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METROLOGICAL ASSURANCE OF ELECTRICAL ENERGY METERING: ACCURACY CLASSES, VERIFICATION, AND THE HARMONIZATION OF NATIONAL AND INTERNATIONAL STANDARDS

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Abstract. The reliability of commercial electrical energy accounting is determined directly by the metrological characteristics of the measuring instruments employed and by the adequacy of the verification and calibration procedures applied to them. This article examines the metrological assurance of electrical energy metering, with particular attention to the system of accuracy classes, the structure of metering errors, and the harmonization of national regulatory documents with international standards. The normative framework established by IEC 62052-11 and the IEC 62053 series, by OIML R 46, and by the corresponding interstate standards GOST 31818.11 and GOST 31819.21–23 is analysed alongside the metrological infrastructure of the Republic of Uzbekistan, which is administered by the Uzbek National Institute of Metrology. The combined error of a transformer-operated metering unit is decomposed into the contributions of the static meter, the current transformer, and the voltage transformer, and the dominant influence of operation at reduced load and low power factor is demonstrated analytically. It is shown that the systematic replacement of low-accuracy induction meters by static meters of accuracy classes 0.5S and 0.2S, supported by a traceable verification system, constitutes the principal instrument for reducing commercial losses. Practical recommendations for strengthening metrological control are formulated.

Keywords: metrology; electrical energy metering; accuracy class; measurement uncertainty; verification; instrument transformers; standardization.

Introduction

Electrical energy is among the most extensively traded physical quantities, and its amount in any commercial transaction is established solely by measurement. The economic relationships between generators, network operators, and consumers therefore rest entirely on the metrological soundness of the metering equipment installed at every accounting point. A measurement error does not remain a purely technical quantity: systematic under-registration is recorded by the utility as a commercial loss, whereas over-registration is borne unjustly by the consumer. For this reason the metrological assurance of electrical energy metering — the totality of standards, measuring instruments, verification procedures, and traceability arrangements that guarantee the accuracy of the measured value — constitutes a problem of both engineering and economic significance.

In the Republic of Uzbekistan the practical scale of the problem is substantial. As of 1 January 2025 the number of registered electricity consumers exceeded 8.3 million, and during 2024 the regional networks delivered approximately 64.8 billion kWh of electrical energy to end users. Technical losses in distribution were estimated at about 13 % in 2024, a figure aggravated by the fact that more than half of the distribution facilities have been in service for over thirty years. In response, large-scale modernization has been undertaken with the support of international financial institutions: approximately 1.4 million smart meters have been installed in the Bukhara, Jizzakh, and Samarkand regions, and a further programme provides for the connection of 150,000 smart meters together with 4,000 data concentrators. Within these programmes the accuracy and verifiability of metering are treated as central instruments of loss reduction rather than as secondary technical details.

At the international level the relevance of the subject has been reinforced by the transition to smart grids, the large-scale integration of renewable generation, and the proliferation of non-linear loads. These developments distort the current and voltage waveforms encountered by meters and instrument transformers, thereby challenging the simplified, near-sinusoidal assumptions on which classical accuracy testing was founded. The present article examines the metrological assurance of electrical energy metering, with emphasis on the system of accuracy classes, the decomposition of metering errors, the verification and traceability framework, and the harmonization of the national normative base of Uzbekistan with the relevant international standards; on this basis, practical recommendations for strengthening metrological control are formulated.

Literature Review

The contemporary normative framework for alternating-current electricity meters is defined principally by the International Electrotechnical Commission. The general requirements, tests, and test conditions are consolidated in IEC 62052-11:2020, while the accuracy-class-specific requirements are distributed across the IEC 62053 series: static meters for active energy of classes 0.5, 1, and 2 are covered by IEC 62053-21:2020, and the more accurate transformer-operated meters of classes 0.1S, 0.2S, and 0.5S by IEC 62053-22:2020. In the 2020 revision the descriptions of general requirements and test methods were moved into IEC 62052-11, so that the individual parts now contain only class-specific provisions. In legal metrology the corresponding instrument is OIML R 46, which establishes internationally recommended requirements for active-energy meters. The interstate standards GOST 31818.11-2012 and GOST 31819.21–23-2012 are modified adoptions of the IEC documents and form the basis of the national normative base applied across the region, including Uzbekistan.

