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K₂U-NODE: DESIGN AND VALIDATION METHODOLOGY OF AN OPEN-SOURCE TWO-GENERATION DEVICE FOR THREE-PHASE VOLTAGE-UNBALANCE MONITORING



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Abstract. This article presents the design and validation methodology of the open-source two-generation K₂U-Node device intended for voltage-unbalance monitoring in three-phase electrical networks. The theoretical limitations of determining the negative-sequence voltage unbalance factor (K_2U) using only phase-voltage RMS magnitudes are analyzed. The Gen-1 device, based on an ESP32 and three PZEM-004T v3.0 modules, is proposed for preliminary screening and distributed monitoring of voltage unbalance. The Gen-2 device, based on the ATM90E32AS metering IC, measures both voltage magnitudes and phase angles, enabling calculation of the complex symmetrical components and the K_2U factor. Numerical examples demonstrate that angular unbalance can produce a significant K_2U value even when all phase-voltage magnitudes are equal. A three-stage calibration and validation methodology is proposed, together with 10-minute aggregation of measurement results in accordance with GOST 32144-2013 and IEC 61000-4-30 requirements. The proposed solution provides a promising basis for multi-point power-quality monitoring, identification of voltage-unbalance sources, and technical assessment of distributed energy facilities.

Keywords: voltage unbalance, negative-sequence voltage unbalance factor, K_2U , three-phase electrical network, ESP32, PZEM-004T, ATM90E32AS, symmetrical components, power quality, open-source device, monitoring, GOST 32144-2013, IEC 61000-4-30.

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K₂U-NODE: ПРОЕКТИРОВАНИЕ И МЕТОДИКА ВАЛИДАЦИИ ДВУХПОКОЛЕННОГО УСТРОЙСТВА С ОТКРЫТЫМ ИСХОДНЫМ КОДОМ ДЛЯ МОНИТОРИНГА НЕСИММЕТРИИ ТРЁХФАЗНЫХ НАПРЯЖЕНИЙ

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Аннотация. В статье представлена методика разработки и валидации двухполюсного устройства с открытым исходным кодом K2U-Node, предназначенного для мониторинга несимметрии напряжений в трёхфазных электрических сетях. Проанализированы теоретические ограничения определения коэффициента несимметрии напряжений по обратной последовательности (K_2U) только по действующим значениям фазных напряжений. Устройство Gen-1 на базе ESP32 и трёх модулей PZEM-004T v3.0 предложено для предварительного скрининга и распределённого мониторинга несимметрии напряжений. В устройстве Gen-2 на базе микросхемы ATM90E32AS реализовано измерение амплитуд и фазовых углов напряжений, позволяющее вычислять комплексные симметричные составляющие и коэффициент K_2U . Расчётные примеры показывают, что даже при одинаковых амплитудах фазных напряжений угловая несимметрия может приводить к значительному значению K_2U . Разработана трёхэтапная методика калибровки и валидации устройства, а также реализованы принципы 10-минутного агрегирования результатов измерений в соответствии с требованиями ГОСТ 32144-2013 и IEC 61000-4-30. Предлагаемое решение является перспективным для многоточечного мониторинга качества электроэнергии, выявления источников несимметрии и оценки технического состояния объектов распределённой энергетики.

Ключевые слова: несимметрия напряжений, коэффициент обратной последовательности, K_2U , трёхфазная электрическая сеть, ESP32, PZEM-004T, ATM90E32AS, симметричные составляющие, качество электроэнергии, устройство с открытым исходным кодом, мониторинг, ГОСТ 32144-2013, IEC 61000-4-30.

K₂U-NODE: UCH FAZALI KUCHLANISHLAR NOSIMMETRIKLIGINI MONITORING QILISH UCHUN OCHIQ KODLI IKKI AVLODDAN IBORAT QURILMANI LOYIHALASH VA VALIDATSIYA METODIKASI

