80°C), the ratio of the etch rates between the crystal planes $\langle 1,1,1 \rangle$ and $\langle 1,0,0 \rangle$ exceeds 1 : 50.

due to thermoelectric effects in the heater, frequency dependence of the resistance due to reactive components, skin effect and dielectric losses were calculated with an uncertainty of $3 \cdot 10^{-7}$; at 1 MHz they were calculated with an uncertainty of $1 \cdot 10^{-5}$. The three-dimensional multijunction thermal converter developed at the

PTB was the first AC-DC transfer standard for which the measurement uncertainty had been calculated. Internationally discussed differences in the audio frequency range between the industrially manufactured single-junction thermal converters so far mainly used and multijunction thermal converters of $2 \cdot 10^{-6}$ [5] could be attributed to thermoelectric effects in both, the single-junction thermal converters and the industrially manufactured multijunction thermal converters.

Within the scope of a European project, multijunction thermal converters were manufactured at the PTB for other National Metrology Institutes. Their construction was, however, most sophisticated and time-consuming as complicated manual work had to be performed under the microscope with wires between 10 μm and 20 μm in diameter.

The planar multijunction thermal converter

When heater and thermocouples are arranged on the same plane and thin-film techniques are applied, manual work and welding can be replaced by photolithography and thermal evaporation and sputtering techniques. In the anisotropic etching technique in silicon [6] (Figure 4) which is known from micro-mechanics, mechanical shaping of the base plate falls away.

A silicon chip takes over the function of the heat sink. By anisotropic etching (Figure 5), a window of exact size is opened in the chip from below and is only just covered by an electrically well insulating thin sandwich membrane of $\text{Si}_3\text{N}_4\text{-SiO}_2\text{-Si}_3\text{N}_4$ of poor conductivity [7]. The bifilar heater and the thermocouples are successively sputtered in thin layers onto this membrane and structured by photolithography. The electrical contacts and the cold junctions of the thermocouples lie on the Si frame. The converter chip is pasted to a ceramic carrier and the electrical connections are established with thin bonding wires.

Due to the small thermal time constants (30 ms) of the heater-thermocouple-membrane system, the transfer difference of the planar multijunction thermal converter strongly increases at frequencies below 100 Hz (Figure 6).

To raise the time constant, a silicon obelisk was arranged below the heater [8]. This obelisk is manufactured when the window is anisotropically etched. It is a special feature of anisotropic etching that concave edges in the Si as occur in the window, are precisely etched, whereas for the convex edges of the obelisk a special protective band structure is necessary to form sharp edges (Figure 7).

Figure 8 shows the considerable reduction of the transfer differences with increasing time constants.

Optimization of the frequency response at low frequencies

The planar design of the multijunction thermal converter has allowed model calculations to further optimize this converter [9] and realize improvements which have influenced its production as early as in the nineties [10]. In the following, however, only the frequency dependence at frequencies below 1000 Hz or at line frequency will be analyzed.

Experience shows that the transfer differences of a thermal converter strongly increase towards low frequencies. Exact knowledge of the physical background of this behaviour which would have been necessary to systematically improve the thermal converter has, however, been lacking. The definition that at low frequencies at which the period of oscillation reaches the order of magnitude of the thermal converter's time constant, the temperature of the heater can follow the Joule heat of the electric current and that the output voltage of the thermocouples shows an AC voltage which has twice the frequency of the input signal and is superposed on the DC voltage which, due to non-linearities between input and output voltage, causes an AC-DC transfer difference, led to the design of the converter with an obelisk to increase the time constant. Measurements showed that the increase in the transfer differences at 10 Hz is considerably reduced but nevertheless only shifted towards low frequencies (Figure 9).

Within the scope of a doctoral thesis, the relationship between the transfer difference at low frequencies and the material parameters as well as heat transport mechanisms in the converter at oscillating input power and output voltage were therefore investigated with the aid of simulation calculations. Figure 10 shows the electro-thermal converter model used, with all its non-linearities. Conversion of AC voltage into Joule heat takes place in the heater resistor $R_H(T)$ which, due to its temperature coefficient, is to be assumed as non-linear. The temperature increase ΔT which is a result of the Joule heat is determined by the non-linear heat conduction $G(T)$ as a result of heat conduction, convection and radiation. Conversion of the temperature increase into an electric voltage U_0 through the Seebeck coefficient $\alpha(T)$ of the thermocouples is temperature-dependent and, therefore, to be assumed as non-linear, too. The solution to the differential, non-linear electro-thermal problem was found with the aid of the finite element method. It allowed the multijunction thermal converter to be further optimized for low frequencies [11].

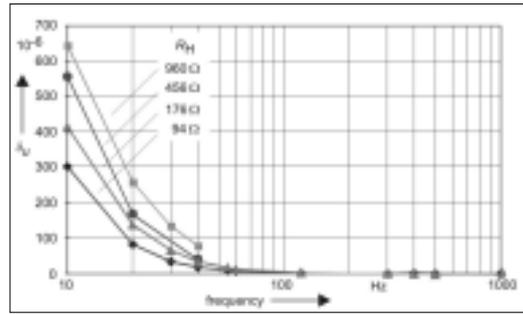


Figure 6: Frequency response of the AC-DC transfer difference of a planar multijunction thermal converter with a time constant of 30 ms at frequencies below 1 kHz for different heater resistances R_H .

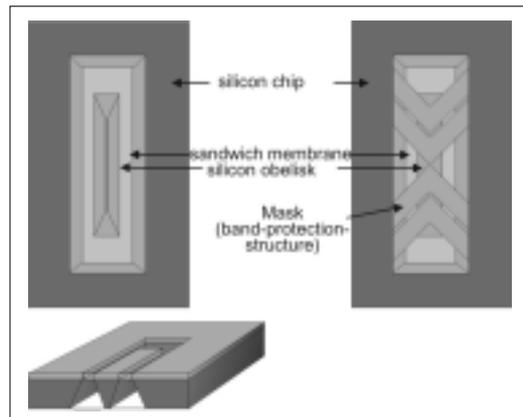


Figure 7: Silicon obelisk to increase the time constant by anisotropic etching.

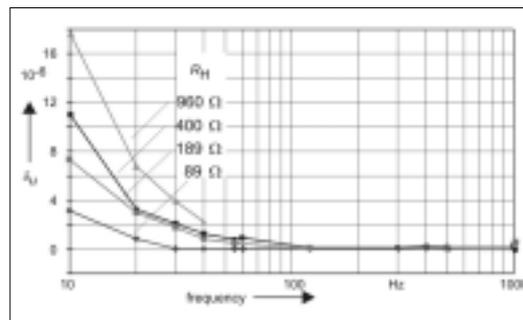


Figure 8: Frequency response of the AC-DC voltage transfer difference of a planar multijunction thermal converter with a time constant of 1,3 s at frequencies below 1 kHz and different heater resistances R_H .

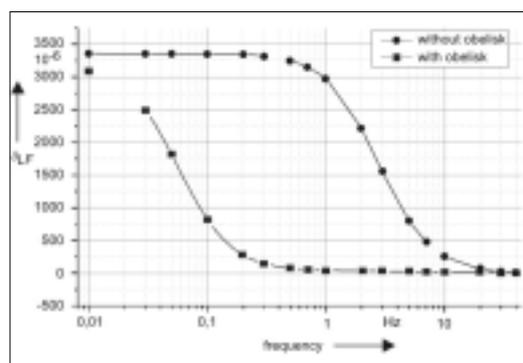


Figure 9: Comparison of the AC-DC voltage transfer difference of planar multijunction thermal converters with obelisk ($t = 1,3$ s) and without obelisk ($t = 30$ ms) at low frequencies.

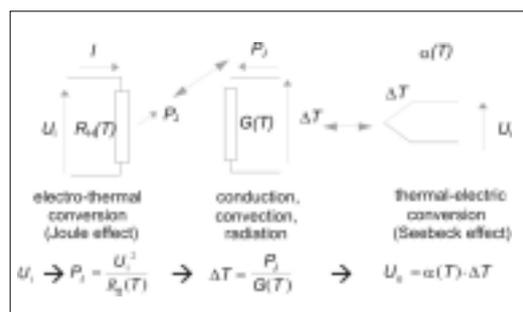


Figure 10: Electrothermal model of a thermal converter.

Influence of the power coefficient of sensitivity on the transfer difference at low frequencies

Non-linearity of the relationship between output voltage and input power can be described by a power coefficient φ_{SU_o} which is defined as $\varphi_{SU_o} = 1/S \cdot dS/dU$. The sensitivity is defined as $S = U_o/P_j$ with output voltage U_o and Joule heat P_j as input power. Figure 11 shows the influence of the power coefficient on the AC-DC voltage transfer difference δ_{LF} . The direct dependence between the two clearly shows that a small transfer difference can be achieved only through a small power coefficient.

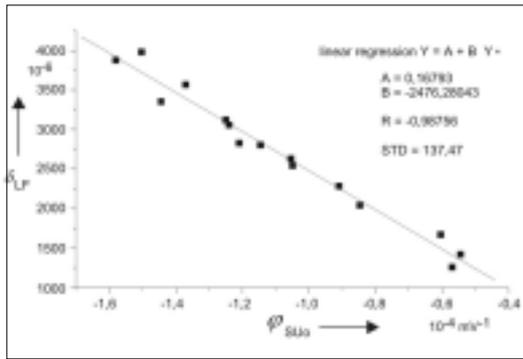


Figure 11: AC-DC transfer difference δ_{LF} as a function of the power coefficient of the sensitivity φ_{SU_o} measured on a series of planar multijunction thermal converters

Influence of the temperature coefficient of the heater resistor

The change ΔR of the real component of the input impedance Z as a result of its temperature coefficient and the oscillating temperature in the heater in part is not a component of the power coefficient as it occurs also in the heater area between Si frame and obelisk when Joule heat is generated. In this area, the heat is not integrated by the obelisk and the temperature can, therefore, follow the oscillating temperature. This range is not covered by the thermocouples, either. A change of the heater resistance causes an AC-DC transfer difference δ_u^R . It can be minimized only with a very small temperature coefficient α_H of the thin-film heater. This was achieved by a special tempering process in the course of which the coefficient of the thin-film heater (made of NiCrSi) was reduced to values of $1 \cdot 10^{-6} \text{ K}^{-1}$. The simulation showed that with $|\alpha_H| < 1 \cdot 10^{-6}$ the transfer difference at 10 Hz is $|\delta_u^R| < 0,1 \cdot 10^{-6}$.

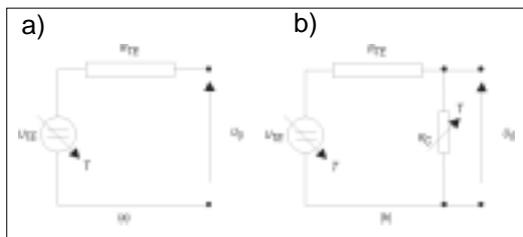


Figure 12: Equivalent circuit diagram of the temperature-dependent output voltage of the thermocouples U_{TE} and internal resistance R_{TE} . a) without b) with compensating resistance R_C

Compensation of the power coefficient with the temperature coefficient of a thin-film resistor on the membrane

Figure 12a shows the equivalent circuit of the converter thermopile. It can be realized by a voltage source U_{TE} with a series resistor R_{TE} . If the temperature T of the heater increases with the input power, the output voltage decreases if the power coefficient is negative. If a resistor with a positive temperature coefficient is now arranged so that it acts, together with R_{TE} , as a voltage divider for the output voltage and also measures the temperature of the heater, the variation of the voltage divider will lead to a rise in

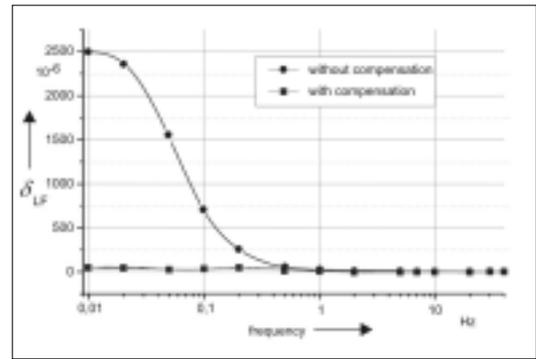


Figure 13: AC-DC transfer differences δ_{LF} of a planar multijunction thermal converter at low frequencies f with and without optimum compensation.

the output voltage (Figure 12b). A thin-film nickel meander ($TC = -2 \cdot 10^{-6} \text{ K}^{-1}$) below the thermocouples, arranged with a resistance of approx. 6 k Ω , almost meets the requirements for compensation of the power coefficient. For further balancing, a balancing resistor can be applied from the outside in series with the thin-film resistor. Figure 13 shows the AC-DC transfer differences with and without such a balancing resistor.

FRDC method for measurement of transfer differences due to thermoelectric effects

At DC current, thermoelectric effects such as the Thomson and Peltier effect may change the temperature profile on the heater and thus cause a temperature difference, whereas they do not occur at AC current because the shift of the temperature profile would be averaged out within one period. In a single-junction thermal converter of the former design, they could cause a transfer difference of up to $1 \cdot 10^{-4}$ as a particularly great Thomson effect occurred if the heaters consisted of CuNi44 (Constantan). Use of quadruple alloys such as Isohm allowed the Thomson effect to be reduced to a few 10^{-6} V^2 . For multijunction thermal converters it was tried to avoid thermoelectric effects by designing a heater with a very small

temperature gradient and avoiding different materials being used in the area of the increased temperature. Up to now, the magnitude of the thermoelectric effects could only be estimated theoretically. The development of the Fast Reversed DC (FRDC) method allows the transfer difference due to thermoelectric effects to be measured with an uncertainty of $1 \cdot 10^{-7}$ [12].

This method is based on the fact that due to the thermal time constant thermoelectric effects such as the Thomson effect ensue with delay after the input voltage has been applied or reversed. As the Thomson effect also depends on the direction of the current, its influence is increasingly suppressed with rising reversing frequency. Variation of the reversing frequency between 0,1 Hz and 10 kHz thus allows the Thomson effect to be investigated metrologically. For the measurement of the transfer differences, a rapidly reversible DC voltage or DC current source was set up allowing single- and multi-junction thermal converters to be automatically measured. For both designs of the multijunction thermal converter, the old three-dimensional and the planar design, the theoretical estimates were confirmed and transfer differences of less than $2 \cdot 10^{-7}$ were measured.

The first DC voltage sources were realized with semiconductor components so that the amplitudes of both positive and negative polarity had to be accurately balanced. Now, a reversible voltage source with Josephson series arrays (superconductor – insulator – normal conductor – insulator – superconductor (SINIS)) has been set up for the first time and used for investigations on planar multijunction thermal converters [13]. The output voltage of the SINIS voltage source is known with the accuracy of a quantum standard and thus is exactly equal in the two polarities. For reversing, the bias current through the series array is simply reversed (Figure 14).

Measurements on two different planar multijunction thermal converters up to reversing frequencies of 200 Hz showed thermoelectric effects of less than 0,2 mV/V. Due to the quantized voltage of the Josephson circuit, the dispersion of the measured values is very small. The measurement uncertainty is determined but by the thermal converter.

The good agreement of this new FRDC source with the semiconductor source increases the confidence placed in the reliability of the FRDC measurement procedure.

1000 V resistor for AC-DC voltage transfer

Multijunction thermal converters have rated voltages of a few volt. Standards for higher voltages up to 1000 V require suitable series resistors.

