# Construction, commissioning and use of a test bench for smart meter accuracy verification

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***Abstract*—As a result of the ever-increasing share of renewable energies in electricity production and the associated volatile supply of renewable generation facilities, overvoltages going beyond the norm already occur today. To counter this and to be able to intervene, the relevant operational values have to be known. This paper describes the construction, commissioning and use of a test bench to verify the accuracy of smart meters deployed for the determination of operating variables. The accuracy of a specific smart meter is verified at the previously developed test bench under the utilization of various test methods, to review the functionality of the test bench. The construction of the test bench and its software allow to check all measurable factors of different smart meter models and make the individual creation and customization of measurement methods possible. The results of the exemplary measurements show that gross errors occur both in the averaging of the angle measurements as well as for the measurement-period adjustment.**

***Keywords-Smart meter; test bench; calibration; renewable energy; accuracy verification***

## I. INTRODUCTION

Based on the experiences and knowledge to the global climate change, there were massive energy and climate political changes in the recent years within the European Union (EU). On the one hand, common climate policy objectives for the reduction of greenhouse gas emissions in the entire EU were defined. On the other hand, every country in the international community received its own targets, which have to be achieved through individual strategies of the member states. The resulting energy concept of the German Federal Republic, based on these specifications to achieve the national targets, is supposed to ensure a reliable, economical and environmentally friendly energy supply. Here, the focus is in particular a sharp rise in the share of renewable energies in addition to the reduction of energy consumption and the reduction of greenhouse gas emissions. To achieve the scheduled share of the renewable energy concept, meaning a share of renewable energies in gross electricity consumption of 35 percent in 2020, the renewable energy law (Erneuerbare-Energien-Gesetz = EEG) was reformed in 2009.

Due to adjustments in the “Erneuerbare-Energien-Gesetz” (EEG) and the associated subvention of renewable energies, there was a huge expansion of decentralized and renewable generation facilities in the last years, which is expected to continue. From the beginning of 2009 until the end of 2013 the share of renewables in gross electricity consumption rose in Germany by 9.1 percentage points to 25.4 percent [1]. Wind and photovoltaic farms feed generally in the high-voltage grid and individual wind turbines and photovoltaic systems exclusively in the low and medium-voltage grid. The volatile supply of renewable energies leads in low and medium voltage networks to voltage increases, so that today the voltage quality in these networks occasionally no longer corresponds to the norm DIN EN 50160. Network operators therefore face the challenge of integrating renewable generation capacities in the networks, while ensuring both a low-interference network operation, as well as a standardized voltage quality. In order to accomplish this task, network operators have in principle the possibilities of network expansion, voltage and reactive power control as well as the down-regulation of the produced power. However, for network operators to act on the grid, the relevant operational values are needed, that means preferably the voltage value and the voltage angle at each network node.

In high voltage networks the classical approach, the monitoring by measurement technologies at the network nodes by SCADA systems (Supervisory Control and Data Acquisition) is used to determine the operating variables for decades. SCADA systems allow the monitoring and control of networks and thus form the basis for visualizations. In low and medium voltage networks, this approach is, however, due to high costs and a huge effort, based on the large number of loads, generators and link points hardly feasible.

The Chair of Energy Systems and Energy Management (ESEM) of the Technical University of Kaiserslautern developed within the framework of the public-funded research project "SmartSCADA for low and medium voltage networks" a method that makes it possible to cost-effectively get similar statements about the condition of low and medium voltage networks. Therefore data from SCADA systems of overlaid networks are combined with predicted performance data of renewable supply and smart meter data as well as processed in a state-estimation method for distribution networks. In this paper, the measurement accuracy and the behavior of a, to the research project comparable smart meter, will be examined and verified using an electricity meter test bench. It is first necessary to develop a concept for such an automatic electricity meter test bench in compliance with laws, standards and guidelines. Based on this concept, the practical construction and initial commissioning as well as the examination of a smart meter will be explained.

## II. CONCEPT DEVELOPMENT

### A. *Necessity for a new test concept*

Power companies have been using electricity meters since decades for the billing of energy amounts. Main purpose of this electricity meter is to measure the transferred energy through the connected circuit [2].