Recent research has drawn attention to the limitations of the prevailing verification practice. Bracale, Janowicz, Kuwałek, and Wiczyński (2026) demonstrate that smart energy meters are typically verified under idealized conditions, or with simplified signal models, that do not reproduce the disturbed states actually occurring in modern power grids. In laboratory tests of meters from several manufacturers, although all units formally complied with the applicable standards, significant discrepancies were observed in the measurement of power-quality indicators relative to a reference class-A instrument. The authors conclude that a new verification procedure, based on realistic yet analytically defined test signals, is required to ensure the reliability of measurements under real operating conditions.

A complementary line of investigation concerns the instrument transformers through which high- and medium-voltage energy is measured. van den Brom (2022) observes that, at medium-voltage levels, measurement is possible only by means of current and voltage transformers, yet no

international standard currently requires the verification of the errors these transformers introduce into power-quality measurements; the study proposes a set of accuracy-verification tests for instrument transformers and validates the procedure on commercial voltage transformers. Taken together with the literature on the influence of reduced load and non-sinusoidal currents on transformer accuracy, this work indicates that the instrument transformers, rather than the meter itself, frequently dominate the uncertainty budget of a transformer-connected metering point.

At the regional level, the modernization programmes documented by the World Bank (2025) and the Asian Development Bank frame metrological assurance as a principal mechanism for reducing commercial losses and improving the financial sustainability of network operators. The literature thus converges on two themes: the international accuracy-class framework provides a sound basis for procurement and type testing, but its effectiveness depends on a rigorous national verification and traceability system, and on the recognition that real operating conditions — light loading, low power factor, and waveform distortion — may degrade accuracy well beyond the limits assumed at type test. The present study addresses this intersection by quantifying the combined-error budget of a transformer-connected metering unit and relating it to the verification practice of the Republic of Uzbekistan.

Methodology

The study employs an analytical, standards-based method comprising two elements: a normative analysis of the international and national documents governing electricity metering, and an error-budget model of the transformer-connected metering unit. The documents consulted include IEC 62052-11:2020, IEC 62053-21:2020 and 62053-22:2020, OIML R 46, ISO/IEC 17025:2017, the Guide to the Expression of Uncertainty in Measurement (JCGM 100:2008), and the interstate standards GOST 31818.11-2012, GOST 31819.21–23-2012, and GOST 7746 for current transformers.

The quantity measured is the active electrical energy consumed over a billing interval T, defined as the time integral of the instantaneous power:

$$W = \int p(t)\,dt = \int u(t)\cdot i(t)\,dt \qquad (1)$$

For metering at medium and high voltage the meter is connected through instrument transformers, so that the registered energy is referred to the primary side by the nominal transformation ratios:

$$W = K_U \cdot K_I \cdot W_s \qquad (2)$$

where K_U and K_I denote the rated ratios of the voltage and current transformers and W_s is the energy registered on the secondary side.

An accuracy class designates the limit, expressed as a percentage, of the permissible relative error of an instrument under specified reference conditions. The combined relative error of a transformer-connected active-energy metering channel may be expressed as the sum of the meter and transformer contributions:

$$\delta_\Sigma = \delta_M + f_I + f_U + (\delta_I - \delta_U)\cdot\tan\varphi \qquad (3)$$

in which δ_M is the intrinsic error of the meter, f_I and f_U are the current and voltage ratio (magnitude) errors of the transformers, δ_I and δ_U are their phase displacements expressed in radians, and φ is the phase angle of the load. Equation (3) exhibits the essential metrological feature of transformer-connected metering: the ratio errors add algebraically, whereas the contribution of the phase displacements is proportional to $\tan\varphi$ and therefore grows rapidly as the power factor decreases.