The stepped design of AC-DC voltage transfer standards for higher voltages presupposes

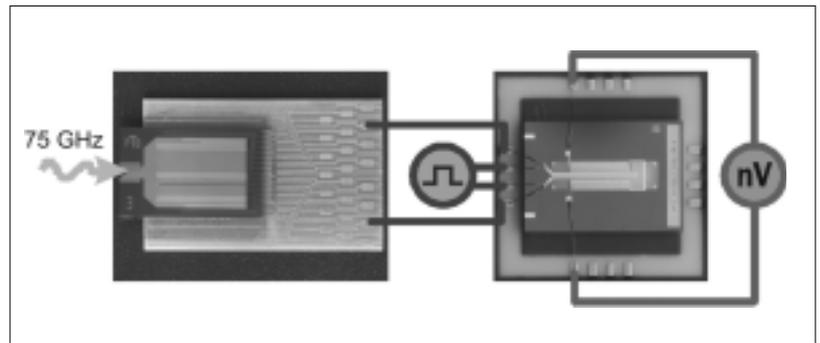


Figure 14:

Reversing voltage source with Josephson chip and planar multijunction thermal converter

that the transfer differences of these standards are voltage-independent in the whole frequency range. At higher frequencies and voltages above 1000 V in particular, variations of the transfer differences were observed for the different designs. They are attributed to variations of the dissipation factor of the parallel capacitance of the series resistor and also of its capacitance with respect to the enclosure when differently heated in its intended voltage range. Within the scope of an international comparison, the last step from 300 V to 1000 V turned out to be particularly critical for all participants. When the 1000 V standard is calibrated at 300 V against the 300 V standard, the temperature of the usual series resistor (100 k Ω) rises by approx. 30 K but when used at 1000 V, its temperature rise increases by approx. 100 K. At frequencies of 100 kHz, variations of the transfer difference of up to $100 \cdot 10^{-6}$ have been observed.

To keep the temperature increases small, very good heat dissipation to laterally arranged heat exchangers was achieved in the new design of the 1000 V resistor by planar arrangement of the resistive film on an aluminium nitride plate of high thermal conductivity (Figure 15).

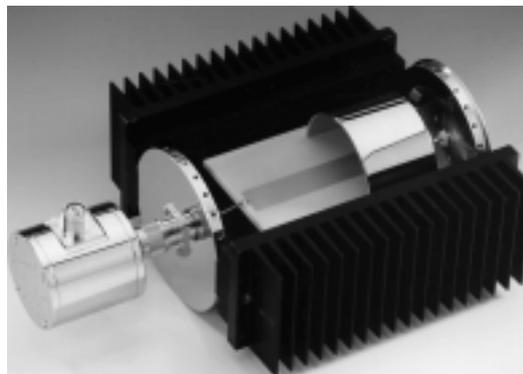


Figure 15:

View into the interior of a 1000 V resistor

At 1000 V, this leads to an increase in the temperature of the resistive film by only 4 K. By annealing, the temperature coefficient of the resistive NiCrSi film could be reduced to $1 \cdot 10^{-6} \text{ K}^{-1}$. This also allowed the warm-up time after voltage application and the sensitivity to external temperature variations to be considerably reduced.

To compensate the frequency response of the transfer difference, an electrostatic screen is arranged so that the electric field no longer lies between resistor and coaxial shield but only between the electrostatic and the coaxial shield. Only then the electric field due to the potential difference between its ends is present in the resistive film. This considerable change in the electric field and in the associated effective capacitance and its dissipation factor in the plane of the aluminium nitride plate will also considerably change the voltage dependence of the transfer difference if the aluminium nitride plate shows voltage-dependent dielectric losses. Measurements with and without electrostatic shield can therefore serve to demonstrate any voltage dependence. They showed that for the new design of a 1000 V resistor of 100 k Ω a negligible voltage dependence with an uncertainty of less than $5 \cdot 10^{-6}$ can be assumed at 100 kHz [14].

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Summary and outlook

The permanent development of multijunction thermal converters for the transfer of AC voltage and AC current to the equivalent DC quantities has allowed the PTB to keep pace with the development of commercial precision measuring instruments for power, AC voltage and AC current and to calibrate the standards of the calibration laboratories of the Deutscher Kalibrierdienst with such small uncertainties that they have always had a considerable competitive advantage worldwide.

In addition, three-dimensional multijunction thermal converters were developed at the PTB in the eighties and, from the nineties till today, planar multijunction thermal converters have been produced in series at the Institut für Physikalische Hochtechnologie e.V. in Jena and placed at the disposal of metrologists all over the world. These standards allowed the quality of the measurement of AC quantities to be continuously raised. In the last few years, international comparisons have shown very good agreement.

The current development activities are aimed at extending the frequency range of the planar multijunction thermal converter towards higher frequencies and reducing its measurement uncertainty at and beyond 1 MHz.

Non-conventional current and voltage transformers

Helmut Seifert¹, Hans-Georg Latzel², Andreas Braun³

1 Introduction

It is the ultimate ambition of public utility undertakings to reliably supply their customers with electric current. When new technologies for instrument transformers – for which the term “non-conventional instrument transformers” will be used in the following – were developed in the early seventies and went into competition with the matured and proven current and voltage transformers, this objective turned out to be a hurdle to a wider use of non-conventional instrument transformers although they promised a great number of advantages. Detached from the transformer principle, from great physical sizes, saturation problems, high insulation costs and high output levels, this “new” technology utilizes other effects as linked, for example, with the names of Faraday and Pockels, or Hall probes or Rogowski coils [1–3]. Meanwhile, a great number of practical tests have increased the confidence in the operational reliability of non-conventional instrument transformers so that they now are already used in some fields of electrical energy measuring techniques and protection technology. Since the mid-seventies, the PTB has followed this subject with interest, made some developments of its own and is involved in recent design work through numerous discussions with potential applicants. The course of these discussions shows that applications for approvals of non-conventional instrument transformers for invoicing are to be expected in not so remote a future.

1.1 Definition

From the viewpoint of legal metrology, a distinction between non-conventional and conventional instrument transformers can at present easily be made on the basis of the two criteria “testability” and “measuring stability.”

According to these criteria, all instrument transformers with secondary values not equal to 1 A, 5 A, $100/\sqrt{3}$ V, 100 V, etc. do not meet the applicable requirements [4, 5] and are, therefore, to be classified as non-conventional. With the test equipment at present available at the state-approved test centres for electricity measuring instruments they cannot be verified.

For standardization, such a mere differentiation is not suitable as a definition; here electronic instrument transformers are affected [6, 7]. As to the contents, the two terms “electronic instrument transformers” and “non-conventional instrument transformers” are almost identical, as non-conventional instrument transformers almost exclusively consist of electronic components.

As to the measuring stability, that is to say long-time reliability, these electronic components are inferior to conventional transformer types. This is why subsequent verifications will be required for non-conventional instrument transformers, all the more so as there is a stronger probability for creeping changes.

1.2 Application

In fields where conventional instrument transformers cause problems or their manufacture is relatively expensive and time-consuming, non-conventional instrument transformers may be used:

- Conventional instrument transformers are limited as regards the frequency response of their transfer function. The standards require compliance with the maximum permissible errors only for the rated frequency. In the case of DC current or DC voltage, their function is restricted by saturation effects; at high frequencies, their output signal is distorted so that in very fast processes protective devices connected to them may fail.
- Operation with high voltage requires sophisticated and thus expensive insulation; destruction as a result of insulation defects is nearly the only failure type for conventional high-voltage transformers. In optical non-conventional instrument transformers, the problem of electrical insulation is, however, already solved by the non-conductive electrical transmission medium.
- The increasing use of digital transmission and processing of the information required for operation and the protection of networks has resulted in an increasing interest in digitizing close to the measuring point and in using instrument transformers or sensors with digital output straight away instead of the conventional instrument transformers (with high rated power) and analog-to-digital converters.

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2 Measurement procedure

2.1 Current measurement

In view of the small physical size, the relatively low-priced material, the longevity and reliability of inductive low-voltage current transformers, there is hardly any measuring instrument which is more effective for high AC currents than the current transformer.

The measuring principle of the conventional inductive current transformer is shown in Figure 1a. The magnetic flux density around the current-carrying primary conductor is concentrated in a soft magnetic, high-permeability toroidal core. Its temporal variation induces a voltage in the secondary winding which if the secondary circuit is approximately short-circuited drives an AC current whose intensity is reduced – compared with the primary current – in first approximation by the secondary number of turns per unit length. Due to the induction principle, these transformers cannot transmit DC current but have been rated for the typical frequencies of electric energy transport, i.e. 50 Hz, 60 Hz or $16\frac{2}{3}$ Hz (for railway facilities).

One measuring principle which also allows DC current measurements to be performed makes use of the Hall effect (Figure 1b). Here, too, the magnetic flux density around the current-carrying primary conductor is concentrated in a toroidal core which is, however, provided with an air gap. In the Hall sensor arranged in it, the magnetic field exerts a force on the charge carriers and generates a voltage proportional to it, which in turn drives a corresponding secondary current. The working range extends from 0 Hz to a few kHz.

Coils without iron core as, for example, the Rogowski coil (Figure 1c), are used especially for monitoring fast processes as in the case of switching processes or failures. Unlike the current transformer, the secondary winding is operated off-load, i.e. the voltage is measured with a high-resistance measuring instrument. This measurand is proportional to the temporal variation of the primary current. It has, therefore, still to be integrated in order that it might map the primary current itself.

While the current transformer for invoicing is nearly unrivalled for low voltage, as has been explained at the beginning of this section, the situation is different in medium and high-voltage systems. The large potential difference between primary and secondary circuits and the insulation required as a result makes the current transformers larger and more expensive. It therefore suggested itself to operate a low-voltage current transformer at the potential of the high-voltage line and to transmit the information about the secondary current to earth potential by non-electrical means. The first designs for non-conventional current transformers have in fact made use of this idea, and some of today's models contain low-voltage current transformers. The analog output signal of a conventional current transformer is digitized and then, via an optical fiber, brought to earth potential, decoded and then digitally or analogously displayed (Figure 1d). The current transformer can also be replaced by current sensors. Accordingly, the working frequency range is determined by both, the analog-to-digital conversion, including optical transmission, and the sensor beha-

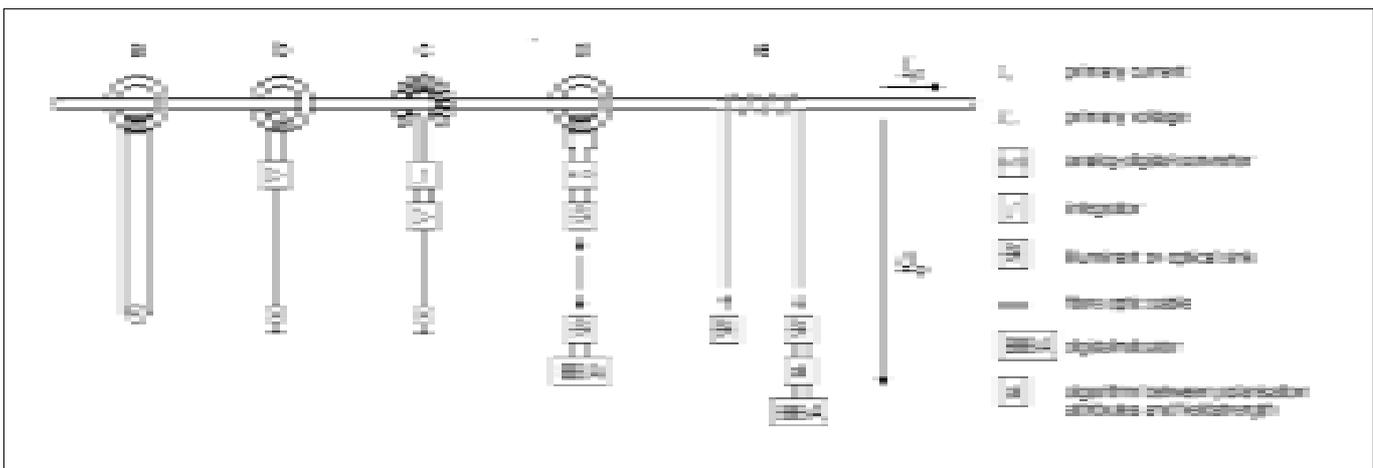


Figure 1:
Measuring principles of conventional and non-conventional current transformers

- a inductive current transformer
- b Hall probe
- c Rogowski coil
- d inductive current transformer with digital optical interface
- e magneto-optical current transformer (Faraday effect)

viour. An important aspect is the energy supply of the components at high-voltage potential which must also be guaranteed in particular in the case of line faults. In the first development phase, small current and voltage transformers at high-voltage potential were provided for this purpose. The decreasing energy demand of the electronic components offered the possibility of using optical fibers to convey the energy from earth to high-voltage potential [8].

If the information is no longer transmitted electrically but optically, it might be desirable to obtain it also by optical means. Figure 1e shows the magneto-optical measuring principle. Here, the optical fiber serves not only as transmission medium but also as current sensor. In the case of the Faraday effect, the plane of polarization through a magnetic field undergoes a rotation in the direction of propagation of the light wave. The primary current can be determined from the positional derivation of the polarization planes from/with respect to input and output which depends on the magnetic field [9–11]. As the magnetic field follows the rotation almost instantaneously, this arrangement is basically suitable for the whole frequency spectrum from 0 Hz to frequencies of a few kHz and is limited only by the frequency response of the electronic evaluation unit. The problem of the energy supply of electronic components at high-voltage potential does not occur here as both, transmitting and receiving components are at earth potential.

This magneto-optical current transformer is also available in another variant in which the end of the optical fiber coil is metal-coated so that no feedback fiber is required [12, 13].

As to the measuring stability, according to the definition above, types 1b to 1e are to be classified as non-conventional as they contain electronic components; the same applies to the “hybrid” design (1d). Inductive current transformers might, however, be regarded as conventional even if their rated secondary current is smaller than 1 A.

2.2 Voltage measurement

Here the situation is different from that of electrical current measurements, as the information of interest – the magnitude of the AC voltage – cannot be obtained at high-voltage potential and still only needs to be transported to earth potential but is the result of the measurement and subsequent division of the potential difference between the high-voltage side and earth. Figure 2 shows different designs of voltage transformers.

Figure 2a shows the measuring principle of the conventional inductive voltage transformer whose secondary is operated almost off-load. The temporal variation of the magnetic flux density which is proportional to the primary voltage induces a voltage in the secondary which is reduced in first approximation by the ratio of the primary to the secondary number of turns per unit length.