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Annotatsiya. Maqolada uch fazali elektr tarmoqlarida kuchlanish nosimmetrikligini monitoring qilish uchun mo'ljallangan ochiq kodli ikki avlodli K2U-Node qurilmasini ishlab chiqish va validatsiya qilish metodikasi bayon etilgan. Kuchlanish nosimmetrikligining teskari ketma-ketlik koeffitsiyentini (K_2U) faqat faza kuchlanishlarining ta'sir etuvchi qiymatlari asosida aniqlashdagi nazariy cheklovlar tahlil qilingan. ESP32 va uchta PZEM-004T v3.0 moduli asosidagi Gen-1 qurilmasi kuchlanish nosimmetrikligini dastlabki skrining va taqsimlangan monitoring qilish uchun taklif etilgan. ATM90E32AS mikrosxemasiga asoslangan Gen-2 qurilmasida esa faza kuchlanishlarining amplitudasi va faza burchaklarini o'lchash orqali simmetrik tashkil etuvchilar hamda K_2U koeffitsiyentini kompleks shaklda hisoblash imkoniyati yaratilgan. Hisoblash misollari faza kuchlanishlari amplitudalari teng bo'lgan holatlarda ham burchak nosimmetrikligi sezilarli K_2U qiymatini yuzaga keltirishi mumkinligini ko'rsatdi. Qurilmani kalibrlash va validatsiya qilishning uch bosqichli metodikasi, shuningdek, GOST 32144-2013 va IEC 61000-4-30 talablariga muvofiq 10 daqiqalik agregatsiya tamoyillari ishlab chiqilgan. Taklif etilgan yechim elektr energiyasi sifatini ko'p nuqtali monitoring qilish, nosimmetriklik manbalarini aniqlash va taqsimlangan energetika obyektlarining texnik holatini baholash uchun istiqbolli hisoblanadi.

Kalit so'zlar: kuchlanish nosimmetrikligi, teskari ketma-ketlik koeffitsiyenti, K_2U , uch fazali elektr tarmog'i, ESP32, PZEM-004T, ATM90E32AS, simmetrik tashkil etuvchilar, elektr energiyasi sifati, ochiq kodli qurilma, monitoring, GOST 32144-2013, IEC 61000-4-30.

Introduction. An ideal three-phase power supply is characterized by three phase voltages of equal magnitude separated by exactly 120°. In practical distribution networks, however, this

condition is rarely maintained because single-phase loads and rooftop photovoltaic inverters are not distributed uniformly among the phases, while network elements may also exhibit asymmetric impedances. The standard quantitative indicator used to characterize voltage unbalance is the negative-sequence voltage unbalance factor, K_2U .

According to Fortescue's method of symmetrical components [1], any unbalanced three-phase voltage system can be uniquely decomposed into positive-sequence, negative-sequence, and zero-sequence components, denoted by U_1 , U_2 , and U_0 , respectively. The negative-sequence voltage unbalance factor is defined as

$$K_{2U} = \frac{|U_2|}{|U_1|} \times 100\% \quad (1)$$

The phase angle of the negative-sequence component can be expressed as

$$\varphi_2 = \arg(U_2), \quad (2)$$

and may provide additional information about the phase primarily associated with the unbalance.

The adverse effects of voltage unbalance on electrical equipment are well established. Since the negative-sequence impedance of rotating electrical machines and power electronic converters is considerably lower than the corresponding positive-sequence impedance, even a 2% voltage unbalance may produce a current unbalance of approximately 15-20% in induction motors. This results in increased electrical losses, additional heating, and accelerated insulation ageing [19]. Different definitions and assessment approaches for voltage unbalance were systematically reviewed by Pillay and Manyage [2]. In grid-connected photovoltaic inverters, negative-sequence voltage components may produce double-frequency ripple in the DC-link and uneven thermal loading of semiconductor devices. At telecommunication facilities, voltage unbalance may also overload individual rectifier modules and motors used in cooling systems.

Two major normative documents define the requirements for correct K_2U measurement. GOST 32144-2013 [6], which is harmonized in scope with EN 50160, establishes two limits at the point of common coupling. The 10-minute aggregated value of K_2U should not exceed 2% during at least 95% of any one-week observation period, while the maximum permissible value of 4% should not be exceeded during 100% of the observation time. The

measurement procedure is specified in GOST 30804.4.30-2013, corresponding to IEC 61000-4-30 [7]. According to these requirements, K_2U is determined from line-to-line voltages, while individual measurement results are aggregated into 10-minute values using quadratic averaging:

$$K_{2U,10min} = \sqrt{\frac{(1)}{(N) \sum_{i=1}^N K_{2U,i}^2}} \quad (3)$$

The aggregation intervals are synchronized with real-time clock boundaries so that measurements obtained from different locations remain directly comparable.