So far electromechanical Ferraris meters were used to measure the amount of energy. However, increasingly also electronic electricity meters are utilized. Electronic electricity meters can, compared to Ferraris meters, include a variety of additional functions. Thus they have, in addition to the acquisition of additional measurement parameters, often the possibility for data transmission, tariff control and load control. The actual functionality varies significantly depending on the manufacturer and uses. Electronic electricity meters providing additional functions are also called smart meters [3]. Unlike traditional electricity meters, smart meters provide the possibility to capture, temporarily store and transmit other parameters such as voltages, currents, phase angles and frequencies in addition to the electrical energy.

As with every machine also the measurement of electricity meters has deviations. These are mainly quantified using an electricity meter test bench. This is typically done by comparing the measurement results of the test object with the measurement results of a more accurate measuring device. The need for accuracy verification of electricity meters arises from the fact that these are used for the allocation of quantities of energy between energy-supply companies and their customers. To protect consumers in the acquisition of measurable goods for erroneous billing, uniform conditions for correct measurements were made in Germany [4]. In cooperation with the "Physikalisch-Technische Bundesanstalt" (PTB) laws, standards and guidelines in relation to instruments of fair trading were issued. The monitoring of the implementation of these laws is the responsibility of the national measurement services.

Supply measuring instruments, such as electricity meters are tested by nationally recognized testing laboratories. This by law required process is called calibration. However, the calibration of electricity meters includes only payroll-relevant metrics such as energy quantities. Non payroll relevant grid parameters, such as voltage and current magnitude, phase angles or services, are not part of a calibration inspection. The quantification of the accuracy by measuring the grid parameters must be carried out, if necessary, in a separate test, for which no specific respectively direct requirements exist. Therefore specific concepts have to be developed for the investigation of the accuracy of grid parameter measurements, as is done in this work. For this purpose certain technical requirements and other regulations, described in the next section have to be considered.

### B. *Relevant technical requirements and legal framework*

The requirements listed below are related to the construction, process and content of an official calibration of electricity meters. The term requirements colloquially stands for laws, standards and guidelines. Hence they represent instructions, whose compliance is expected or they request a specific behavior or action. Fig. 1 provides an overview of the relevant regulations regarding the development of a smart meter test bench.

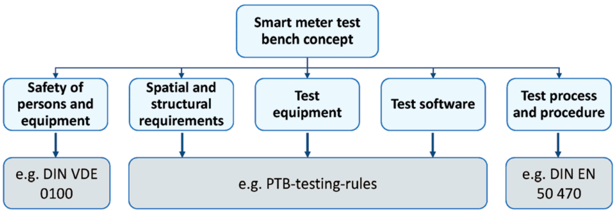


Figure 1. Overview of relevant legislation

However, not only technical calibration regulation must be observed, that deal with the structural and technical requirements. Any technical calibration regulations must always be seen in the context of occupational health and safety at work. The aim of this is to ensure a safe and accident-free execution and handling of resources.

The specific structure, content and procedures of an official calibration are described in the calibration requirements. The purpose of this is to provide a single framework for the performance of calibration processes and to define general requirements for measuring instruments.

Since the commencement of the European Measuring Instruments Directive (MID) in 2004, the German calibration laws and regulations are no longer to be considered only nationally, but in a European context. The requirements contained in these guidelines were incorporated into the German law in February 2007 due to changes to the Weights and Measures Act and the adjustment of Weights and Measures Regulations. This development is, in line with other European standards, a further standardization of measuring instruments for fair trade within the European Union.

As mentioned above, the calibration regulations do not include testing the accuracy of operational values, because these are not part of the official calibration inspection. The relevant regulations treat neither the structure nor the sequence of a functional check or verification of the measurement of operational values. Nevertheless, it is reasonable to base an electricity meter test bench concept on calibration regulations and requirements, since these regulations build a uniform basis and comparability. Furthermore, this procedure achieves, that the requirements of the existing law are transferred to the checking of operational values and therefore represent equally high standards as an electricity meter calibration inspection.