With increasing rated voltage, the insulation required by the inductive division principle increases disproportionately. A possible solution to this problem consists in connecting a capacitive before the inductive division path. Figure 2b shows the principle of the capacitive voltage transformer. Here, the voltage to be measured is

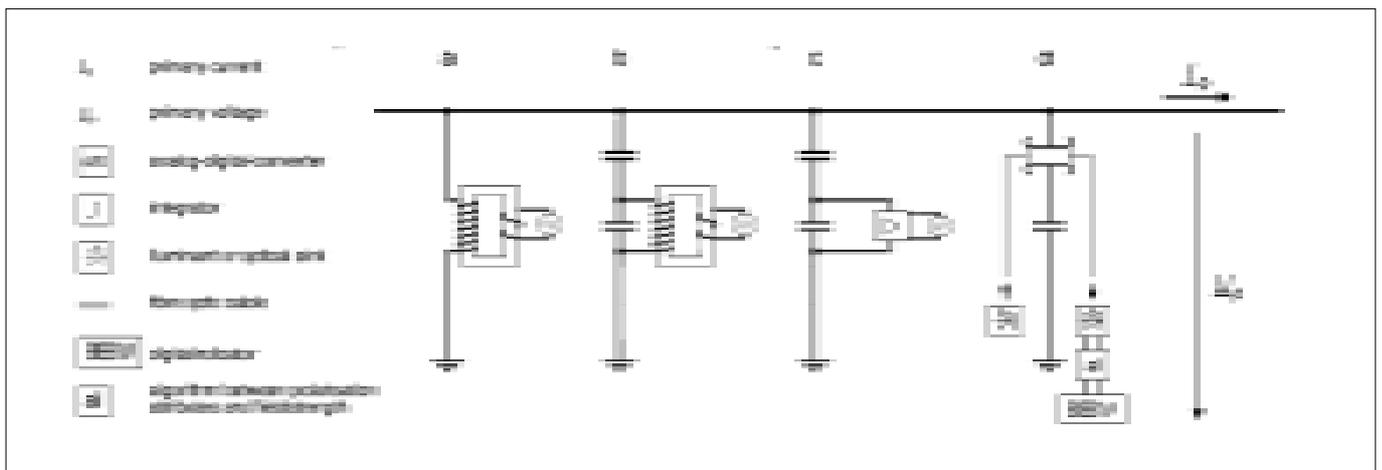


Figure 2 :
Measuring principles of conventional and non-conventional voltage transformers

- a inductive voltage transformer
- b capacitive voltage transformer with inductive part
- c capacitive divider (secondary voltage on low-voltage side)
- d capacitive divider with electrooptical voltage transformer (transversal component of Pockels effect)

first reduced with the aid of a capacitive divider and only then is it reduced by an inductive voltage transformer to the level required. Due to the interaction of capacitances and inductances, passive suppressor circuits are required to avoid resonance problems. Due to the capacitive division principle, the transformer can be used only for AC voltage measurements. As it does not comprise any electronic components, this transformer type is classified as conventional as far as its measuring stability is concerned.

The inductive section can be dispensed with if only low power is required in the measuring circuit. In Figure 2c, the capacitive divider takes over the whole transformation process. The secondary capacitor may be loaded only with very high impedance to avoid falsification of the division ratio. A suitable amplifier supplies the measuring circuit; it also determines the behaviour at high frequencies. Such dividers are, for example, used in gas-insulated switchgears.

For the principle shown in Figure 2d, the optical fiber serves not only as transmission medium but also as a sensor for the electric field and thus – at an appropriately defined electrode spacing – for the voltage. In the case of the Pockels effect, the polarization state of the light wave is changed by an electric field (for example: linearly polarized light is changed into elliptically polarized light) [14 to 16]. Like the magneto-optical current transformer, the electro-optical voltage transformer is basically suitable for the whole frequency spectrum from 0 Hz up to high frequencies and is limited only by the frequency response of the electronic evaluation unit. As the electronic components are at earth potential, they can easily be supplied with energy. For direct bonding of the spacing by a longitudinally sensitive sensor as required from the viewpoint of high-voltage engineering, suitable materials of the length required are not available; to solve this problem, the longitudinal sensor was divided into several segments [17].

As far as the measuring stability is concerned, according to the definition stated above, types 2c and 2d are to be classified as non-con-

ventional as they contain electronic components. Inductive voltage transformers might, however, be regarded as conventional even if their rated secondary voltage is smaller than $100 \text{ V}/\sqrt{3}$.

3 State of standardization

Parallel to the research and development activities performed in connection with electronic current and voltage transformers, the first draft standards for this transformer type were developed under the direction of TC 38 (Instrument Transformers) of the International Electrotechnical Commission (IEC) and published in late 2000 as provisional versions of IEC 60 044-7 (EN 60 044-7) [6] and IEC 60 044-6, vol. 1 [7].

The requirements specified in these standards can be placed in four groups:

- Components for analog or digital systems
- Secondary rated values for analog or digital output
- Design of analog or digital outputs
- Electromagnetic compatibility.

A transmission system carries the information from the primary to the secondary device; this transmission system can, for example, be an optical fiber. In the standard, the transit time of the signal to be transmitted is referred to as delay time and expressed as phase displacement angle in units of time.

In the secondary of an analog electronic current transformer, the incoming signals are converted into a voltage proportional to the current. For the output voltage of these transformers, standard values between 22,5 mV and 4 V have been fixed. These signals are sufficient to directly supply modern meters, protective and control devices as well as supplementary devices.

In the case of digitally operating electronic current transformers, instantaneous values of current and voltage are, for example, transmitted which are determined with a small deviation of a few microseconds. It is necessary to synchronize the signals, for example the currents and voltages, of the three outer conductors of a three-phase system before they are pooled in the merging unit and transferred in a data protocol to secondary devices. The merging unit may comprise optical (e.g. optocouplers) or electronic interfaces (e.g. RS 232). A PC with digital measuring bridge could, for example, be provided behind the merging unit as a peripheral device.

In contrast to electronic current transformers, only electronic voltage transformers with an analog output are at present considered in the standard. In addition to the secondary rated voltages stated for conventional voltage transformers in IEC 60 044-2, the values from 1,625 V to 6,5 V have been determined as rated values of the output voltage (cf. also Fig. 3).

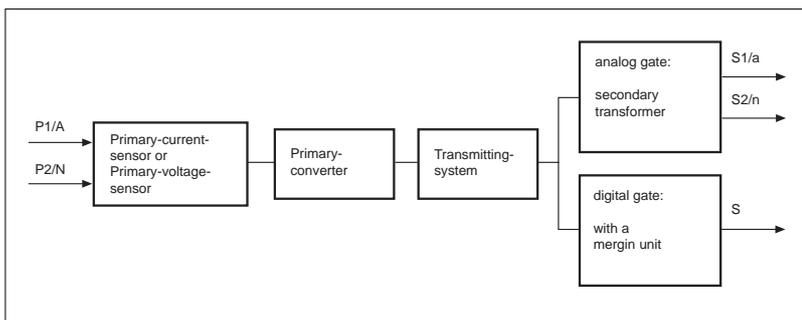


Figure 3:
Block diagram for electronic current and voltage transformers

4 Role of the PTB in the approval of non-conventional instrument transformers

In the past, the PTB tried to support this technology which then was new by investigations of its own [18]. As it seems, the market did not, however, require in the past 40 years that this technique be applied directly and a measuring instrument acceptable for approval be developed which was suitable for invoicing. Lately, manufacturers of instrument transformers have again presented concepts for non-conventional instrument transformers. From the technical point of view, the “Instrument Transformers and High Voltage” Section of the PTB is already in a position to handle applications for approval of non-conventional instrument transformers, provided the manufacturer provides the interface between non-conventional instrument transformers and conventional measurement standards (standard transformer, transformer test sets). These “adapters” are also a prerequisite for granting the approval, as they are required for verification of non-conventional instrument transformers by the state-approved test centres. Moreover, special requirements and test specifications must be covered by the approval. Parallel to the progressing adjustment of the standards, the PTB will develop generally valid procedures, test specifications and measuring facilities

Compared with the approval of conventional instrument transformers, the type approval procedure for non-conventional instrument transformers is as follows (see also Figure 4):

If the electronic transformer is exclusively used for measuring and control purposes as in the past, i.e. if it is not used in the area subject to legal control, no special requirements are to be met by the interface. Special requirements for transformers used for invoicing exist, however, under the Verification Act. In the PTB Requirements PTB-A 50.1 [19, 20], such design requirements are specified for measuring instruments and supplementary devices subject to type approval with respect to the testing and use of periphery interfaces. Interfaces describe the physical, electrical and logical functions at the point of transfer to a measuring instrument or a supplementary device. In addition, PTB-A.50.1 defines terms such as non-interaction, inadmissible influence and security of data transfer which will be checked within the scope of type approval for electronic instrument transformers. If a non-conventional instrument transformer with secondary metering unit is the common measuring instrument, the interfaces are referred to as internal interfaces which are not subject to PTB Requirements.

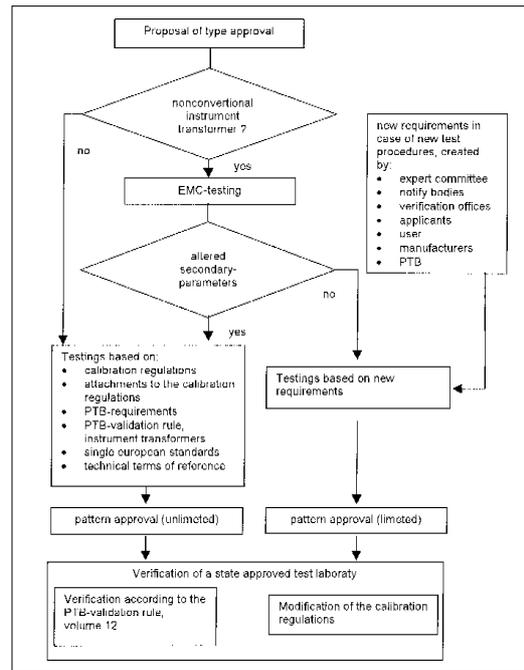


Figure 4

Conventional and non-conventional transformers in the approval procedure

An essential point is the testability of the non-conventional instrument transformer, i.e. the possibility of determining its measurement deviations. The testing technique and, thus, the equipment of the state-approved test centres has so far been appropriate only for conventional transformers. Adapters which facilitate calibration of non-conventional instrument transformers against a conventional standard transformer and a conventional measuring bridge might be a first step towards adaptation.

Under the Law on electromagnetic compatibility (EMC Act) [20] of January 1st, 1996, not only the provisions of the Verification Ordinance but also the protection requirements of the EMC Act have to be met in order that a measuring instrument subject to legal control, including the non-conventional transformers described here, might be placed on the market and operated. The list of test requirements extends from wire-borne interferences (voltage dips, bursts, etc.) to magnetic and electromagnetic fields to electrostatic discharges. The evaluation criteria given in the standards must be complied with. Results of accredited EMC laboratories are recognized by the Physikalisch-Technische Bundesanstalt.

Verification is performed after an instrument type has been approved by the PTB and before it is put into operation. Here, additional questions arise which have to be clarified by superior bodies, such as the Plenary Assembly, parallel to the developments performed at the PTB:

- Are the state-approved test centres equipped with transformer test sets/adapters suitable for non-conventional instrument transformers?

- Must all test centres in Germany be provided with this equipment or will this requirement be limited to a few state-approved test centres?
- Who will bear the costs for the adaptation of the equipment and the transfer of expertise in the state-approved test centres?
- At what intervals shall standards and measuring facilities be calibrated or tested at the PTB?

This shows that before non-conventional transformers can be used for legal metrology purposes, concepts will have to be elaborated in cooperation with all parties involved – i.e. manufacturers, users, state-approved test centres and the PTB – to help these devices on the road to success.

5 Outlook

Although the development of non-conventional instrument transformers started more than forty years ago, they so far have not been generally accepted. This is mainly due to the high accuracy and measuring stability of conventional instrument transformers. Accuracy means that the measurement deviation must not exceed specified limits (see also Figure 5). The experience gained with conventional instrument transformers in the course of many decades has shown that the occurring failures are almost exclusively though fortunately very rarely complete

failures such as the destruction of a high-voltage transformer due to an insulation defect. With electronic instrument transformers, however, there is a considerably stronger probability of creeping changes which cannot be recognized. Also, due to the electronic components in non-conventional instrument transformers, a lower measuring stability is to be expected. This is why in contrast to conventional transformers, the period of validity of the verification for non-conventional instrument transformers needs to be limited and why subsequent verifications, which require great expenditure of personnel and equipment, are necessary. This economic disadvantage is one of the main reasons why no non-conventional instrument transformer has so far been approved and verified.

It is to be expected that the need for digital information transfer and processing will further increase. At low signal levels, the advantage of the digital over the analog transfer technology is, among other things, its interference immunity. This is why conversion of the analog value into a digital signal must take place as close to the point of origin as possible. If the product “power” is computationally measured in an electronic meter from the digital information about voltage and current and if the energy is measured by integration over time, it seems logical to redistribute these working steps to the components in accordance with the capabilities of future measuring systems. Via an optional transmission medium, separate current and voltage sensors could feed the information in a digital form via voltage and current - together with time stamp and sensor reference number - into a data network which is also used for other purposes. With the aid of computers connected to this network it would, for example, be possible for the end user, energy distributor and network operator to “read” the amount of electric energy received. Needless to say that both, the transmission and the programs must be secured in the computer from verification and metrological aspects. Compared to the present state, an essential change would take place: the end user would no longer be able to read the meter content directly on the measuring instrument in his flat. Great reliability of the data transfer, including the sensor assignment, would thus be required for such a system to become accepted.

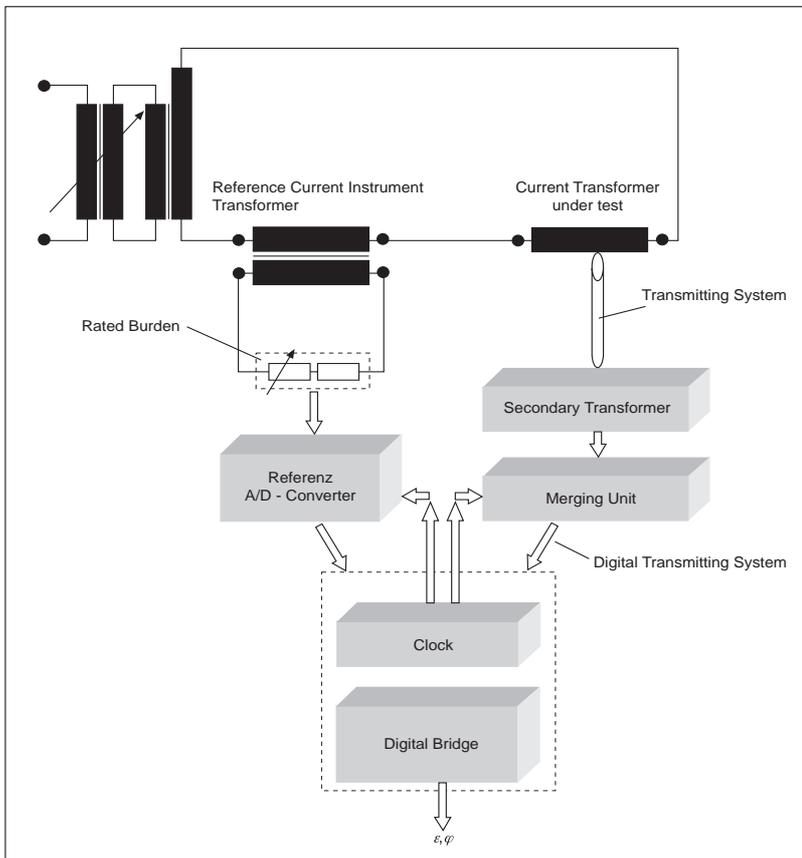


Figure 5: Test circuit for accuracy measurement

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Development and calibration of high-voltage and high-current measuring devices

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Günter Roeissle⁵

Introduction

For reasons of efficiency, the transmission of electric energy from the power station to the consumer takes place at high-voltage potential. In Europe mainly AC voltage and only occasionally DC voltage is in demand. The equipment must undergo detailed tests with respect to its operational reliability at high DC, AC and impulse voltages. Similar test requirements must be met by the instrument transformers used together with electricity meters for invoicing electric energy. Devices used for other purposes than energy supply such as power and TV electronics or accelerator technology are also tested at high voltage.

According to the test and quality assurance specifications, the measuring instruments used for testing must be calibrated by a competent body and have been traced back to national or international standards. The PTB has adapted itself in good time to this requirement the high-voltage sector has had to meet for about one decade so that a large part of the calibration tasks demanded by industry and calibration and test laboratories can meanwhile be performed. This task was facilitated by the completion of the Schering Building in 1994, in which the high-voltage laboratory is now accommodated in suitable calibration rooms, by the renovation of the high-voltage hall [1, 2] and by intense cooperation in national and international working groups in which the bases of novel high-voltage measuring techniques and their standardization were investigated and tested in numerous inter-comparisons.