A fundamental measurement-theory limitation is particularly important when designing low-cost monitoring devices. After excluding a common phase reference, a sinusoidal three-phase voltage system has five independent degrees of freedom: three voltage magnitudes and two independent phase angles. A device that measures only the three phase-to-neutral RMS voltage magnitudes therefore observes only three scalar quantities. Consequently, two independent angular degrees of freedom remain unobserved, and K_2U cannot, in general, be uniquely identified from phase-to-neutral RMS magnitudes alone.

This limitation is structural and cannot be eliminated by calibration, filtering, or temporal averaging. For example, two three-phase systems may have identical phase-voltage magnitudes but significantly different phase angles and, consequently, different values of K_2U . The numerical example considered in this study demonstrates that identical voltage magnitudes may correspond to $K_2U=0\%$ in one case and $K_2U=5.17\%$ in another.

This result should not be confused with the finding of Ghijsselen and Van den Bossche [3], who demonstrated that three line-to-line RMS voltage magnitudes are sufficient to determine the positive- and negative-sequence magnitudes U_1 and U_2 without direct phase-angle measurements. Phase-to-neutral voltages provide additional information required primarily for determining the zero-sequence component. The practical differences between line-voltage-based and phase-voltage-based unbalance assessment were also investigated experimentally by Kim et al. [4]. Moreover, IEC 61000-4-30 explicitly notes that magnitude-only phase-voltage approaches do not account for phase-

angle displacement [7].

In real distribution feeders, the resulting estimation error is not purely random but depends on the electrical characteristics of the feeder. If a dominant single-phase load is the main source of voltage unbalance, the corresponding voltage drop is represented by a phasor aligned with the feeder impedance. A magnitude-only measurement detects only the component projected onto the supply-voltage direction. Consequently, the estimated negative-sequence component may approximately recover only the fraction

$$K_{2U,est} \approx K_{2U,true} \cos(\psi - \varphi), \quad (4)$$

Where $\psi = \arctan\left(\frac{X}{R}\right)$ is the feeder impedance angle, RR and XX are the feeder resistance and reactance, respectively, and φ is the load displacement angle.

Thus, the degree of underestimation depends directly on the feeder parameters. Hashmi et al. [5], analyzing 161 Spanish low-voltage feeders with $R/XR/X$ ratios ranging from 2.87 to 14.68, found that phase-magnitude-based metrics could provide a reasonable approximation of the actual voltage unbalance in predominantly resistive networks. This agrees with the relationship above because a small impedance angle $(\psi - \varphi)\cos(\psi - \varphi)$ to approach unity. Conversely, near distribution transformers or in networks dominated by reactance and power electronic converters, larger ψ values may cause significant underestimation.

Therefore, magnitude-only measurement should not be considered useless; rather, its validity depends on feeder parameters that the measuring instrument itself does not observe. For this reason, such measurements may be suitable for preliminary screening but cannot alone support a formal statement of compliance with power-quality standards.

This identifiability constraint divides the available measurement solutions into several practical categories and reveals a significant cost gap. Certified IEC 61000-4-30 Class A power-quality analyzers provide standards-compliant measurements with high accuracy, but their cost may reach several thousand US dollars per measurement point. Their proprietary hardware and software also limit their suitability for continuous large-scale deployment, for example, across

hundreds of telecommunication sites or small distributed-generation facilities.

Commercial IoT energy monitors are considerably less expensive and typically provide cloud connectivity, but they are mainly intended for energy metering and generic RMS monitoring and generally do not implement the GOST/IEC procedure for negative-sequence voltage unbalance assessment.

Open-source energy monitoring platforms are more closely related to the present work. The CircuitSetup Expandable 6-Channel ESP32 Energy Meter uses the same ATM90E32AS metering IC selected for the Gen-2 K_2U -Node [8,9]. Similarly, OpenEnergyMonitor has developed mature open-source energy-monitoring hardware over more than a decade [10]. However, both platforms primarily target energy accounting and conventional electrical measurements rather than the direct evaluation of complex symmetrical components.

The closest comparable development is openZmeter. Its three-phase implementation calculates symmetrical components and a voltage-unbalance index and targets IEC 61000-4-30 Class A aggregation together with EN 50160 evaluation [17,18]. The system is based on an embedded Linux platform with a dedicated acquisition front end, and its reported manufacturing cost is below USD 100.