When designing the electricity meter test bench, the relevant parts of the legislation, standards and guidelines are selected in a way that the relevance and scope of testing electricity meters is justified. This includes guidelines regarding occupational safety and security, requirements of the environment, hardware and software.

## III. TEST BENCH STRUCTURE AND COMPONENTS

### *A. Testing fixture and test equipment*

The electricity meter test bench is located in the test room and consists of a table, superstructures and the testing equipment. The testing fixture is located on the table. It consists of a perforated plate being attached to two T-shaped studs. There, different samples can be fixed individually, in proper form and vibration free. On the front of the testing fixture a DIN rail with terminal blocks is applied, to simplify the wiring of the components. In addition, this provides a clear and structured arrangement of the various wires, even with different connection diagrams of the test objects. This has the aim of avoiding false wiring. Fig. 2 shows the principle wiring diagram of the smart meter test bench.

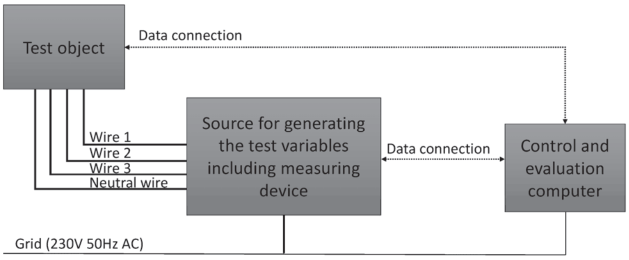


Figure 2. Wiring of smart meter test bench

The data connection between the test object and the control computer is realized by a USB to infrared read/write head (D0) according to the data structure of IEC 62056-21 and IEC 61107. The data transmission between the control computer and the reference source is a LAN connection using a Omicron manufacturer-specific protocol. In addition to the test fixture, the test equipment described below and a control computer are positioned on the table. Fig. 3 provides an overview of the components used.

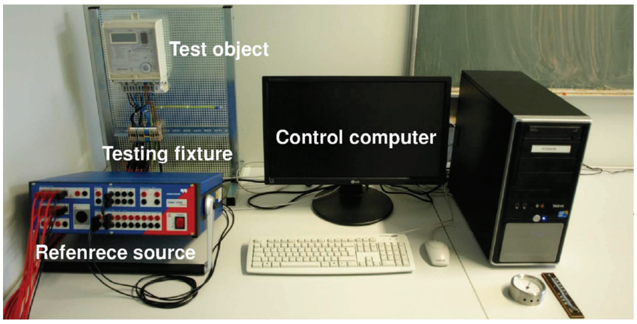


Figure 3. Setup of the smart meter test bench

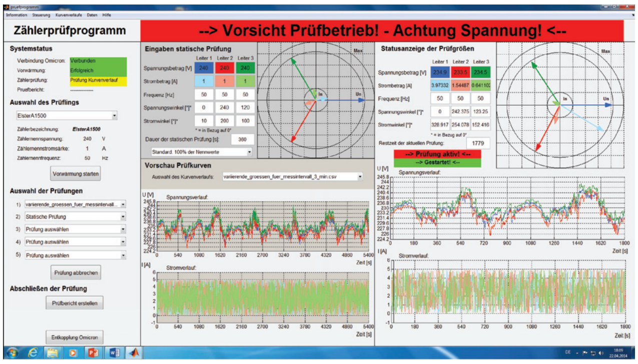
The sources for generating the test values and the necessary measuring devices are realized in the test arrangement as a single unit, the reference source. This is the fully electronic, computerized protection-test and universal calibration instrument Omicron CMC 256plus. This reference source provides a high accuracy for test applications and allows the calibration of electricity meters up to class 0.2.

For computer-controlled automatic operation of the fully electronic smart meter test bench a control computer with input and output medium is used. This is also used as a control indicator for monitoring the test parameters. Thus the test parameters and measured variables are predetermined and controlled by the measurement procedures on the computer. This general setup of the smart meter test bench and the used communication standard allows to test any electrical electricity meter using the mentioned standard.