Two distinct procedures maintain the accuracy of a measuring instrument in service. Verification establishes, within the legal-metrology framework, whether an instrument conforms to its accuracy class; calibration determines the relationship between the indicated and the true value together with the associated uncertainty. Both rely on metrological traceability: the working meter is compared with a reference standard, which is itself traceable — through the national primary standards maintained by the Uzbek National Institute of Metrology — to the units of the International System (SI). The interval between successive verifications, the inter-verification interval, is established at type approval and typically ranges from eight to sixteen years for static billing meters. The competence of the laboratories performing these operations is assessed against ISO/IEC 17025:2017, and the uncertainty of the result is evaluated according to the Guide to the Expression of Uncertainty in Measurement, combining the individual components in quadrature:

$$u_c = \sqrt{(u_M^2 + u_I^2 + u_U^2 + \dots)} \qquad U = k \cdot u_c \quad (k = 2) \qquad (4)$$

where u_c is the combined standard uncertainty and U the expanded uncertainty for a coverage factor k = 2, corresponding to a level of confidence of approximately 95 %.

Results and Discussion

Table 1 summarizes selected limits of permissible error for the principal accuracy classes of static active-energy meters, as defined by the IEC 62053 series and the corresponding GOST documents. Two features are of practical importance. First, the permissible error widens substantially at low current: a class 0.5S meter is permitted ±0.5 % in the upper part of its range but ±1.0 % between 1 % and 5 % of rated current. Second, the transformer-operated S classes extend accurate measurement down to 1 % of rated current, whereas the ordinary classes are specified only from 5 %.

Table 1. Selected limits of permissible error of static active-energy meters.

Accuracy class	Reference standard	MPE at rated current, PF = 1	MPE at low current, PF = 1	Typical application
0.2S	IEC 62053-22 / GOST 31819.22	±0.2 %	±0.4 %	Wholesale / boundary metering
0.5S	IEC 62053-22 / GOST 31819.22	±0.5 %	±1.0 %	Industrial / transformer-connected
1	IEC 62053-21 / GOST 31819.21	±1.0 %	±1.5 %	Residential / small commercial
2	IEC 62053-21 / GOST 31819.21	±2.0 %	±2.5 %	Legacy (being phased out)

MPE — maximum permissible error; I_n — rated current. Low-current band: 1–5 % of I_n for classes 0.2S and 0.5S, and 5–10 % of I_n for classes 1 and 2. Values are referred to a balanced load.

The aggregate accuracy of a metering point, however, is governed not by the meter alone but by the complete channel described in Equation (3). Table 2 presents an illustrative worst-case error budget for a transformer-connected unit comprising a class 0.5S meter, a class 0.5S current transformer, and a class 0.5 voltage transformer. At rated current and unity power factor the phase-displacement term vanishes and the worst-case arithmetic sum of errors is ±1.5 %. At a power factor of 0.5 the same components yield a worst-case combined error of about ±3.0 %, the additional contribution arising entirely from the phase-displacement term. The phase displacements in Table 2 are taken at the rated-current class limits; under light loading, at approximately 5 % of rated current, the permissible phase error of the current transformer widens and the combined error at low power factor increases accordingly. In practice the individual errors partially compensate, so that the quadratic (root-sum-square) combination gives a smaller typical value; nevertheless, the worst-case bound is the quantity that governs metrological risk and contractual exposure.

Table 2. Illustrative worst-case error budget of a transformer-connected metering unit.

Error component	Accuracy class	At PF = 1.0	At PF = 0.5 (ind.)
Static meter (δ_M)	0.5S	±0.5 %	±0.5 %
CT ratio error (f_I)	0.5S	±0.5 %	±0.5 %
VT ratio error (f_U)	0.5	±0.5 %	±0.5 %
Phase term ($\delta_I - \delta_U$)·tan φ	—	0	±1.5 %
Combined error (worst-case sum)	—	**±1.5 %**	**±3.0 %**

Phase displacements taken at rated-current class limits (CT ≈ ±10′, VT ≈ ±20′); at light load the CT phase-error limit widens and the PF = 0.5 figure increases further. Individual errors partly compensate in practice, but the worst-case sum bounds the metrological risk.