The contribution of the present work is different. K_2U -Node implements a microcontroller-class architecture that directly accesses the voltage-phasor angle registers of a commercially available metering IC, including the required angle-zero calibration procedure. The measured phasors are then used to calculate the symmetrical components in complex form:

$$U_0 = \frac{(1)}{(3)(U_A + U_B + U_C)}, \quad (5)$$

$$U_1 = \frac{(1)}{(3)(U_A + aU_B + a^2U_C)}, \quad (6)$$

$$U_2 = \frac{(1)}{(3)(U_A + a^2U_B + aU_C)}, \quad (7)$$

where

$$a = e^{j120^\circ} = -\frac{(1)}{(2)} + \frac{j(\sqrt{3})}{(2)}. \quad (8)$$

The device subsequently evaluates K_2U according to GOST 32144-2013. At the same time, the study explicitly defines the capabilities and fundamental limitations of the lower-cost magnitude-only monitoring tier. This provides the

theoretical basis for a two-generation K_2U -Node architecture in which a large number of inexpensive screening nodes can be deployed for wide-area monitoring, while phasor-capable nodes are installed at critical measurement points requiring accurate negative-sequence assessment.

Literature Review and Methods. K_2U -Node was developed in two generations, with their respective functions defined by the identifiability limitations discussed above. Gen-1 is designed as a low-cost screening node and combines an ESP32 microcontroller with three PZEM-004T v3.0 modules to measure phase-to-neutral RMS voltage magnitudes. This configuration enables large-scale monitoring of the occurrence and temporal variation of magnitude-based voltage unbalance. However, because phase-angle information is not measured, Gen-1 cannot independently provide the information required for a formal GOST conformity assessment.

Gen-2 is a phasor-capable node based on the ATM90E32AS energy-metering IC. Unlike Gen-1, it acquires both the magnitudes and phase angles of all three phase voltages, enabling the complex symmetrical components and the actual negative-sequence voltage unbalance factor to be calculated. The two-generation concept therefore combines widespread low-cost screening with more comprehensive phasor-based measurements at critical monitoring points.

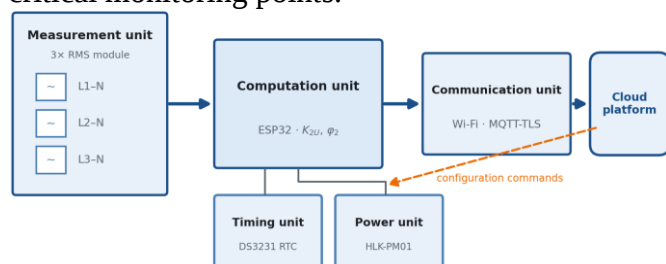


Fig.1. Five-block functional architecture shared by both node generations.

Both generations employ a common five-block functional architecture (Figure 1): (1) a galvanically isolated voltage-measurement block; (2) a processing block based on the ESP32-WROOM-32 dual-core 240 MHz microcontroller with Wi-Fi connectivity and FreeRTOS support [11]; (3) a communication block using MQTT over TLS 1.2 or later, with store-and-forward buffering and security measures based on the NISTIR 8259A

cybersecurity baseline [14]; (4) a time-synchronization block comprising a DS3231 real-time clock (RTC) supported by Network Time Protocol (NTP) synchronization; and (5) an isolated 220 V AC-to-5 V DC power-supply block.

In Gen-1, three PZEM-004T v3.0 modules—factory-calibrated to $\pm 0.5\%$ [12] and used as isolated front ends, an assumption to be confirmed by a dielectric test during the build—are connected to the three phase-to-neutral voltages L1-N, L2-N, and L3-N [12]. The module's 80–260 V input range itself dictates this connection (Figure 2), since a 380 V line-to-line tap is out of range. The modules return RMS voltage over Modbus-RTU/UART, and the ESP32 polls them by UART multiplexing, with the full three-module cycle staying under 200 ms within the 1 s measurement period. An alternative front end—three ZMPT101B transformers connected to a 16-bit ADS1115 ADC—was rejected: 860 SPS across three channels leaves about 5.7 samples per 50 Hz period, which is insufficient for phasor extraction. The PZEM route trades phase information for factory calibration, isolation, and simplicity, and is acceptable only because the node's role is limited to screening. Because the PZEMs report magnitudes only, Gen-1 reconstructs the line voltages under the nominal 120° assumption. The result is a screening estimate, exact when the unbalance is purely of the magnitude type and systematically low whenever angular unbalance is present; the firmware and telemetry schema label the output accordingly.