### *B. Test software*

To be able to change settings at the reference source using the computer, a test software is necessary. This must provide functions to pass parameters and metrics on a case-specific required interface and automatically perform the test sequence, without constant manual control by the operator.

The realization of the test software was carried out in two steps. In the first step, the actual test program in MATLAB was developed and in the second step in MS Excel a tool for evaluation of the processed test data was created. As a basis for the programming of the test software, MATLAB's OpenGUI layout editor was used. With this software the graphical user interface could be built by drag and drop. Fig. 4 shows the graphical user interface.



Zählerprüfprogramm

--> Vorsicht Prüfbetrieb! - Achtung Spannung! <--

**Systemstatus**

Verbindung Omicron: Verbunden
Vorwärmung: Erfolgreich
Zählerprüfung: Prüfung Kurvenverlauf
Pruefbericht: ------------

**Auswahl des Prüflings**

ElsterA1500
Zählerbezeichnung: ElsterA1500
Zählernennspannung: 240 V
Zählernennstromsärke: 1 A
Zählernennfrequenz: 50 Hz

**Auswahl der Prüfungen**

1) variierende_groessen_fuer_messintervall...
2) Statische Prüfung
3) Prüfung auswählen
4) Prüfung auswählen
5) Prüfung auswählen

**Abschließen der Prüfung**

**Eingaben statische Prüfung**

| | Leiter 1 | Leiter 2 | Leiter 3 |
|---|---|---|---|
| Spannungsbetrag [V] | 240 | 240 | 240 |
| Strombetrag [A] | 1 | 1 | 1 |
| Frequenz [Hz] | 50 | 50 | 50 |
| Spannungswinkel [°]* | 0 | 240 | 120 |
| Stromwinkel [°]* | 10 | 200 | 100 |

* = in Bezug auf 0°

Dauer der statischen Prüfung [s]: 360
Standard: 100% der Nennwerte

**Vorschau Prüfkurven**

Auswahl des Kurvenverlaufs: variierende_groessen_fuer_messintervall_3_min.csv

**Statusanzeige der Prüfgrößen**

| | Leiter 1 | Leiter 2 | Leiter 3 |
|---|---|---|---|
| Spannungsbetrag [V] | 234.9 | 233.5 | 234.5 |
| Strombetrag [A] | 3.97332 | 1.54487 | 0.64110 |
| Frequenz [Hz] | 50 | 50 | 50 |
| Spannungswinkel [°]* | 0 | 242.375 | 123.25 |
| Stromwinkel [°]* | 328.917 | 254.078 | 152.416 |

* = in Bezug auf 0°

Restzeit der aktuellen Prüfung: 1779

--> Prüfung aktiv! <--
--> Gestartet! <--

Figure 4. Grapical user interface

### *C. Test Object*

The examined test device is a smart meter from the Elster Messtechnik GmbH. The model used is the "alpha Zähler A1500" with the accuracy class 1. The nominal voltage of the smart meter is 3 x 240 V and the nominal current is 1 A. The limiting current of the electricity meter is 5 A. In addition to the energy measurement, the device is capable of both load profiles as well as operational value acquisition. The measurement interval for load profile memory and operational value measurement can be varied between one and 60 minutes. In the load memory positive reactive and active power are stored. Maximum, minimum and average values can be recorded for the following measured parameters: apparent power, active power, reactive power, current and voltage angle, voltage and current magnitude, power factor and harmonics. The parameterization of the smart meter is done by using the software "alphaSET". To control external devices, the smart meter uses a measurement period output, which can adjust the measurement period and starting time of the examination. To submit parameterization and measurement data, the Elster A1500 uses an optical interface.

## IV. TESTING PROCESS

### A. *Procedures of testing process*

The test procedures describe the steps that are necessary to perform the audit of the smart meter on the test bench. The testing process can be split into three main steps:

1. Preparation
2. Examination
3. Documentation

The different parts of the preparation are the incorporation into the components used as well as the test software, an external quality review of the test object and the installation and wiring of the components on the test bench. This is followed by the actual main part of the study, the examination. This includes a system test, the preheating of the components and the metrological testing of the object. During the metrological testing the accuracy of smart meters is verified. Since there are no specific requirements for the metrological examination of operational values, three tests are described below, which can be used together to verify the accuracy of the operational value measurement.