Today, the dissemination of the most important high-voltage measurands is ensured together with approximately 20 calibration laboratories which have been accredited by the Deutscher Kalibrierdienst (DKD) and whose standards are controlled by the PTB at regular intervals. These calibration laboratories mainly perform the number of routine calibrations which increases permanently and thus make a valuable contribution to the quality of industrial products. Their range of influence extends far beyond the frontiers of Germany and Europe.

This article will first give a survey of the PTB's basic equipment and rooms for high voltage and then deal with some developments and results recently obtained in this field.

1 Rooms and equipment

In 1994, the High-voltage Section of the PTB was accommodated in a new building [2] which was named after the outstanding scientist Harald Schering who at the former PTR between 1905 and 1927 developed a number of devices in the field of instrument transformers and high-voltage whose design principles in part are still valid today [1]. The Schering Building accommodates three medium-sized rooms for high-voltage measurements, several rooms with electronics and computer workplaces and the offices of the employees. One of the measurement rooms is shielded and air-conditioned. Within the scope of the construction work, the high-voltage hall which had already been put into service in 1964, was completely overhauled and modernized. The useful area of the shielded and air-conditioned hall is 20 m × 10 m and the mean hall height 11 m. Next to the hall is the cooling tower which is also shielded; it is 6,5 m in diameter and has a ceiling height of 11 m. In addition to the high-voltage generators and high-voltage measuring devices, the laboratory equipment also comprises facilities for the current generation and measurement of electric currents (Table 1).

The test unit is generally calibrated by a comparison measurement against the respective PTB standard using specified measuring procedures (Figure 1). In the past few years, tightened requirements due to new test specifications, incorporation of the DKD calibration laboratories into the measurement hierarchy for the dissemination of the units of measurement and the demand of the manufacturers of high-voltage measuring facilities for more exact measurement capabilities for their own quality control have required special efforts for the measurands to be disseminated with the uncertainties required [3, 4].

Due to the large dimensions, the transport of high-voltage devices and measuring facilities

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often requires great effort. In the case of impulse voltage measurements, the measurement result may also depend on the waveform of the test voltage generated and the earthing conditions at the high-voltage test laboratory. This is why high-voltage calibrations must frequently be performed in situ at the customer's. For this purpose, the PTB has transportable measuring facilities and special calibration procedures at its disposal.

2 Shielded DC voltage divider of highest accuracy

Figure 2 shows the design principle of a new generation of standard voltage dividers developed at the PTB for the exact measurement of high DC voltages [5]. In contrast to conventional types, the voltage divider proper (3) is accommodated in a gas-insulated, temperature-regulated metal tank so that it is scarcely affected by external disturbances and temperature variations. The voltage divider may, therefore, be designed for high resistance to guarantee feeble self-heating when voltage is applied. The voltage divider presented which has a rated voltage of 100 kV has a total resistance of approximately 1 GΩ. A Peltier element with heat exchangers allows the gas temperature in the metal tank to be kept constant to 26 °C ± 0,15 K up to the highest operating voltage.

A number of other measures and detail solutions contribute to the excellent measuring behaviour. The one hundred wire resistors of 10 MΩ each used in the high-voltage section were carefully selected from a large batch to obtain as

Table 1: Testing and measurement capabilities

Measurand	Range	Features
DC voltage	-100 kV to +300 kV	Measurement up to 400 kV
AC voltage	up to 200 kV to 800 kV up to 800 kV	5 Hz to 500 Hz 15 Hz to 300 Hz
AC current	up to 100 kA	15 Hz to 300 Hz
Lightning impulse voltage and switching impulse voltage	up to 1,6 MV	Measurement up to 2 MV
Impulse current 8/20	up to 20 kA	Measurement up to 100 kA
Temperature	-40 °C to +60 °C	up to 300 kV

small a temperature coefficient as possible (within ± 1 · 10⁻⁶ K⁻¹). These resistors were then combined in pairs so that after application of a DC voltage the remaining positive and negative resistance variations are largely compensated. The temperature and warm-up behaviour of the whole voltage divider with the resistors arranged in pairs is by far better than that of the single resistors.

The resistors (3 in Figure 2) arranged in the form of a helix on Teflon insulators are subdivided into five sections and protected against transient overvoltages by a parallel resistive-capacitive auxiliary divider. Control electrodes (2) restrict the electric field strength in the gas compartment between resistor stack and surrounding tank wall to maximally 25 kV/cm. Sulphur hexafluoride (SF₆) with a pressure of 2 bar

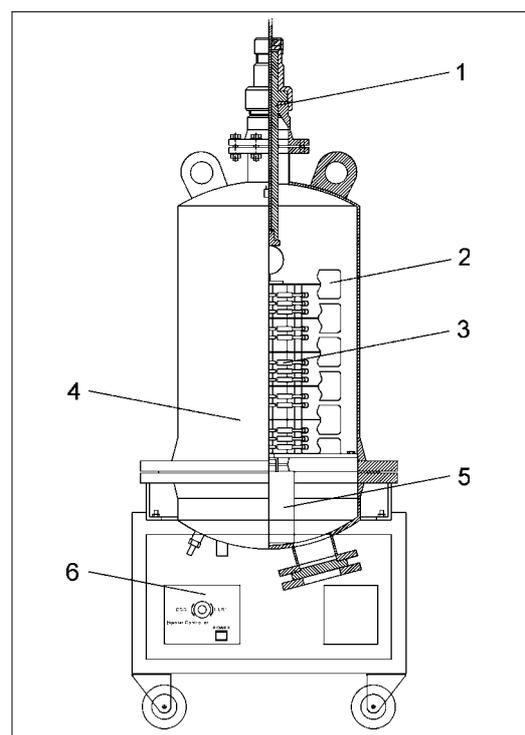
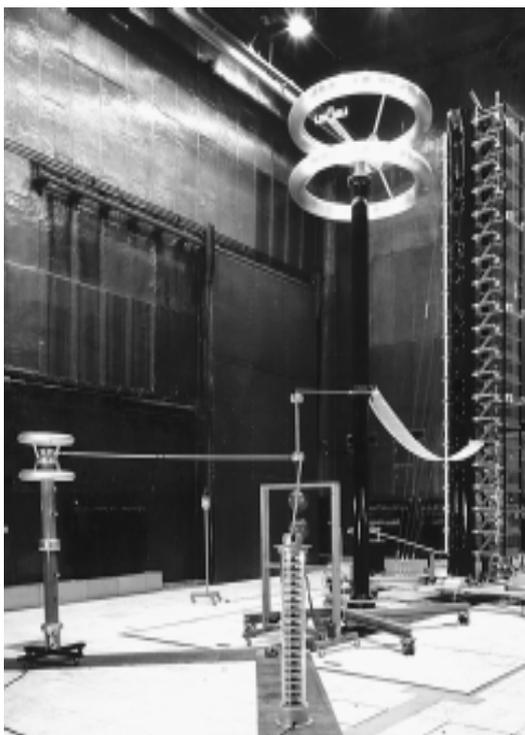


Figure 1: Comparison of a voltage divider (on the left), with standard divider (in the foreground) at impulse voltage

Figure 2: Standard voltage divider for DC voltage up to 100 kV (cross-section)
 1 high-voltage bushing
 2 control electrodes
 3 resistor section
 4 metal tank
 5 heat exchanger
 6 Peltier element for heating and cooling

as is normally used in high-voltage systems serves as the insulating gas. The high voltage is applied to the bushing on the divider head through a shielded coaxial cable. Figure 3 is an outside view of the completely mounted standard voltage divider (up to 100 kV).

Voltage taps performed on two resistors in the low-voltage section which have also been very carefully calibrated allow a divider ratio of either 100 : 1 or 10 000 : 1 to be selected. While tapping at 10 000 : 1 is mainly intended for high-voltage measurements, tapping at 100 : 1 is suitable for exact calibrations of the voltage divider using the measuring means known from low-voltage technology which up to 1000 V are affected by a small uncertainty.

The two divider ratios of the complete voltage divider and quantities possibly influencing the measuring behaviour were determined by a large number of measurements at low and high voltage. A second, similarly designed 300 kV divider was used to perform comparison measurements up to 100 kV to check the linearity and

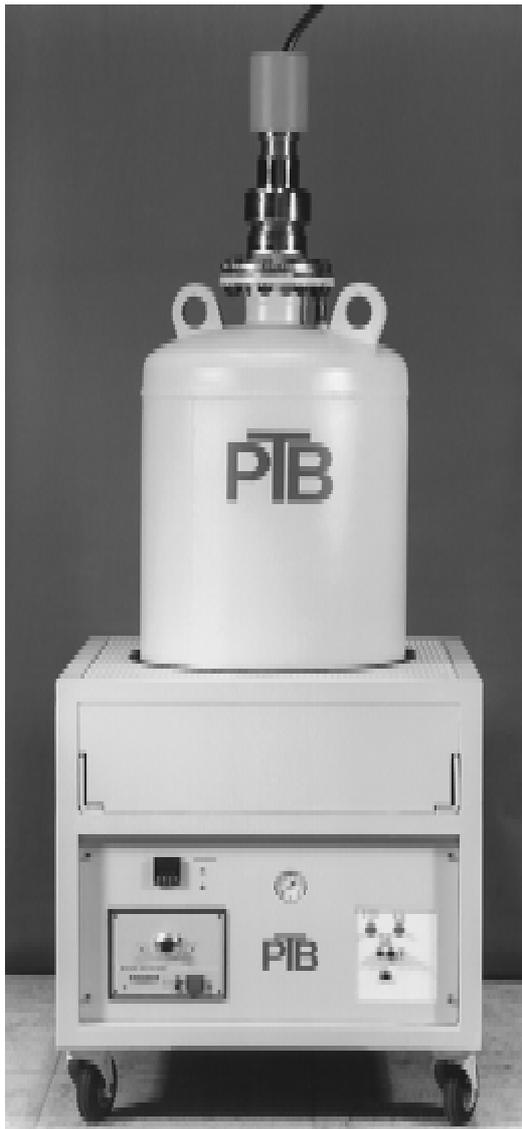


Figure 3:
View of the completely mounted standard voltage divider for DC voltage up to 100 kV

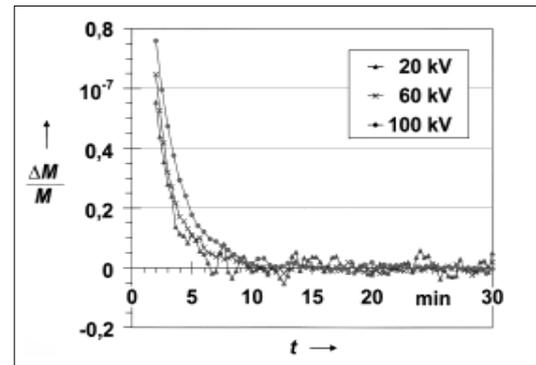


Figure 4:
Variation of the divider ratio with time (rated value 10 000 : 1) after application of high voltage (20 kV, 60 kV and 100 kV).

short-time stability. The measurement results in Figure 4 show that the divider ratio for tapping at 10 000 : 1 tends to a constant value within $\pm 1 \cdot 10^{-8}$ only a few minutes after DC voltage has been applied. The small differences between the curves measured for 20 kV, 60 kV and 100 kV demonstrate excellent thermal balancing of the voltage divider for each voltage value.

From the results for the single resistors and the complete divider, the expanded uncertainty ($k = 2$) of the standard voltage divider was determined to be $1,2 \cdot 10^{-6}$ for the divider ratio from 100 : 1 to 1000 V, and $2 \cdot 10^{-6}$ for the divider ratio from 10000 : 1 to 100 kV. It seems that these values cannot be further improved with the materials and investigation capabilities available. Of particular importance is the excellent short-time stability of the standard divider which leads to a considerable reduction in the measuring times when exactly calibrated. As the investigations which have not yet been completed have already shown, the long-time stability is considerably better than that of the oil-insulated standard dividers so far used.

3 Measuring facility for high AC voltages

In AC voltage tests of equipment for electric energy supply, the peak value of the test voltage is frequently measured as this value is decisive for flashover and breakdown of high-voltage insulations in the case of short-time loading. The r.m.s. value is, however, the more suitable measurand for long-time loading and instrument transformers used to measure energy consumption. Another measurand is the total harmonic distortion of the test voltage which characterizes the deviation from the ideal sinusoidal oscillation. For the determination of these AC quantities, a series of different measurement methods is available which offer specific advantages and likewise are affected by specific disadvantages.

At the PTB, a modified measurement procedure according to Chubb and Fortescue is preferably applied for peak value measurements. Under specific conditions the peak value \hat{u} here is proportional to the arithmetic mean i_m of the rectified AC current flowing through a high-voltage capacitor connected to the test voltage. At the PTB, a peak voltage measuring facility with a patented electronic converter working on this principle was developed and has, due to its specific advantages for the calibration of other measuring devices, proved its worth in ten years of application [6]. Compressed gas capacitors of the Schering and Vieweg type with capacitances from 40 pF to 100 pF are used as measuring capacitors for the different voltage levels. Capacitors of this type show an excellent measuring behaviour, in particular a very small voltage dependence, and are therefore available at almost all high-voltage laboratories. For in situ measurements, they can be used as measuring capacitors after a relatively simple calibration to measure up to the highest voltages together with the PTB peak voltmeter. International comparison measurements have confirmed the measurement uncertainty of a few 10^{-4} stated for the peak voltmeter, including the compressed gas capacitor.

The increased demand for calibrations of the r.m.s. value of high AC voltages called for the development of a new universal measuring facility for AC quantities. Here, the measuring signal for the evaluation is again obtained via the high-voltage capacitor C , similar to the measuring principle according to Chubb and Fortescue. Figure 5 shows the block diagram of the new measuring facility. The protective circuit at the input prevents line-frequency or transient overvoltages from damaging the measuring instrument. After conversion into a proportional voltage signal, the capacitor current $i(t)$ is digitized by an analog-to-digital converter with 16-bit resolution and 10^6 samplings per second and stored as numerical data set. In the next step, numerical integration takes place in the PC compensating the preceding differentiation due to the effect of the measuring capacitor. The positive and negative peak values u_+ and u_- , the peak-to-peak voltage u_{ss} , the r.m.s. value u_{eff} , the frequency f and the total harmonic distortion are numerically calculated from the new data set, which now truly maps the high voltage $u(t)$.

From previous investigations, a measurement uncertainty similar to that of the old peak voltmeter can be inferred. An even higher accuracy could be achieved at some additional expense but due to the instability of the high AC voltage it could not be profited from in practical measurements. Moreover, the test standards do no specify up to which harmonic the AC quanti-

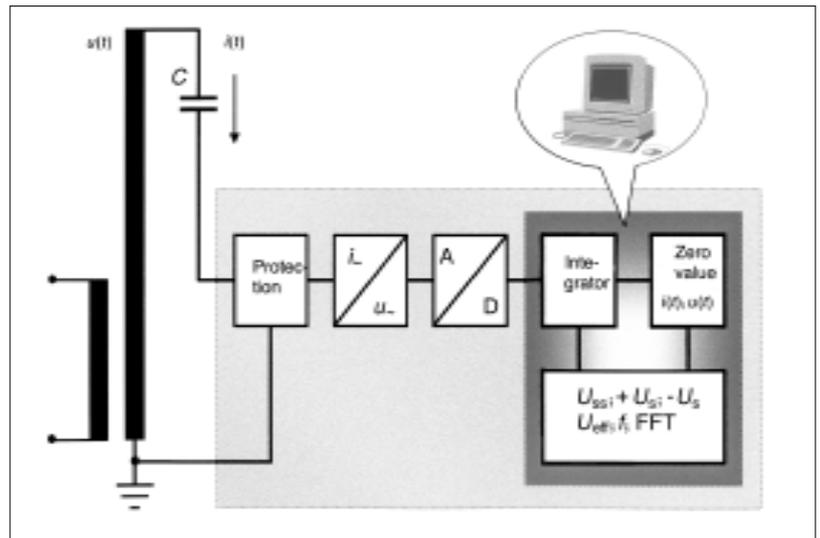


Figure 5:

Block diagram of the new AC voltage measuring facility with digital evaluation of peak and r.m.s. value

ties are to be measured. Another advantage of the new measuring facility is that transient signals which are not too fast as, for example, short-circuit and switching voltages in the supply network, can in principle be digitally recorded and evaluated with the appropriate software.