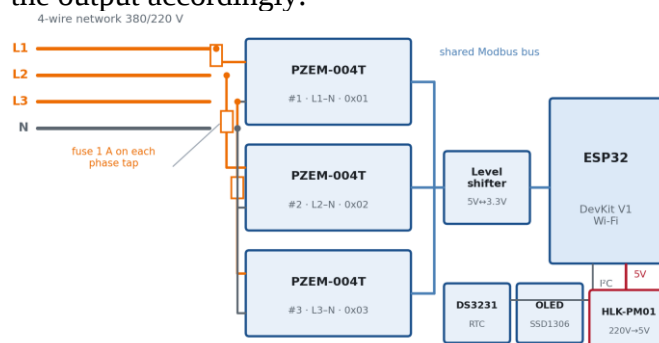


Fig.2. Wiring schematic of the Gen-1 screening node (ESP32 and three PZEM-004T v3.0 modules): RMS magnitudes only; phase angles are not measured.

The line-to-line measurement alternative warrants specific consideration because Ghijselen and Van den Bossche [3] demonstrated that three

line-to-line RMS voltage magnitudes are sufficient to determine K_2U exactly, while GOST 30804.4.30-2013 defines the measurement procedure in terms of line voltages. However, the 380 V line-to-line voltage exceeds the 80–260 V input range of the PZEM-004T v3.0 module. Therefore, a line-to-line implementation would require either a voltage divider or a small potential transformer at the input of each measurement channel. This approach would eliminate one of the main advantages of the PZEM module—its factory calibration—and introduce an additional transformation-ratio uncertainty determined by the external conditioning circuit. For example, a 0.5 % channel-ratio error may introduce an error of approximately 0.17 percentage points in K_2U . In addition, the β -based formulation becomes numerically sensitive near the balanced condition, where the difference between fourth-power voltage terms becomes small. Consequently, a line-to-line screening node is technically feasible, but it was not implemented in the present work and is not claimed as part of the proposed system. Moreover, such a configuration would still not provide the negative-sequence phase angle φ_2 , a separate estimate of the zero-sequence factor K_0U , or full per-second voltage phasors. For these reasons, Gen-2 was designed to measure phase angles directly rather than simply adding additional magnitude-measurement channels.

In Gen-2, the measurement front end is replaced by the Microchip ATM90E32AS three-phase metering IC (Figure 3). The device integrates three per-phase 16-bit sigma-delta ADC channels, supports an SPI host interface, and is specified for energy-metering applications with accuracy up to $\pm 0.5\%$ [13]. The commercially available board used in the CircuitSetup energy meter [8] provides a suitable hardware carrier for this implementation. Two implementation details were found to be particularly important. First, the ATM90E32AS provides two different groups of angle registers. The PAngle registers, located at addresses 0xF9–0xFB, represent the angle between the voltage and current of each phase, whereas the Uangle registers, located at 0xFD–0xFF, represent the phase angle of each voltage phasor relative to the internal reference. Since the symmetrical-component calculation requires voltage-phasor angles, the Uangle registers must be used.

The commonly used open-source CircuitSetup ATM90E32 library [9] and the ESPHome atm90e32 component define these register addresses, but their standard phase-angle outputs are associated with PAngle rather than Uangle. They also do not provide a dedicated high-level interface for using the voltage-phasor angles in symmetrical-component calculations. The Gen-2 firmware therefore reads the Uangle registers directly through the generic register-access interface and passes the resulting values to the symmetrical-components calculation module.

A second important issue is phase-angle calibration. According to the datasheet, the fiducial-error specification corresponds to an angular uncertainty that may reach approximately $\pm 0.9^\circ$ over a 180° scale, although the documentation does not explicitly state whether this limit applies directly to the Uangle registers. Because even a small angular error may noticeably affect the calculated voltage-unbalance factor, phase-angle offset calibration is required. During calibration, the three voltage inputs are supplied in parallel from the same transformer secondary so that the true inter-channel phase difference is nominally zero. The offsets of channels B and C relative to channel A are then recorded over a 60 s interval, averaged, stored in non-volatile memory, and subsequently subtracted from the measured phase angles during operation.