- *Static test:* This is used in particular for the determination of systematic measurement errors. During the static test, static test variables are passed from the reference source to the test object for a specific time, predefined by the examiner. The comparison of the predetermined and the measured data of the device during the test results in the static deviation of the different measured variables.
- *Test with variable test values:* This test is intended for detecting errors in the averaging of smart meter measurements. The different variable test parameters are specified via a predefined period as a whole by the test program. During this test period, the test values fluctuate within a predefined range around a core value. The change from one set to the next value takes place at fixed time intervals until the end of the total period is reached.
- *Default arbitrary and real test-curves:* This test can also be used to determine errors in the averaging of the smart meters. Here, the testing periods and test values are specified manually by the user or in the form of a real measurement series. Those are passed through the reference source to the test object in accordance to the test with variable test values over the defined period.

This structure of the tests makes it possible to examine both different predefined scenarios, as well as individual adjustments and checks. Manual entries and also predefined data tables are checked and verified by the test software before starting the test sequence. Therefore technical limitations of the test equipment and the test object have to be taken into account. During the examination the current operating status of the test program is always shown by the test software.

After the metrological testing the documentation of the testing process follows. Here, the predetermined and measured data are processed and evaluated. Based on the differences between the predefined test values and the measurements, the measurement accuracy as well as conceptual and design-related errors in the measurements can be determined. These results and the used data are aggregated and documented in the test report.

### B. *Test values, metrics and measurement interval times*

The relevant test values in this work include test voltage, test current, voltage angle, current angle and frequency. These are delivered by the test hardware and recorded in the smart meter as measured variables. As measurement values the following values are recorded by the smart meter: voltage and current levels, voltage and current angle, frequency, active, reactive and apparent power. For comparison of the measurement accuracy of different measuring intervals, the measurement intervals (MI) 1, 3, 5 and 15 minutes were used for different test value combinations.

In order to ensure a sufficient validity of the results, a requirement of 99% was given to the confidence level (z-value = 2.57), which corresponds approximately to the Six Sigma criterion of 99.7%. The required accuracy is 0.1%. Together with the empirically determined standard deviation of 0.065% from the mean, this results in a sample size of three measurements. Since this is too small to assume a normal distribution, the sample size was increased up to 30.

### C. *Specifications*

In the static test, the test parameters shown in Tab. 1 were examined.

TABLE I. SPECIFICATIONS OF STATIC TEST

| Test parameter | Wire L1 | Wire L2 | Wire L3 |
|---|---|---|---|
| Voltage value [V] | 240 | 240 | 240 |
| Current value [A] | 1 | 1 | 1 |
| Voltage angle [°] | 0 | 240 | 120 |
| Current angle [°] | 45 | 285 | 165 |
| Frequency [Hz] | 50 | | |

A further test of the averaging of the smart meter was made in the second step by using varying test parameters on the basis of a real voltage curve. All other test parameters were generated randomly within limits shown by Tab. 2.

TABLE II. LIMITS OF RANDOM GENERATED TEST VALUES

| Test parameter | Minimum | Maximum |
|---|---|---|
| Current value [A] | 0 | 5 |
| Change of Voltage angle [°] | -10 | +10 |
| Change of current angle [°] | -45 | +45 |
| Frequency [Hz] | 0 | 0 |

The interval of the specified test parameters, send to the test object, was two seconds per value. Due to the varying test parameters in the measurement period, it is possible to analyze the mean value of the test sample and the effects of varying sizes on the accuracy of the average value in more detail.

## V. RESULTS

### A. Examination with static predefined values

The evaluation of the plausibility check shows that each first value of a series of measurements deviates from the other values. All other measurements scatter with very low standard deviation around the respective actual value. This suggests a systematic error. Furthermore the plausibility check shows that the measured values of the voltage angle in phase L1 differ strongly scattering from the actual values. The other measured values have deviations, which are far below the specified smart meter margin of error (0.5%) [5]. This is the case for all four MI times. The distribution of the deviations of the measured values corresponds approximately to a normal distribution. This shows an example Fig. 5, which reflects the distribution of the measured deviations of the voltage measurement.