4 Impulse voltages and impulse currents

In the power supply system, very high transient voltages and currents may occur due to lightning strikes, short-circuits and switching operations. To furnish proof of their operational reliability, the devices used for power supply must therefore be tested not only at high AC or DC voltages but also at standard impulse voltages or impulse currents. Measurement and evaluation of the impulses with rise times down to 0,5 ms and peak values of up to a few megavolt and some 100 kA, respectively, therefore make particularly great demands on the measuring systems and their calibration.

Particularly in this field, fundamental changes in measuring techniques and calibration procedures have in the past decade been made and proposed for standardization with intensive support from the PTB [4, 7, 8, 9]. In this context, the increasing demand for traceability of the measurements was also taken into account.

4.1 Inspection of impulse calibrators

Today, almost all high-voltage laboratories use digital recorders instead of analog storage oscilloscopes for the recording of impulse voltages and currents. At the PTB, this development started already 25 years ago, and a num-

ber of publications are dealing with the characteristics of the digital recorders used for impulse measurements, their calibration and the software applied for data evaluation [10 to 13]. For a few years, impulse calibrators have been available which allow digital recorders to be checked easily and rapidly in accordance with IEC 61083-1. The impulse calibrator is decisive for the measurement accuracy of a digital recorder and thus also for the uncertainty of impulse voltage measurements.

In cooperation with several instrument manufacturers and DKD calibration laboratories, the PTB has developed a computer-controlled measuring set-up for the inspection of impulse calibrators which then will serve as reference instruments in manufacture or for further calibrations. In this measuring set-up, the calibration impulses generated are recorded with a digital

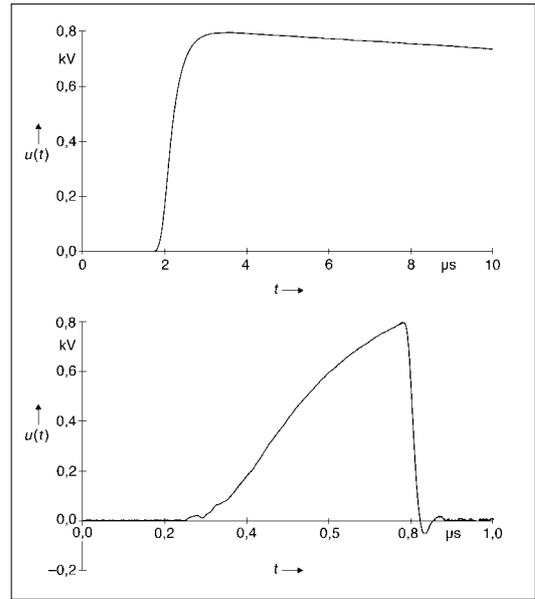


Figure 6:
Time curve of calibration impulses
Top: full lightning impulse voltage
Bottom: chopped lightning impulse voltage

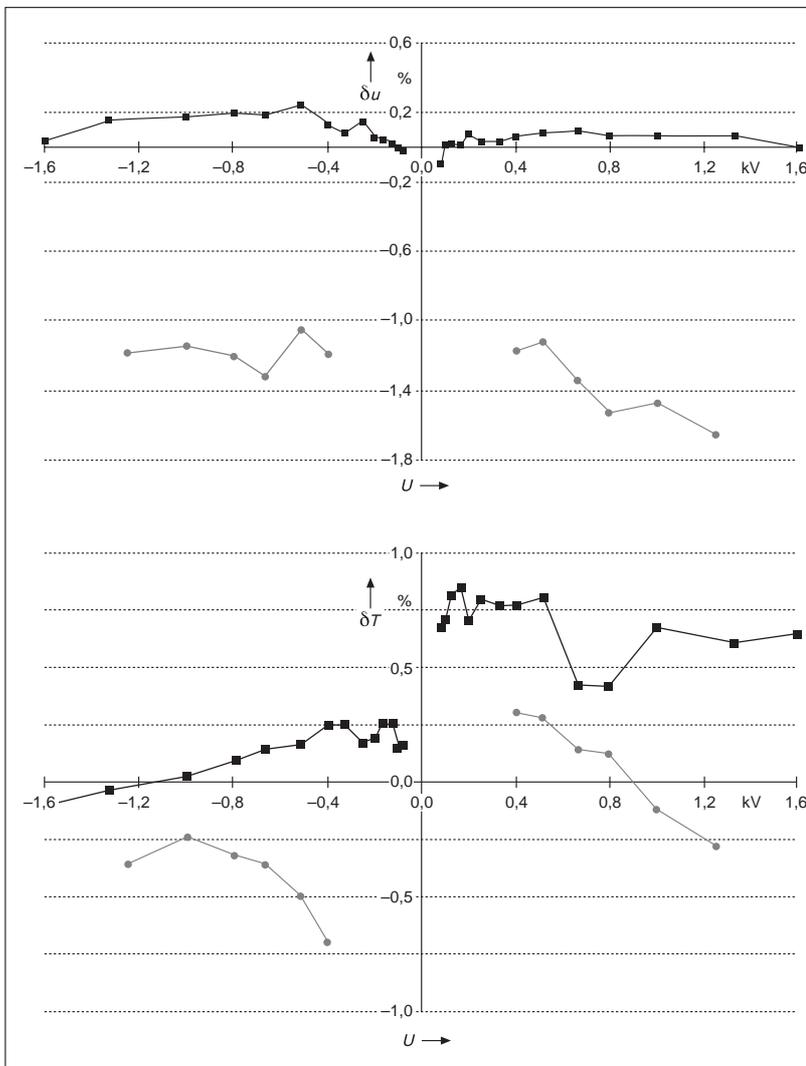


Figure 7:
Inspection of an impulse calibrator for full and chopped lightning impulse voltages
a: relative mean deviation of peak value
b: relative mean deviation of front time and time-to-chopping
■ full impulse • chopped impulse

recorder and evaluated with the software with respect to the peak value and the time parameters. The 8-bit digital recorder with attenuator used for this purpose was carefully investigated with respect to its measurement deviations [10, 11]. Special calibration and evaluation techniques allow the digitizing error, which makes an essential contribution to the uncertainty of the calibration, to be kept small.

As an example, Figure 6a shows the time curve for a full lightning impulse voltage, and Figure 6b that for a front-chopped lightning impulse voltage generated at a specified load by the impulse calibrator to be tested. The relative deviations of the peak value of up to 1600 V (full impulse) and 800 V (chopped impulse) and the time-to-chopping were determined as the mean value of ten impulses each and stated in the calibration certificate (Figures 7a and 7b). Here, negative deviations mean that the values measured are greater than the values set on the calibrator. What is striking are the larger deviations of the peak values for the chopped impulse, some of which lie outside the permissible range of $\pm 1\%$. This is due to the very pronounced peak of the chopped lightning impulse voltage which was measured with a bandwidth of 70 MHz and a sampling rate of 10^9 s^{-1} of the PTB measuring facility. The digital recorders usually used in high-voltage laboratories normally have a smaller bandwidth and a lower sampling rate. The mean deviations can be used to correct the respective settings so that the limiting values given in the test specifications are

complied with. The deviations of the time parameters are less than the permissible limiting values of $\pm 2\%$. At the PTB, the long-time behaviour of the reference devices is checked by annual repeat measurements.

4.2 Standard measuring device for impulse current

While the competence of many high-voltage laboratories for the measurement of impulse voltages meanwhile meets the requirements of the test standards thanks to a great number of international intercomparisons and an ever denser network of calibration laboratories, the situation is unsatisfactory from the metrological point of view both on the national and on the international level as regards measurements of transient current with peak values up to a few 100 kA. In a joint action, several power test laboratories and metrological state institutes in Europe, Asia and America therefore intend to set up and calibrate three reference shunts for the measurement of transient currents up to 200 kA and to confirm them as international standards within the scope of intercomparisons. The measurement uncertainty aimed at is 1 %.

In a first step towards setting up a PTB standard measuring device for transient currents, the characteristics of different shunts and measuring coils with high-permeability core were investigated. The output signals were recorded with a floating digital recorder operated and evaluated with respect to the impulse parameters. An advantage of low-resistance, coaxial shunts as are usually used for electrical current measurements is that they have a large bandwidth and can be measured with high accuracy at direct current. If they are connected in series into the circuit and used as standard for the calibration of other shunts, measurement problems may occur due to the earthing conditions which frequently are unsatisfactory. Measuring coils, however, allow potential-free current measurement and, consequently, low-interference calibration of other shunts but they have the disadvantage that low-frequency signals and their DC component cannot be accounted for.

The characteristics of two commercially available measuring coils for impulse currents up to 5 kA and 20 kA were determined individually and in the complete measuring system, together with the digital recorder [14]. In the lower frequency range, the dynamic behaviour of the measuring coils was determined with AC current and at higher frequencies from the step response (Figure 8). The measurement results mainly confirm the lower and upper 3 dB cut-off frequency of a few hertz or a few megahertz stated by the manufacturer. Instead of the 3 dB cut-off frequencies, the measured values can

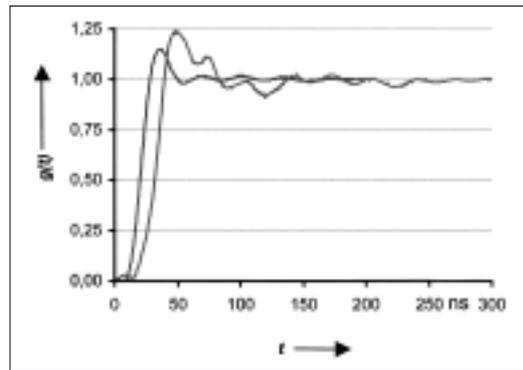


Figure 8: Standardized step response of measuring coils for 5 kA (black) and 20 kA (blue)

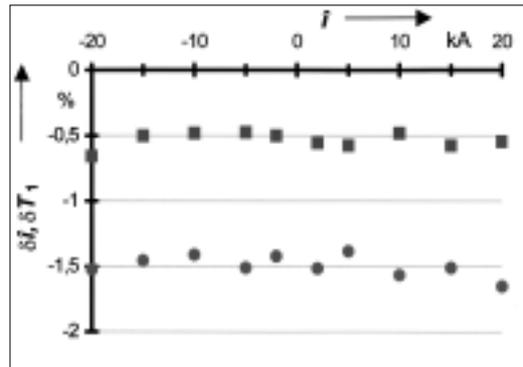


Figure 9: Relative deviations of the standard measuring device with measuring coil for peak value (•) and front time (■) of impulse currents

also be used to determine the cut-off frequencies for any small amplitude drop, for example 0,2 %, which does not yet make an essential contribution to the measurement uncertainty.

The impulse scale factor and the linearity of the complete standard measuring device with the two measuring coils were determined by comparison measurements with a 100 kA shunt at impulse current 8/20 (8 μ s front time, 20 μ s time to half-value). Although, according to this determination, the impulse scale factor of the two measuring coils, including a 10 : 1 attenuator, differs from the respective rated value, it remains constant up to the maximum current within $\pm 0,2\%$ for impulse currents of both polarities. As an example, Figure 9 shows the mean deviations of the peak values and front times measured with the measuring coil up to 20 kA. Further investigations show that the disturbances due to stray electric and magnetic fields are infinitesimal. If all influencing parameters are taken into account, the expanded uncertainty ($k = 2$) of the standard measuring device amounts to 0,5 % for the impulse scale factor and to 1 % for the measurement of the time parameters of impulse currents up to 20 kA.

The use of three coaxial shunts in the standard measuring device was also investigated in detail. The upper cut-off frequency of 100 MHz stated by the manufacturer was confirmed on the basis of the experimental step response and its evaluation. On the basis of the resistance measured with a low measurement uncertainty at direct current, the linearity of the shunts was

limit current of 120 A. Figure 13 shows the temporal variations of the numerically calculated energy content for impulse currents and sinusoidal half-cycles of equal amplitude; in this representation, it is impossible to distinguish between the curve for 1 kA and the abscissa. The comparison shows that after 10 ms – i.e. after one half-cycle of the 50 Hz sinusoidal oscillation – the energy content of the impulse currents is by 10 % to 20 % lower than that for the respective sinusoidal half-cycle. Theoretically, it can be shown that the differences of the energy contents would still amount to only a few percent if the impulse peak value was increased by 5 %.

5 Calibrator for the simulation of partial discharge impulses

Partial discharges in general relate to pulse-shaped, very small electrical discharges which are likely to occur in insulation arrangements in the case of high field strengths. They often indicate defects in the production of the high-voltage insulation. If partial discharges occur in equipment for electricity supply over a prolonged period of time, i.e. over months or years, manifold damaging mechanisms may cause a complete breakdown of the insulation. This normally leads to the equipment failing and to irregularities in the power supply. A test for partial discharges is therefore performed before equipment is used and to an increasing extent also during its operation.

In accordance with test standard IEC 60270 which has lately been revised, the scope of the calibration for measuring instruments and charge calibrators used for partial discharge tests has to be considerably extended. As a basis for the requirements established, the PTB organized an intercomparison sponsored by the EU between metrological state institutes, calibration laboratories and test laboratories. The final report summarizes the existing measurement and calibration capabilities for the impulse charge q , the decisive measurand for partial discharges [15]. For impulse charges from 1 pC to 500 pC, the deviations of the 13 participating laboratories from the common mean value lie – with a few exceptions – within $\pm (0,1 \text{ pC} + 0,03 q)$. The calibration procedure applied for the impulse charge q by the majority of the participants was included in the test standard, and the uncertainty was determined to be 5% for partial discharge calibrators and 10% for partial discharge measuring instruments.