After calibration, the firmware reconstructs the three phase-voltage phasors as

$$\underline{U}_A = U_A e^{j\theta_A}, \quad (9)$$

$$\underline{U}_B = U_B e^{j\theta_B}, \quad (10)$$

$$\underline{U}_C = U_C e^{j\theta_C}. \quad (11)$$

The corresponding line-to-line phasors are obtained by complex subtraction:

$$\underline{U}_{AB} = \underline{U}_A - \underline{U}_B, \quad (12)$$

$$\underline{U}_{BC} = \underline{U}_B - \underline{U}_C, \quad (13)$$

$$\underline{U}_{CA} = \underline{U}_C - \underline{U}_A. \quad (14)$$

The positive-, negative-, and zero-sequence components are then calculated using the rotation operator $a = e^{j120^\circ}$, as

$$\underline{U}_0 = \frac{1}{3}(\underline{U}_A + \underline{U}_B + \underline{U}_C), \quad (15)$$

$$\underline{U}_1 = \frac{1}{3}(\underline{U}_A + a\underline{U}_B + a^2\underline{U}_C), \quad (16)$$

$$\underline{U}_2 = \frac{1}{3}(\underline{U}_A + a^2\underline{U}_B + a\underline{U}_C). \quad (17)$$

The voltage-unbalance factors are

subsequently determined as $K_{2U} = \frac{|U_2|}{|U_1|} \times 100\%$ and $K_{0U} = \frac{|U_0|}{|U_1|} \times 100\%$.

The negative-sequence phase angle is evaluated as $\varphi_2 = \arg(\underline{U}_2)$.

If the magnitude of $\underline{U}_2$ is too small for the phase angle to be physically meaningful, the firmware returns NaN rather than reporting an artificial value of zero.

Gen-2 is intended for autonomous monitoring campaigns lasting up to 30 days. Measurement data are stored locally on a microSD card, with files rotated daily to simplify long-term data management and recovery. Wi-Fi and MQTT communication are used mainly for status reporting, remote configuration, and supervisory access rather than as the primary data-storage path. This design choice improves robustness in rural and weak-coverage distribution networks, where continuous wireless connectivity cannot be assumed.

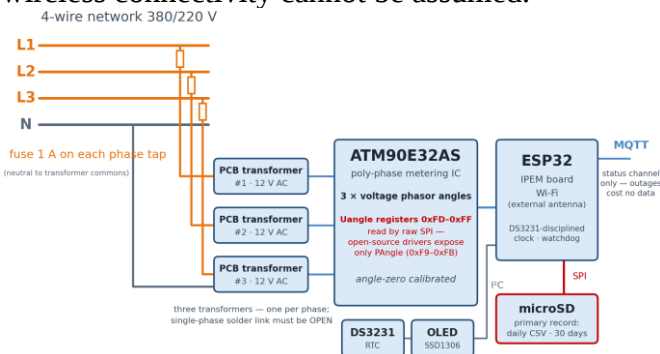


Fig.3. Wiring schematic of the Gen-2 phasor node (ATM90E32AS metering circuit, one voltage transformer per phase): all three voltage-phasor angles are measured, so true K_{2U} , K_{0U} and the negative-sequence angle are reported.

Both generations run the same four-stage processing pipeline (Figure 4), differing only in what enters Stage 3. Stage 1, acquisition at s: Gen-1 polls the PZEMs, while Gen-2 reads the ATM90E32AS magnitude and Uangle registers. Stage 2, filtering and plausibility control: frames with CRC errors are discarded, while readings outside the front end's 80–260 V window are retained and flagged rather than dropped, after the manner of IEC 61000-4-30, so that deep sags and phase loss—the states of highest unbalance, and those exercised by the test suite—are not silently