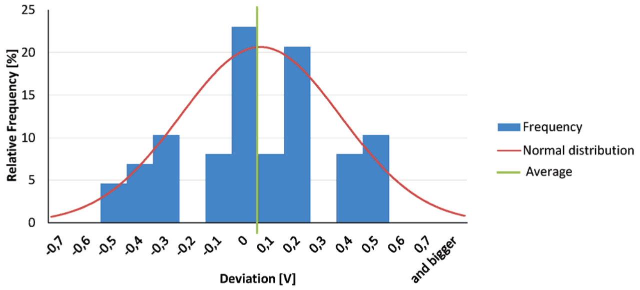


Figure 5. Deviations from the true value of the voltage magnitudes (MI = 1 min)

### B. Examination with time variant values

The results of the examination of varying sizes show that the maximum absolute deviations and the standard deviations are much larger compared to the results of the static test. The deviations of the mean values exceed the manufacturer's specified accuracy. For all MI lengths and metrics the deviations are higher than during the static test. Still, the deviations are smaller, the longer the MI length is chosen. The variations within the series of measurements reveal no trend. However, it is noticeable that the measured values fluctuate greatly. Despite major differences, still a normal distribution is recognizable (Fig. 6). In addition, both the maximum absolute deviation and the standard deviations, decrease with increasing length of the measuring interval.

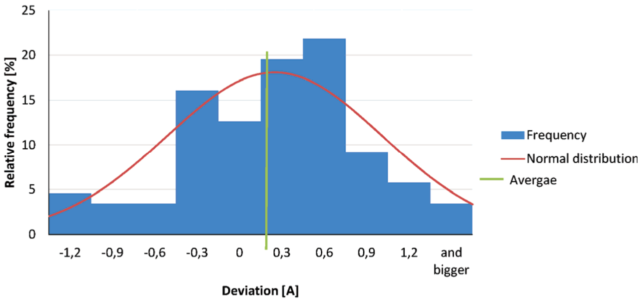


Figure 6. Deviations from the true value of the current magnitudes (MI = 1 min)

### C. Error Determination

#### 1) Nonconformity of the first measured value

The data of the static test show, that the first measured values do not match the expected values. However, since the test period and measurement period are synchronized by the measurement period output, it should not lead to a deviation of the measured values out of tolerance. A possible cause for the still existing deviation could be a time delay between detection of the values and the actual measurement period assignment. This corroborated the fact that according to the product description of the counter, the time for detecting and calculating operational values is approximately eight seconds. Through to variation of MI length, a negative correlation between MI length and deviation can be observed. By enhancing MI length, the number of mismatched sizes compared to the total number of measurement points of a MI decreases. Although this finding explains the deviation of the first mean value and the deviation in the examination of a rectangular course, but not the strong fluctuations in repeated measurements with the same test value.

#### 2) Varying deviation when testing the same signals

The deviation of the first value can be explained by the measured value shift described above. All other measurements should show the same values, due to the period synchronization. But still, repeated tests with the same parameters and values show significant variations between the averages for all the different measured operation variables.

The averaging shows a shift to later measurement intervals. The shifted part corresponds, on average, to the difference between the measured value and the test value of the previous period. Fig. 7 illustrates this correlation.

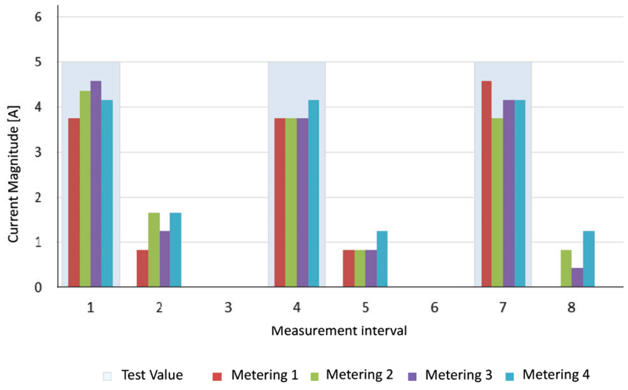


Figure 7. Current magnitude comparison of test value and measurements (MI = 1 min)

Because the results in the context of the static test showed a very high accuracy and measurement periods are clocked synchronously, a varying detection and calculation time of the measurements seems to be most likely. As a result of differences in the time shift, the number of readings per MI is not constant (Fig. 8). This leads not only to the general shift of the individual readings, but also to an additional misclassification.