The construction of the commercially available impulse calibrators so far used for calibration is relatively simple and can be used for the new, far more extensive requirements only to a limited extent. This is why a new calibrator for comprehensive performance testing of partial dis-

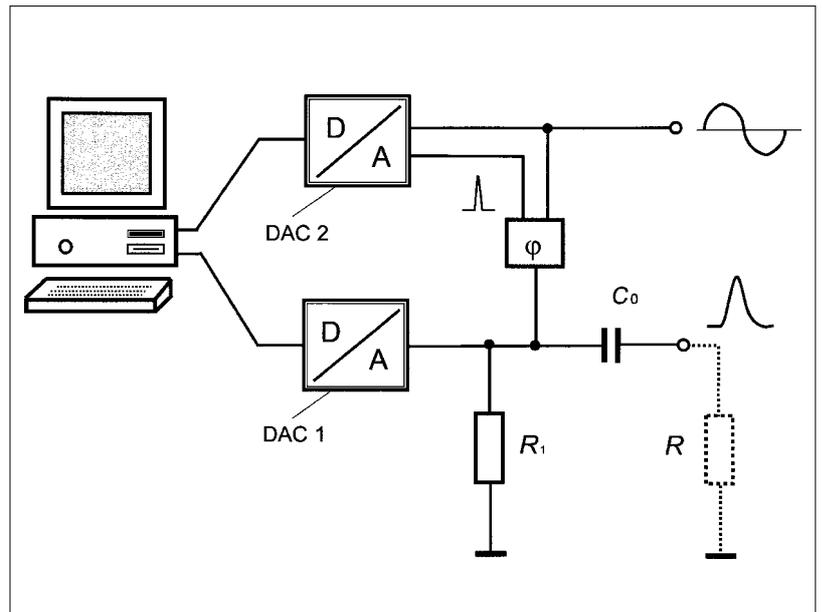


Figure 14:
Block diagram of the programmable calibrator for impulse charges
DAC 1: Digital-to-analog converter for generation of the charge impulses
DAC 2: Digital-to-analog converter for generation of sinusoidal voltage with mains frequency φ : phase shift of the charge impulse with respect to the sinusoidal voltage

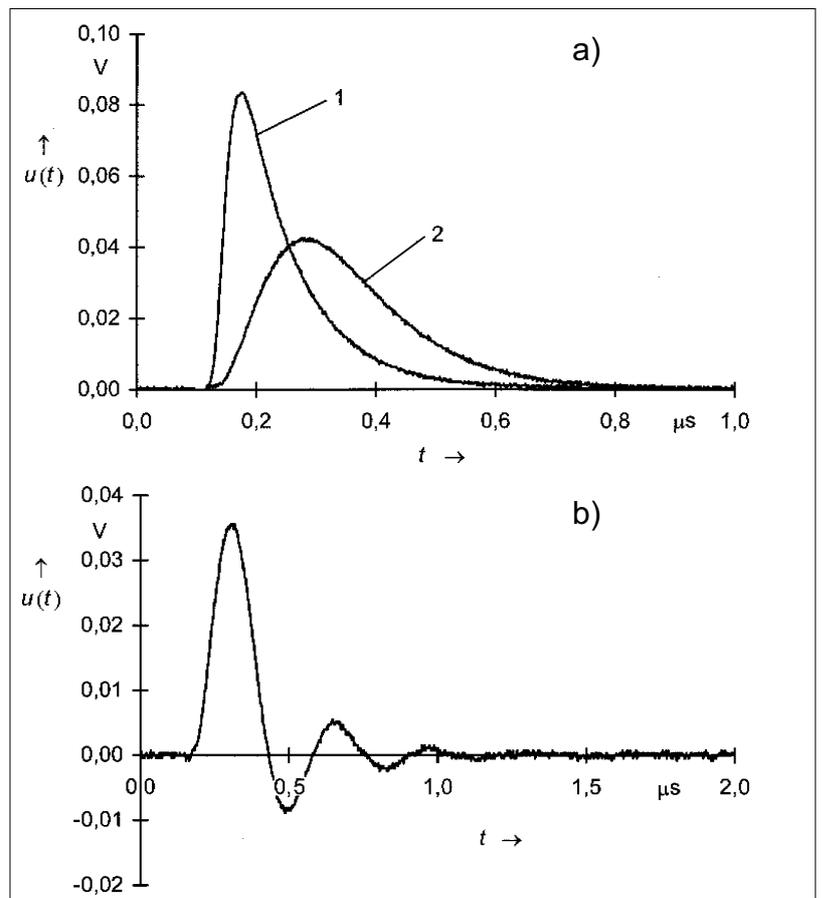


Figure 15:
Examples of charge impulses for the calibration of partial discharge measuring instruments
a) Impulses of different duration, but identical charge
b) Impulse with oscillation

charge measuring instruments has been developed at the PTB [16]. The main item of the programmable calibrator is a digital-to-analog converter (DAC 1) with 12-bit resolution and 50 MHz clock frequency arranged on a plug-in card in a PC (Figure 14). The numerical input data for generating the analog output signal are calculated with a software developed in "Visual Basic." After conversion of the converter output signal by a series capacitor, the charge impulse required for the calibration is generated.

The programmable calibrator allows a series of impulse parameters to be varied so that the calibration impulses can be better matched to the partial discharges actually occurring in the high-voltage circuit than with the conventional calibrators so far used. This is necessary as orientating measurements performed on different partial discharge measuring instruments have occasionally shown a dependence of the charge indication on the pulse shape. In addition to impulse charge, repetition rate and polarity, it is also possible to specify the impulse width, the component of superposed oscillations and the magnitude of individual impulse charges within a series of ten impulses. The values desired are entered into the PC under menu control. Figure 15 shows two examples of different pulse shapes. Another advantage of the programmable calibrator is the automated or semi-automated performance of calibrations.

The phase angle between partial discharge and operating voltage allows conclusions to be drawn for specific insulation arrangements as regards the cause and type of partial discharges or the state of the insulation. Digital partial dis-

charge measuring instruments therefore allow the phase angle to be continuously recorded and evaluated. For calibration of the indication, the second digital-to-analog converter of the calibrator (DAC 2 in Figure 14) is used to generate a sinusoidal voltage with mains frequency 50 Hz, 60 Hz or $16\frac{2}{3}$ Hz which is applied to the input of the measuring instrument for the high-voltage measurement. With the aid of the numerical phase shifter j , a specific phase angle between sinusoidal and calibration impulse can then be preset and compared with the indication of the measuring instrument.

Summary

Calibration and testing of reference measuring devices for accredited calibration laboratories, state-approved test centres for electricity measuring instruments and other metrological state institutes are the main tasks of the PTB's High Voltage Section. A large part of these measuring devices are directly or indirectly used for high-voltage and high-current tests of equipment used for electricity supply so that the PTB makes an important contribution to their operational reliability. A great part of the standards with a low uncertainty required for the calibration and testing activities, and the software for the calculation of the parameter values searched were developed and investigated in detail at the PTB and confirmed in a large number of international inter-comparisons. They are adapted to allow for changes in the test requirements for the measurement uncertainties called for. Also, the experience of the PTB enters into standardization. The PTB thus has an efficient centre for the calibration of high-voltage measuring devices and the dissemination of units at its disposal.

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Measures to assure the reliability of digital information

Martin Kahmann*

Since April 2002 the PTB has been running an internet service to assure the reliability of digital documents. This service includes the publication of checksums (so-called hash codes) of digitized versions of selected documents, the PTB draws up or assesses within the scope of its official tasks. For the time being this service is on offer in the area of type approvals for electricity meters under the entry "Trust service for

digital information (tsdi)." Two programs for the calculation of checksums are provided on the relevant www-pages for downloading. These programs are implementations of the checksum algorithm RIPEMD-160 [1, 2]. Whether these programs are uncorrupted can be checked by calculation of their own RIPEMD-160-hash codes. Unaltered or uncorrupted programs lead to the following hash codes:

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program	RIPEMD-160-Hash-Code
hashtest.exe	e4fe9bef70fc0b77dcbc3a93c5ad57ca746ff616
winhash.exe	8921b3c39d8bbfee6870ec112d24251a78af4d7c



Further details concerning tsvi can be found under:
www.ptb.de, button "search", search item "tsdi"

To further increase security, the two programs are provided by different servers. Downloading is also possible from the following pages:

<http://www.sachsen.de/de/bf/verwaltung/eichbehoerde/elt/index.html>
<http://www.agme.de>

Furthermore tsvi is described in the E-Government Manual of the Federal Department for Security in Information Technology (www.bsi.de).

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Challenges to Legal Metrology in terms of Metering and Information Technology due to the Liberalization of the Power Market

Peter Zayer*

In the first part of this essay, the regulatory framework and the market regulations of the German market model will be presented, along with a detailed description of the regulations and mechanisms of the MeteringCode and of the VDEW / DVG-Guideline on “Data Exchange and Accounting of Energy Quantities”.

Based on the objectives of legal metrology, the second part will describe the effects competence and responsibility have on metering, and the involvement of legal metrology from the point of view of operational practice in competition. Finally, the effects on test centres will be briefly elucidated.

1 Regulatory Framework and Market Regulations

When EU-Directive 96/92 concerning common rules for the internal electricity market was implemented into national law, the Act on revising energy industry legislation (Energiewirtschaftsgesetz – EnWG) of April 24, 1998, was created [1]. Compared to its European neighbours, the German market model exhibits a few exceptional features which have also, among other things, an effect on metering and data management. In the interest of competition and electricity consumers, a step-by-step opening of the market has been foregone. The organization of the market, especially the technical and organizational prerequisites, have also been left to the market participants themselves. Only a few principles have to be derived from the Energy Industry Act (EnWG).

The Associations’ Agreement [2] regulates the organization of electricity network usage in contractual terms. The main emphasis of the Associations’ Agreement is on economic regulations and the description of the market model, and on the allocation of roles and tasks to the market participants. The responsibility for metering, data recording and data management is allocated to network operators.

Technical and organizational details, however, are not laid down in the Associations’ Agreement but in the subordinated market regulations (see Figure 1)

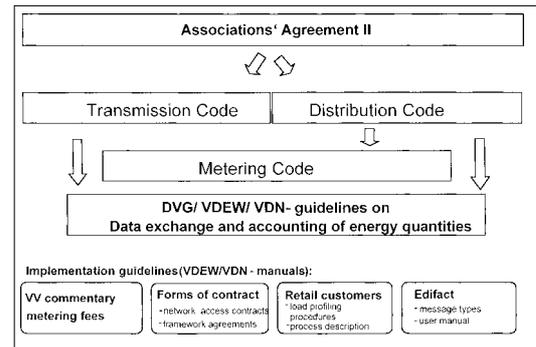


Figure 1: Market regulations

The GridCode [3] describes the network and system rules of transmission system operators, and the DistributionCode [4] the rules for access to the distribution networks. While of high importance, both codes shall not be treated in detail in this article, due to space limitations. Instead, the focus will be on the MeteringCode [5] that describes details for metering and data management and the VDEW / DVG-Guideline “Data Exchange and Accounting of Energy Quantities” [6] which will be introduced briefly below.

1.1 The MeteringCode

The MeteringCode, which has been published as VDEW-Guideline on “Metering for Billing and Data Supply”, describes the minimum requirements for metering, specifies the requirements for the installation and operation of the meters and measuring instruments and furnishes some information on the provision of metered data in a competitive environment (see Figure 2).

In the following chapters, key ideas of the metering code such as the distribution of competence and responsibility, the importance of clear cut information on metered data and the minimum requirements for metering and measuring devices will be elucidated.

1.1.1 Competence and Responsibility

The Associations’ Agreement allocates the competence and responsibility for metering and energy data management to the network operator. In the German market model, network opera-

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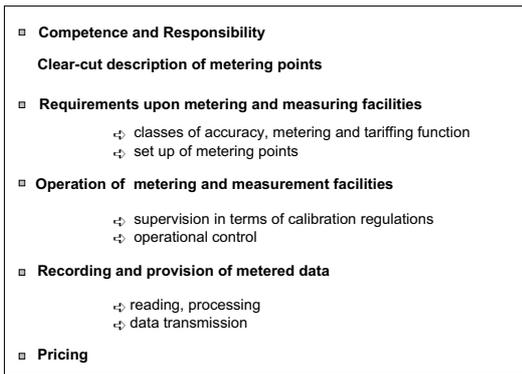


Figure 2: Metering Code 2000

tors have thus been assigned the role of independent service providers who are supposed to be able to fulfil this task best within the scope of legal provisions (Energy Industry Act, Metrology and Verification Act (hereinafter briefly: Verification Act). The fact that this role is assigned to the network operators puts great responsibility on the latter and requires high commitment from them (see Figure 3).

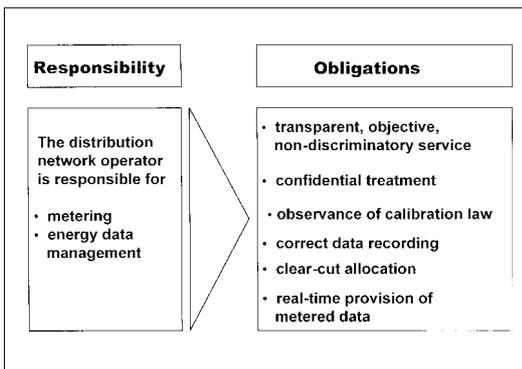


Figure 3: Metering responsibilities and obligations

The network operators, however, do not only function as managers for metering values and data of third parties, but they also require metered values for themselves in order to get an overview of the feed-in and extraction quantities and services in their own network zone. If such information is not properly available, or if it is unreliable, distribution network operators are not only threatened with considerable economic loss, but the security of supply is also jeopardized for everyone receiving power from the network.

Since the beginning of liberalization, the special position of network operators with regard to the metering task has been heatedly discussed. A great disadvantage in this discussion is the fact that market regulations can be legally enforced to a limited extent only, although they clearly take the function of legal ordinances. Associations' Agreement, GridCode, Distribution-Code and MeteringCode are considered as private-law regulations, i. e. as so-called "Associa-

tion Contracts", which legally have the rank of DIN- or EN-Standards. It must be noted, however, that in the case of non-observance of market regulations, the German power-market model would probably have to be regarded as having failed.

The fact is that due to the complex feed-in and extraction operations performed by third-party power users, distribution network operators can hardly, or not at all, ensure economically efficient and trouble-free network operation (and thus a general security of supply) unless they are given guaranteed control over the metered values of the energy flow. This is a matter of responsibility, and the point is not to limit competition but – on the contrary – to create the necessary preconditions for it.

The operative business in metering and data technology is to be dissociated from responsibility and competence. As the present development shows, also external service providers have their chances here. Most network operators commission external service providers with the fulfilment of their tasks, e. g. meter installation, remote meter reading, data clearings or data exchange. Nevertheless, providing the market participant with true information about his metered energy quantities remains the responsibility of the network operator.

1.1.2 Clear-Cut Information on Metered Data

The numbering systems power suppliers have used so far are not suitable for data exchange between different network operators. Only clear-cut, unambiguous and permanent designations of metering points will ensure that each feed-in and/or extraction point can clearly be identified in the deregulated market and that the metered data can be unambiguously allocated.

This means that a new, central element will have to be installed in the IT systems of network operators in which both the respective meters and the information on the metered values will be integrated, with a link to the associated contracts and balancing groups. In addition to the designation of metering points, the EDIS system of characteristic numbers (energy data identification system) [7] is needed to ensure that unambiguous and clearly assignable information on metering values is provided. Modern meters (e. g. VDEW performance specification meters) are able to display the metered values and the measurement type and assign them to the respective EDIS characteristic numbers. This allocation of a metering point to an EDIS characteristic number has to be maintained during the entire period of market communication until billing takes place.

A special feature are the so-called "virtual designations of metering points". These have to be

assigned when sums and/or sum differences, e. g. aggregated load curves, are exchanged within the scope of competition communication. These *virtual* designations are subject to the same formation rules as *real* ones. As these *virtual* metering points denote *sums* and/or *sum differences*, a computing rule must be defined for each virtual metering point. This rule has to be agreed between the market partners, for example in the form of an annex which is added to a framework agreement and/or a cooperation agreement.

1.1.3 Minimum Requirements for Metering and Measuring Devices

The requirements for proper metering are laid down in the MeteringCode and specify

- the minimum standards (class accuracies of the measuring devices to be employed),
- the use of approved and verified measuring and metering devices,
- installation instructions,
- the requirements for supervision during operation,
- the requirement for supervision under the Verification Act.

In the minimum requirements mentioned above, only those standards are laid down which reflect the actual state of metering technology in Germany, and are necessary and sufficient for proper metering.

1.1.4 Network Customer Groups

To avoid burdensome exchange and modification of meters in the context of customer switching, a simplified method has been determined in the Associations' Agreement for the group of retail customers. For this method, load profiles are used. These "*load profiles*" are representative time series for certain customer groups which have been determined statistically from already existing load-curve data. They permit to assign to each customer wishing to change supplier the load profile best suited for him, on the basis of simple and verifiable criteria. The representative load profile is used instead of a measured load curve.