The replacement of legacy induction meters by static meters yields a direct metrological benefit. Substituting a class 2 induction meter with a class 0.5S static meter reduces the permissible error at rated load fourfold, and the improvement is greater still at low load, where induction mechanisms exhibit pronounced friction and starting-current effects. The economic weight of these figures is considerable. For a system delivering 64.8 billion kWh per year, a systematic under-registration of only 0.5 % corresponds to approximately 324 GWh of energy that is delivered but not billed; a 1 % bias corresponds to about 648 GWh. A substantial part of what is recorded as commercial loss is therefore metrological in origin and can be addressed by improving the accuracy class and verification of the metering park rather than by field inspection alone.

A frequent and often overlooked source of such metrological under-registration is the systematic over-sizing of current transformers on lightly loaded feeders. When the operating current falls to a few percent of the transformer rated value, both the ratio and the phase errors increase markedly, as reflected in the widened low-current limits of Table 1, and the metering point delivers a systematically low reading. This effect is properly classified as a metrological deficiency of the measurement channel and is best remedied by matching the transformer rating to the actual load and by selecting S accuracy classes.

The progressive deployment of advanced metering infrastructure in Uzbekistan introduces remote reading, time-of-use tariffs, and tamper detection, and it materially reduces the commercial

losses associated with manual reading and estimation. The metrological caveats identified in the literature nevertheless remain pertinent. The findings of Bracale et al. (2026) and van den Brom (2022) indicate that compliance with type-test requirements does not by itself guarantee accurate measurement under the distorted, lightly loaded, and low-power-factor conditions characteristic of modern networks. Verification practice should accordingly evolve from purely laboratory type testing toward periodic confirmation of the accuracy of installed metering channels, including the instrument transformers, under representative operating conditions.

From the institutional perspective, the metrological assurance of metering in Uzbekistan rests on the type approval of measuring instruments and their entry in the State Register, on periodic verification administered through the Uzbek National Institute of Metrology, and on the accreditation of testing and calibration laboratories. The adoption of the GOST 31818.11 and 31819 series as modified versions of IEC 62052/62053 facilitates the procurement of compliant class 0.5S and 0.2S meters and aligns national practice with international expectations. Continued harmonization with the current 2020 editions of the IEC documents and with OIML R 46 is therefore a logical direction of development.

Conclusions

The accuracy of commercial electrical energy metering is determined by the complete measurement channel — meter and instrument transformers — and by the verification and traceability system that maintains its accuracy in service. The analysis has shown that the contribution of instrument transformers, and in particular the phase-displacement term proportional to tan φ, may dominate the error budget of a transformer-connected metering point, and that operation at light load and low power factor degrades accuracy well beyond the meter nominal class. Given the scale of energy delivered in Uzbekistan, even a fraction of a percent of systematic bias represents hundreds of GWh annually, so that a measurable part of commercial loss is metrological in nature and amenable to correction through improved metering. On the basis of the analysis, the following recommendations are formulated:

1. Standardize on static meters of accuracy class 0.5S for industrial and transformer-connected points and 0.2S for boundary and wholesale metering, and progressively withdraw induction meters of class 2 and below.
2. Match the accuracy class of the current and voltage transformers to that of the meter (a class 0.5S meter requires at least a class 0.5S current transformer and a class 0.5 voltage transformer), and avoid over-sizing transformers so that the operating current remains above 5–20 % of the rated value.
3. Maintain traceable verification through the Uzbek National Institute of Metrology, enforce the inter-verification intervals defined at type approval, and accredit utility laboratories to ISO/IEC 17025:2017.
4. Supplement laboratory type testing with periodic confirmation of the accuracy of installed metering channels — including the instrument transformers — under representative operating conditions, consistent with the requirements of modern, distorted networks.
5. Continue to harmonize the national normative base (GOST 31818.11, the GOST 31819 series, and national O‘z DSt documents) with the current 2020 editions of IEC 62052 and 62053 and with OIML R 46.
6. Construct uncertainty budgets in accordance with the Guide to the Expression of Uncertainty in Measurement for all boundary metering points, and treat metrological under-registration as a distinct, addressable component of commercial loss.

Implementing these measures would strengthen the metrological reliability of electrical energy accounting and convert a recognized source of commercial loss into a controllable engineering parameter.

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