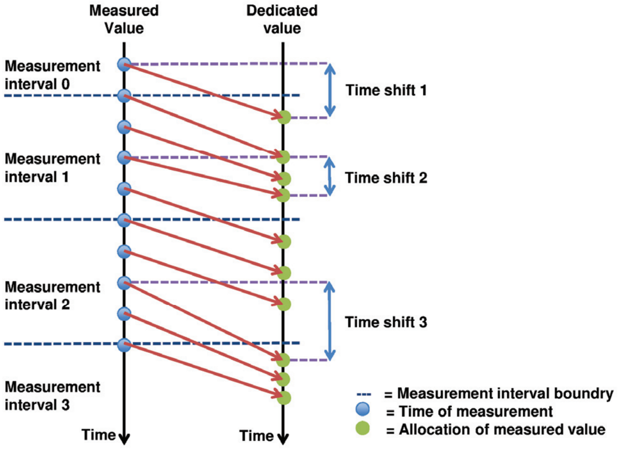


Figure 8. Assignment of the measured variables to measurement intervals (varying shift)

## VI. CONCLUSION AND OUTLOOK

Within this paper a concept of a smart meter test bench to verify the accuracy of smart meters was developed. Based on this concept, the test bench was build, commissioned and the Smart Meters Elster A1500 was tested.

The concept development showed that no direct regulations for verifying the accuracy of smart meters exist. However, it was still possible to develop a complete smart meter test bench concept based on legal regulations, industry standards and occupational health and safety regulations. Detailed specifications for construction, commissioning and safety were mostly taken from the existing rules. For the definition of the test sequence and test mechanisms, however almost no specifications could be found. The test procedure was therefore derived in strong accordance with the official calibration test. The tests, or testing mechanisms were designed on the basis of operational values and further developed by new findings. The resulting concept and its structure are therefore generally able to verify the accuracy of all measurable smart meters parameters by predefined and customizable tests.

The review of the operational value measurement of the Smart Meter Elster A1500 showed two main errors. Firstly the angle measurement leads to erroneous results due to the arithmetic averaging. Thus this smart meter cannot be for angle measurement in network operation. Secondly a wrong allocation of some measured values happens due to the recording and processing time of individual measured values. The consequence is an incorrect averaging. This effect is amplified by a non-constant length of the recording and processing and the resulting displacement. Smaller measurement interval increases the effect of displacement and hence the measurement error grows. The same applies to the change frequency of the measured quantities. The stronger and faster the values change, the greater are the deviations.

For the practical use of the Elster A1500 in terms of operational value measurement, this leads to an optimization problem. Firstly, the measuring interval must be kept short, so that the real average value is closest to the measured values. On the other hand the deviation from the smart meter is greater, the shorter the measured interval is. To optimize this problem, the smart meter should be checked with real curves for all measurements in order to develop an optimal measurement period. For a final statement about the accuracy of the smart meter reviewed in this work, further measurements under real conditions are required. The main question to be answered is, how quickly and how widely different values change in reality.

Summarizing, the main goal, to construct and commission a specific test bench for the verification of operating variables, was accomplished. Furthermore the test of a specific smart meter has shown many errors in its operating value measurement. Based on those results, in further studies, primarily the following three points should be examined in further research. First, operational values have to be recorded by precise measurement units under reals conditions for different scenarios. These have to be examined according to the change rate in amount and time interval of the fluctuations. Second, the findings and the discoveries shall be placed on the creation of test scenarios. Third, more smart meters have to be tested for comparison, both with the previously designed and with the newly developed test scenarios in order to identify more or similar errors and to solve the optimization problem.

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