Retail Customers

Thanks to the special regulation described above, simplified methods can be used for retail customers (private households, small enterprises, farming). Meanwhile, both an analytical [8] and a synthetic method [9] have been developed with regard to the supply of retail customers. Both methods use representative load profiles as auxiliary means [10]. Therefore, customers of this group can usually keep on using their old meters.

The decision in favour of or against one of these methods must be taken by each network

operator on his own responsibility. Furthermore, the limit up to which the method can be used for retail customers must be fixed by each network operator. At the beginning of competition, many network operators determined an output of 30 kW and/or an annual energy quantity of 30 000 kWh as limiting value. Today, there is a tendency towards higher annual energy quantities (100 000 kWh to 200 000 kWh). For the sake of competition, a general increase of limiting values and of power and/or energy values is desirable, since it extends the use of statistical load profiles to a larger group of customers and thus eases customer switching. The increase of limiting values can be achieved by refining the representative load profiles, a necessary condition if the accounting and network balancing security is to be maintained.

Business Customers and Large-scale Customers

For the customer group above the specified limiting values, the measured $\frac{1}{4}$ -h-load curve is needed.

The new requirements are especially met by the standard load curve meters complying with the VDEW performance specification [11]. The envisaged refinement of the VDEW performance specification will lead to a standardization of the process communication between the meter and the control centre for distant reading of metered values. This will be achieved e. g. by the specifications according to the DLMS/Cosem Standard [12] (Device Language Messages Specification / Companion Specification for Energy Metering).

An important requirement for measured load curves, i. e. for the time series of the measured $\frac{1}{4}$ -h-values, is time synchronization, as can be achieved by the radio clock signal of the long-wave transmitter DCF 77.

1.1.5 Recording and Provision of Metered Values

The requirements for data read-off, data transmission, data treatment, the formation of substitute values and data provision require that new organizational and technical methods as well as appropriate tools be available to network operators so as to enable them to send the necessary information to suppliers and/or balancing coordinators right in time.

Figure 4 shows the transmission chain from the metering point to the point of data transmission, together with the required security concepts.

The energy consumption values of retail customers are read off electronically or manually on location. In the case of large-scale customers, communication with the sub-points, i. e. the meters, the meters for distant reading etc., takes place via all communication paths being available and economically usable, such as the public

telephone network, GSM networks, or Power Line Carrier systems. Like in the case of data recording, metering data transmission requires different methods and procedures depending on the customer group.

To ensure uniform external data provision, the metered values must first be treated after their recording.

Here, the main tasks are:

- securing of raw data
- plausibilization
- conversion of data into a uniform format
- checking and/or allocation of the EDIS identification number
- conversion into primary values (i. e. taking account of the conversion constant)
- allocation of the status
- allocation of the substitute value (as far as this is feasible for the network operator)

The necessary information can then be supplied to the authorized persons, provided that data protection and confidentiality are ensured.

After having presented the MeteringCode with its most essential regulatory contents, the regulations on data management will be presented in the following.

1.2 VDEW/DVG Guideline on “Data Exchange and Accounting of Energy Quantities”

The aim of this guideline [6] is to describe the minimum requirements, the method of data exchange and the method used for accounting of energy quantities. The specifications of the GridCode and of the DistributionCode with regard to the balancing groups and the required data exchange are implemented in a practice-oriented manner (see Figure 5).

In cooperation with market partners and the IT industry (Edna Initiative), the guideline is currently updated with regard to business models, deadlines and process descriptions.

1.2.1 Balancing Groups

A *balancing group* is a virtual structure in which an equilibrium between feed-in and extractions is aimed at by the *party in charge of a balancing group* (PBG). “*Feed-in*”, refers both to the allocated feeding points and to schedule-based supplies from other balancing groups (*procurement*). “*Extractions*” are allocated extraction points and schedule-based deliveries to other balancing groups (*deliveries*). The schedule indicates for each quarter of an hour within the duration of the respective transmission how much power has been exchanged between the balancing groups, or how much power has been fed in at the feeding nodes, or has been extracted at the extraction nodes (see Figure 6).



Figure 4: Data recording and data management

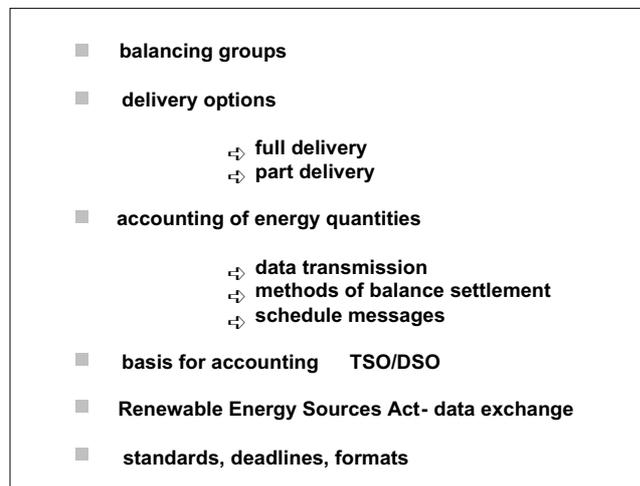


Figure 5: VDEW/DVG Guidelines on data exchanges and accounting of energy quantities

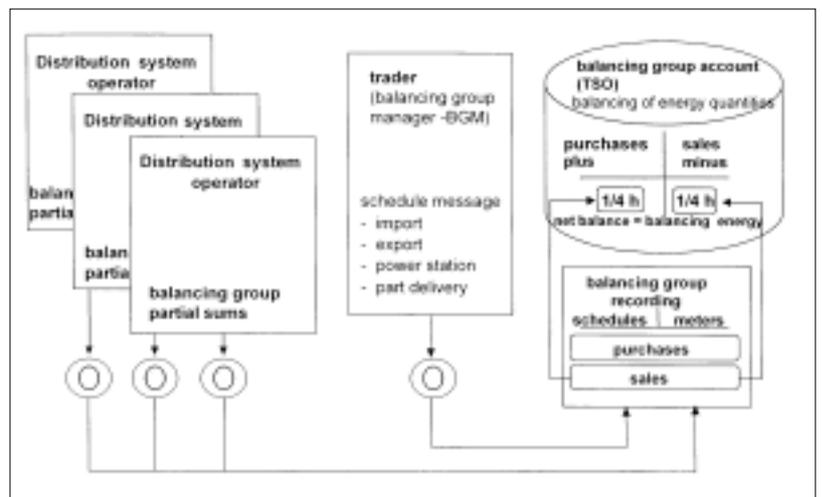


Figure 6: Balancing group management and determination of balancing group deviations

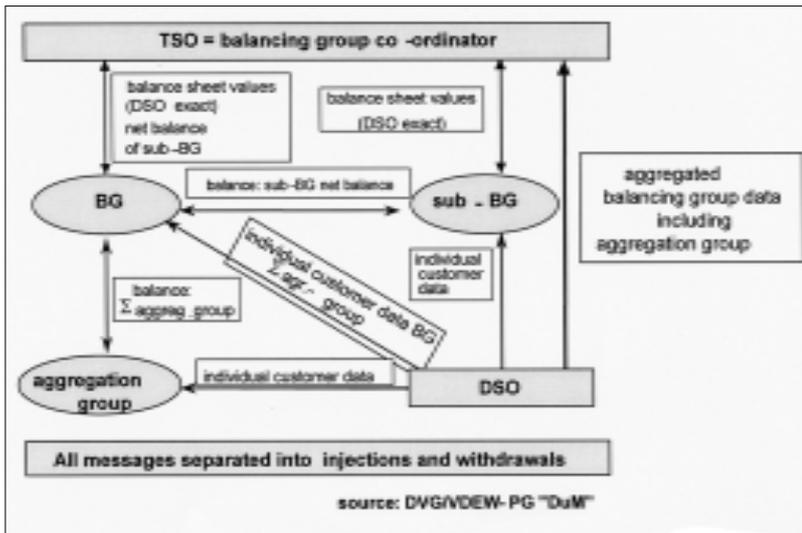


Figure 7: Message channels and data balancing

In each quarter of an hour, the PBG is thus responsible for a balanced account between procurement and extraction. The function of a PBG can be assumed by power traders, marketing departments or large-scale customers. The so-called “parties in charge of a sub-balancing group” (PSBG) and the *aggregators* are allocated to a PBG in contractual terms. The *sub-balancing group* is a balancing group which is not responsible for balancing the deviations vis-à-vis the balancing group account (TSO). An *aggregator* is a supplier who does not have a balancing group of his own but who has a supply contract with a PBG or PSBG and allocates his customers to the respective balancing group.

To determine the balance deviations of the balancing groups in one zone, all necessary data of the balancing groups have to be collected by the TSO (balance coordinator). For this purpose, the relevant energy quantities in the ¼-hour-raster have to be aggregated at the level of the distribution network operators according to the affiliation to a particular balance group and have to be passed on to the TSO. The TSO can then determine the balance deviations (tolerance band), taking into account the schedule-based procurements and/or deliveries.

To implement the balancing group model, a variety of new contract regulations is needed in practice. Data flows between market partners will also have to be agreed upon in these regulations, Figure 7 shows the different market participants with the required data flows.

1.2.2 Balancing Method for Distribution Network Operators

“Balancing” means that the feed-in and extraction quantities in a network area are divided completely among the balancing groups. Due to the fact that the feed-in and the extraction points have not yet been totally equipped with load curve meters, the so-called difference balancing method has currently to be applied to determine the supply quantities of the local trader (e. g. municipality). The basis for this method is the measured load curves and/or time series or schedules. The calculation result is the basis for accounting of the local trader’s open power supply contract with a power supplier.

1.2.3 Types of Supply

As a matter of principle, a distinction is made between *full* and *partial supply*. “*Full supply*” of a customer means that this customer is supplied by only one supplier. “*Partial supply*” means that a customer is supplied by several suppliers. Partial supply is only feasible and reasonable for large-scale customers with measured load curve. In the case of a partial supply, all supplies, except for one, are based on schedules. The remaining share of the supplied energy quantity is allocated to the supplier with the open contract. For realizing partial supply, three different models are envisaged:

- service model
- sub-balancing group model with two variants
- partial supply identification model

They differ in the requirements placed upon the customer, in the complexity of data communication and in the degree of data anonymization.

1.2.4 Exchange of Data

The only possibility of mastering the enormous requirements for data exchange in the competitive market is the clear-cut and unambiguous fixing of communication standards with the aim of achieving an automated, secure exchange of data. For data exchange, the market regulations therefore prescribe the utilization of UN-EDIFACT [13] (Electronic-Data-Interchange-For-Administration-Commerce-and-Transport) Standard which has already become well-proven common practice. In Scandinavia, the EDIFACT Standard has already passed the test some years ago and is now being employed successfully under the name of “EDIEL” by 300 market participants. Meanwhile, a number of other countries have taken interest in the EDIFACT Standard so that we are on the best way to achieving a common European standard for electronic data exchange.

2 Impacts on Legal Metrology

After having presented in the first part of this essay the market model with the two market regulations important for metering and data management, we are now going to explain the impacts on legal metrology. Starting from the objectives of the Verification Act, we will describe the competence and responsibility for legal metrology, its implementation within the companies and the effects on test centres.

As already explained above, the Verification Act also applies to the liberalized power market. Therefore, also preventive measures provided for by the Verification Act – such as approval and calibration of measuring instruments – have been included in the Metering-Code as a minimum requirement for metering in the competitive market. However, there are still different points of view with regard to the regulation requirements and the need for protection of individual consumer groups.

According to section 1 of the Verification Act, the aim is to protect private and commercial consumers as purchasers of measured goods and to create the metrological conditions for a fair trade with measured goods [14]. When implementing these targets, account must be taken of the fact that there is a diversity of market partners which all have different market power and thus different needs for protection in the liberalized power market [15]. The greatest need for protection certainly have, now as before, private households and small enterprises. As soon as measurements go beyond the usual annual electricity bill, these customer groups are no longer in a position to verify whether the measurement has been correct or not. In contrast to this, large industrial companies and large-scale customers at special rates usually have expert knowledge and staff resources to check and plausibilize their bills so that it can be assumed that their need for protection is lower. In many European countries, metrological consumer protection by the state is hence not considered necessary for these customer groups. Market regulations agreed upon by private companies, such as the MeteringCode, systematically try to take these differences into account by regulations tailored to the specific needs of target groups. It seems worth discussing whether such flexibility could also be incorporated to a higher degree in the verification regulations.

As a matter of principle, it can be stated that the customer image is gradually changing in the consumer policy of modern industrial nations. Self-responsibility and flexibility of citizens are increasing as a result of measures taken to improve their knowledge and capabilities. When

assessing the need for consumer protection, the average consumer is increasingly assumed to be “... informed, alert and judicious” – a term used in current jurisdiction. Examples of such approaches are specialized consumer committees (“Consumer Councils”) under preparation in Great Britain or the development of consumer protection on the German Telecommunication Market. Such models should be taken into account when considering the need for consumer protection in the liberalized power market .

2.1 Competence and Responsibility

As the competence and responsibility for metering have been allocated to the network operator, the responsibility as defined in the Verification Act (i. e. the correct use of measuring techniques), too, lies in the approved hands of network operators. In Germany, this means the responsibility for the accuracy of approx. 42 million electricity meters used in commercial business, and observance of the requirements under the Verification Act. Thus, a well-functioning system is available which ensures – with the interaction of supervising verification authorities and accredited test centres of network operators – compliance with the Verification Act. Supervising the measuring constancy of the meters and ensuring measurement reliability are long-term tasks. Despite short-term economic advantages we should not lose sight of the fact that meters have to be supervised permanently, so this is an important task of consumer protection. This system has so far helped to ensure that no substantial problems have occurred and that failures of meters probably due to technical reasons have been noticed early enough to take the necessary action.

Such findings can only be obtained by supervising a stock of meters over a long period of time. Therefore, it is not sufficient to just define technical requirements for metering without carrying out permanent checks afterwards. Special attention is paid by network operators to the supervision and extension of the calibration validity. Thus, great part of the electricity meters installed today is subjected to sampling inspection, a method that is used for the extension of the calibration validity.

In the liberalized power market, a market supervision without clear-cut allocation and assignment of responsibility has no chances. From the economic point of view it would therefore make sense to maintain the approved, efficient and effective system of simple market supervision, in the interest of all market participants and – thus – for the benefit of consumer protection. Unambiguous regulations of the legislator would be very desirable in this regard.

2.2 Application of the Verification Act in the Liberalized Power Market

For legal metrology it is certainly one of the greatest challenges of our times to contribute actively to the German power market model with all its new requirements for metering and data management. For a functioning power market it will, however, be imperative to adjust the corpus of regulations that will follow the law (Verification Ordinance, PTB-Requirements). Referring to pure “theory” will not be of any help at the moment. Pragmatic solutions which lead to a balance of interests between all market participants and are oriented towards the common weal, are required here.

In the past, legal metrology has proven at various occasions to be able to adjust to a changing society and to new requirements resulting therefrom. Also in the current situation, such flexibility is required. It is, however, not sufficient that authorities in charge of legal metrology utter a general feeling of unease about the results of self-regulation, as for example the MeteringCode. What is needed are legal regulations which are not only clear-cut but also adequate in the light of the risk of damage which might occur to the consumer in electricity billing. At the same time, it should by all means be aimed at achieving a harmonization of the regulation level within the EU.

As national power markets are currently developing rapidly into a single European power market, the requirements of consumer protection should be harmonized more strongly amongst the European neighbours. If, in a common European power market, companies seated in the zone of validity of the Verification Act suffer from competition disadvantages due to different consumer and Verification Acts in the individual countries, barriers to trade are being built up which, in the long run, have a negative impact on our economy and thus on the common wealth, and should therefore be considered as being just as detrimental as lacking consumer protection.

2.2.1 Directives and Requirements

With the introduction of the European “Measuring Instruments Directive” (MID) [17] (its implementation at the national level being planned for 2005), a new situation will arise for legal metrology. The regulations for introducing measuring instruments into the market that are subject to legal control will then be harmonized at European level. As the annexes to MID do not specify all detail requirements, such as software requirements, WELMEC (European Cooperation in Legal Metrology) is preparing a guide which shall serve as a basis for requirements upon

measuring instruments not be covered by MID [18]. An example for this are auxiliary devices requiring national standards, e. g. “intelligent measuring instruments”. In Germany, the PTB-Requirements 50.7 [19] are available for these. Compared to other European countries, these requirements constitute a relatively strong state interference in the metering and billing processes of the liberalized power market. In view of the fact that in our neighbouring countries obviously no regulations for “intelligent” measuring instruments are planned which will reach as far as the PTB-Requirements 50.7, we should take care not to manoeuvre ourselves offside by overregulation in Germany. Especially the definition of new measurement values in the PTB-Requirements 50.7 – and thus the requirement for mandatory verification – should, in view of the requirements of the liberalized power market (e.g. treatment and billing of aggregated time series), remain open for critical discussion.

Should it become apparent that the requirements do not work or that, in comparison with our European neighbours, they entail economic disadvantages, or that they interfere with other legislative areas such as civil or commercial law, a rapid correction of the respective regulations will be indispensable.

2.2.2 Solution Approaches in the Companies

As described in Part 1, the prerequisite of a well-functioning, liberalized power market is the real-time provision of information on measured energy quantities. This information is needed by a wide variety of market partners. Network operators for example need the data to invoice their use-of-system charges, traders to invoice their power deliveries, and customers to check their electricity bills. All eligible market participants must therefore have neutral and non-discriminatory access to the metered values, and these must have been measured correctly in compliance with the Verification Act. To master the organizational implementation of competition in technical terms, new IT solutions are required from all market participants. The available variants are quite manifold, as in most cases, the IT environment has grown historically. Usually, tasks are solved by several autonomous IT systems, such as ZFA, network usage systems, prognosis and trade systems.

For illustration purposes, the newly developed, integrated customer information and billing system of SAP called “IS-U/CCS” shall be presented here exemplarily in brief [20]. Currently, this software system is being used by several large supply companies. Depending on the design of the software, this system can be used both for network and supplier purposes (see Figure 8).

As can be seen from the chart, the data are measured and treated in accordance with customer-group-specific requirements. Thus, not only the $\frac{1}{4}$ -h-load curves of large customers at special rates are measured daily and made available by means of a remote metering system. Also the electricity consumption of retail customers is measured, either once a year or when a change of supplier takes place. Data treatment, rating, balancing, data transfer, and invoicing is effected by taking account of the certified "Principles of Proper Accounting" in the integrated SAP modules. As the effort needed to approve and verify such systems is intolerably high, a customer-group-specific consumer protection must be built up outside such complex IT systems.

2.2.2.1 Implementation of the Requirements for Different Network Customer Groups

Retail Customers

For the consumer group made up of private households, farming and small-sized enterprises, protection should be highest. Due to the fact that for this customer group billing is not carried out on the basis of measured load curves, the customers of this group have, now as before, the possibility of checking their bills via the display of their approved and verified meters. As the ordinary meter can only indicate the actual value but not the values measured in the past, customers must, for their own check, note down the relevant readings. This is, for example, necessary when customers switch to another supplier. In case of queries and need for clarification concerning the metered values, the network operator is the first party to be approached by the customer. The right to have one's bill officially checked still exists as a means to clarify difficult cases.

Business and Large-scale Customers

Billing of this customer group, which encompasses e. g. larger-scale customers from trade and industry as well as distributors, is effected today on the basis of measured load curves. Thereby, load curves are generated at the respective metering point in calibrated measuring instruments or auxiliary devices, stored and transmitted to the accounting systems. Monthly visits to read off the meters manually, which was absolutely normal until a couple of years ago, are no longer effected since the introduction of remote reading.

The in-situ-checking of $\frac{1}{4}$ -h-load curves, i. e. of single $\frac{1}{4}$ -h-values, is today usually possible with the newly approved multi-function-meters and auxiliary devices. By operating a – partially very complex – manufacturer-specific display menu, the single $\frac{1}{4}$ -h-values are displayed

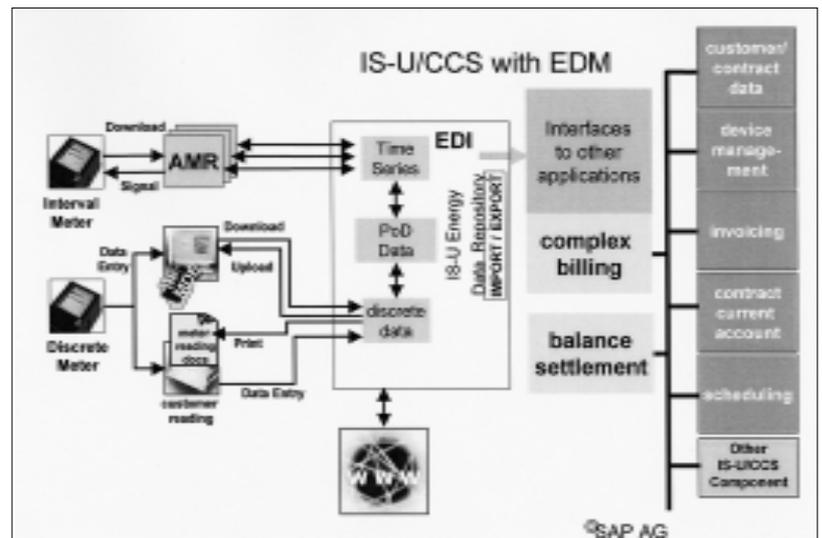


Figure 8:
IS-U/CCS scheme with EDM

within the storage volume of the device. The requirement that measured data of an invoice must, as a matter of principle and in a way tolerable to the customer, be traceable for the customer to the data measured in calibrated measuring devices can only be achieved partially with today's solution. The "Certified Readout Software", which is just under discussion, represents a more practicable means of control, and can be made available to the interested customer. With this software, customers would be able to read off their load curve from the verified metering device quite comfortably in order to check the bill for network usage and the bill of the supplier.

2.2.2.2 Limits to the Verifiability of a Bill via the Display of a Measuring Instrument or an Auxiliary Device

Fulfilling the previous requirement of checking any energy bill via the display of a meter or of an auxiliary device can become extremely difficult, if not impossible, in the liberalized power market. Here, the partial supply shall be given as an example.

In all partial supply models, the DSO in charge of energy data management usually has no knowledge of partial supplies. Partial supply schedules are only available to the TSO and – depending on the model – to the supplier with the open contract. For the purpose of illustration, the scheme of partial supply is shown below according to the sub-balancing group model (Figure 9).

It must be noted that checking the partial supply bill is no longer possible on the measuring instrument alone. Contract agreements between the customer (usually, only large-scale customers are concerned by such a case) and his

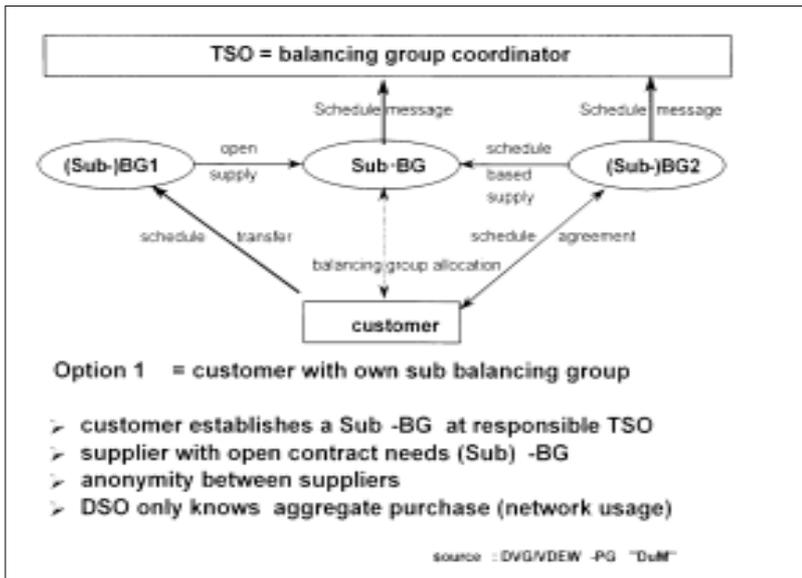


Figure 9: Partial supply according to sub-balancing group scheme

suppliers are needed which regulate the transparency of the billing process. Here, the role of the Verification Act can only be to create legal security in the billing process insofar as it cannot be created by another law, e.g. Commercial and Trade Law. Although there is consensus that there must not be any unlegislated spaces, an extension of the Verification Act to activities which are already regulated by Commercial and Trade Law seems, however, to be little beneficial for legal security.

2.2.2.3 Data Transmission

From the point of view of the verification authorities, there is currently a problem with the Verification Act in the field of data transmission – between measuring point and energy data management system. On the other hand, it has to be noted that already before liberalization until the present day, the data exchange of load curve information for large-scale customers (customers with several feeds, electricity supply contracts with various special supply agreements) has been practiced without any problems. Load curve data are measured via remote reading and stored as safeguarded raw data before being processed. On request, this dataset is also available to the customer. By various plausibility checks, e. g. an evaluation of the technical status information and an annual check of the meter reading (i. e. comparison of the transferred previous value with the meter reading of the calibrated meter in situ), the load curves are verified.

Manufacturer-specific protocol formats are partly used as transfer protocols. The tasks of access protection and data security are solved with traditional technologies. This is certainly

not a solution for the future, as business operations will then be required to be automated and secure.

The practice of sending Excelfiles by standard e-mail in data exchange must, due to the high risk of manipulation and faults, soon be a thing of the past. The implementation of the secure Edifact-Standard which is called for in the market regulations – with its messages “MSCONS“ [21] for the metering value information and “UTILMD“ [22] for the master data – is urgently required.

2.2.3 Refinement of Legal Metrology

In summary, the following requirements can be derived from practice:

- Approved, calibrated measuring instruments and auxiliary devices **should be** used which store the metered values and offer them, protected within the scope of the Verification Act, for market communication.
- Data transmission must - as far as possible - take place outside the zone which is protected by the Verification Act. It would make sense to define a sector solution here – comparable to the banking sector.
- Such a solution should orientate itself to the Signature Law [23] and to the Signature Ordinance [24]. In this way, framework conditions would be created for shaping seamless electronical business operations with probative force [25].

An essential contribution to solve this task can perhaps be expected from the SELMA project which was launched in October 2001. SELMA is one of the projects promoted within the scope of the Ideas Competition “VERNET – Secure and Reliable Transactions in Open Communication Networks” which was promoted by the Federal Ministry of Economics and Technology (BMWi) for the development and testing of new technologies.

Different authorities (i. e. the AGME, the Bundesanstalt für Sicherheit in der Informationstechnik and the PTB), research institutes, manufacturers and users are working together in this project. The objective of SELMA (Secure Electronic Measurement Data Exchange) is to make approved methods available by which measured data can securely be transmitted from a measuring point via open networks. The integrity of the data can thereby be checked by the recipient or by another authorized body at any time. (Here the question arises whether accredited test centres could be an appropriate authority suitable for this purpose). The solution is based on the application of a signature procedure for the datasets as provided by the Signature Law for electronic signing in electronic trade.

The secure access to data via open networks (Internet) is a vision for the future which might, however, be simple to realize one day with the experience of the SELMA project.

2.3 Test Centres in the Competitive Market

As a result of competition, many accredited test centres have come under pressure, and their right of existence is put into question by their holders. Due to this, the interaction between the state and private test centres, which so far has worked well, is threatened to break up. The reasons for this are manifold. First of all, economic reasons must be mentioned. The holder companies are under massive pressure to create positive economic returns and “shareholder value” and thus are compelled to make full use internally of all cost reduction and profit potentials. There are no longer Taboo-Areas! Values such as trustworthiness and metrological competence, built up by the test centres in long years of work, lose importance relative to economic considerations.

Another reason for test centres to be jeopardized is the Manufacturer’s Initial Verification which will – once the European Measuring Instruments Directive (MID) will have been issued in the foreseeable future – reduce the number of initial verifications carried out at test centres, especially as far as meters are concerned which are connected directly in large numbers. It will then become increasingly difficult for the test centres to recover their cost by means of the verification fees. As already mentioned above, clear signals on behalf of the legislator have unfortunately been missing so far as to whether the system of independent, sovereign test centres – which, by nature, undisputably serve the common wealth – will be maintained or will be sacrificed to an ever increased competition in the field of metrological services. For the approx. 215 accredited test centres still existing, this strained situation means in any case that, in agreement with the holding enterprises, they will have to re-orientate themselves in a difficult environment.

Re-orientation means orientation towards costs and new tasks. This may imply activities like

- cost saving, staff adaptations
- cooperation between test centres
- establishment of economically stable regional and communal test centres
- application of higher-quality and more efficient testing techniques,
- extension of the quality assurance system between the different operators, comprising e. g. acceptance tests, network supervision, systems for the supervision of the verification validity, contact point for all market par-

ticipants in questions concerning the correctness of the invoiced values or time series,

- opening up of new fields of work in agreement with the legislator, e.g. by extending competences for activities and tasks within the scope of market surveillance.

In the course of such a re-orientation, the accredited test centres must present themselves as stable, competent and modern providers of metrological services. A fast implementation of the above-mentioned tasks and cost-saving measures is therefore mandatory and must be carried out without delay.

3 Summary and Conclusion

A liberalized power market - and this applies in the same way to the emerging liberalized gas market - is unthinkable without legal metrology. End customers – especially retail customers - must be sure that the applied measuring instruments function correctly, and they must be able to compare their energy bills with the base data provided by the verified measuring instruments. The more customers move in a competitive environment, the more they must endeavour to find their own checking mechanisms. This should be taken into consideration when adapting the verification legislation.

A practice-oriented European solution has to be found which meets not only the requirements of consumer protection – taking due account of the technical progress in measuring and safety techniques – but also those of the free market.

Author’s Remarks in August 2004 Since the initial publication of this article in 2002, the regulatory framework has been in a continuous process of change. Although the new energy legislation (EnWG) with its manifold sub-regulations is still being discussed in German legislative bodies (i. e. the German Parliament), the framework is adapting continuously in anticipation of this new law. One of the coming key innovations could be the installation of a regulatory body (Regulierungsbehörde) as early as in the beginning of 2005. Envisioned is a small and efficient body, that will drive and further develop the market liberalization. In consequence of the organic development of market conditions, details of the market regulations have been overhauled repeatedly and were republished by the newly created VDN, the network operators association (www.vdn-berlin.de). Readers should note that only details have been changed, while the general market model as described in this article remained unchanged. Further, the inaction of the European Measuring Instruments Directive (MID) in spring 2004, which was still in planning in 2002 (see chapter 2.2.1), requires an adaptation of the German verification act by 2006. Simultaneously, other regulations in the German verification act that are not touched by the MID act will be updated. While it is too early to speculate about specific details of the new act, it is well possible (and desirable), that some ideas presented in this article (e. g. new tasks for test centers) will find their way into the new verification act. First drafts however should not be expected before 2006.