deleted from the record; each aggregate carries its valid-sample count. A 5-point sliding median filter suppresses short transients on the display and alerting path only, and is bypassed on the aggregation path, since pre-filtering the basic measurements would bias the quantity on which conformity is judged. Stage 3, K_{2U} computation: Gen-2 computes the complex symmetrical components as above, while Gen-1 applies the IEC 61000-4-30 magnitude method to the reconstructed line voltages via and, in double precision with β clamped to $[1/3, 1/2]$; the β formula is exact for true line-to-line RMS values [3], but on Gen-1's reconstructed values it is a screening estimate. Stage 4, standard aggregation: 1 s values are combined into 10-minute windows by quadratic averaging per GOST 30804.4.30-2013, with windows anchored to the RTC at minutes :00, :10 and so on; each window records mean, minimum, maximum, dwell time above the 2% and 4% limits, and its valid-sample count, while the weekly 95th-percentile evaluation runs server-side. The firmware is organised as five FreeRTOS tasks and fits within the flash and RAM of a standard ESP32-WROOM-32; the node runs from a single isolated 5 V supply.

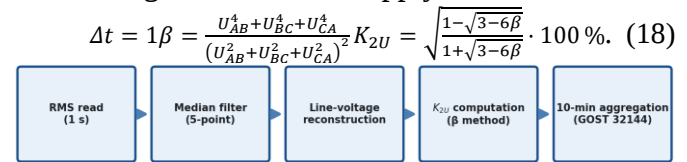


Fig.4. Four-stage processing pipeline: acquisition, filtering, K_{2U} computation and aggregation. In Gen-1, the line-voltage reconstruction assumes 120-degree spacing, which makes its K_{2U} a screening estimate.

Physically, the node is assembled in an IP₆₅ DIN-rail enclosure (about 200 × 150 × 80 mm) for installation in or beside a distribution panel, with protection and supply on the upper rail, the measurement modules and ESP32 on the middle rail, and the OLED status display on the door (Figure 5). The bill of materials comprises components common to both generations (ESP32 DevKit, HLK-PM01 supply, DS3231 RTC, SSD1306 OLED, level shifter, enclosure, MCB, fuses, glands and terminal blocks), the three PZEM-004T v3.0 modules for Gen-1, and, for Gen-2, the ATM90E32AS metering board, three 230:12 V AC

voltage transformers—one per phase, providing galvanic isolation of the voltage inputs—and the microSD subsystem. A resistive divider must not be substituted, since it would place the logic side at mains potential. A Gen-1 node totals about 74 USD at indicative single-unit prices, while a Gen-2 node is dominated by the metering board and the transformers and is correspondingly more expensive; final figures will be reported from purchase invoices. All design files—schematics, enclosure layout, both PlatformIO firmware projects, the hardware-independent symmetrical-components C module with its host test bench, and the JSON telemetry schema—are released under the MIT license at github.com/sherbaev/unbalance and github.com/sherbaev/k2u.

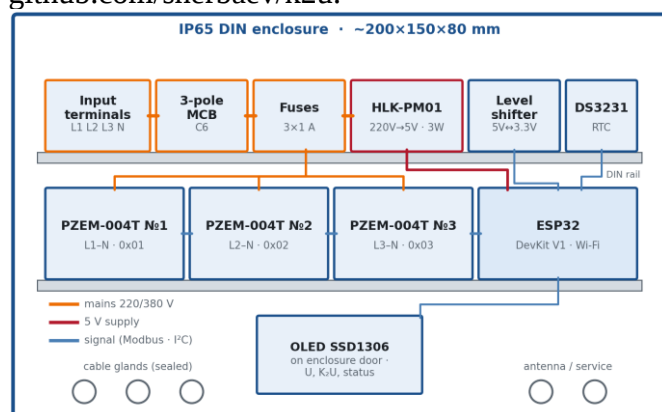


Figure 5. Component layout in the IP₆₅ DIN-rail enclosure (drawing, not to scale).

This division corresponds to the instrument classes defined by the measurement standard itself. IEC 61000-4-30 distinguishes Class A, for results that must be reproducible and contractually binding, from Class S, intended for statistical surveys over many points with a reduced parameter set and relaxed uncertainty. Gen-1 falls below Class S: it does not measure the quantity defined by the standard and is reported as an exposure indicator. Gen-2 implements the Class S computation and aggregation chain; whether it meets the Class S uncertainty requirement is what the pending characterisation must establish, and no class conformity is claimed in advance of that determination.

The system-level validation methodology has three stages, with acceptance limits fixed with the reference laboratory before the campaign; the quantitative results will be reported upon its

completion. Stage 1 compares each channel against a certified reference voltmeter at five points spanning 80–260 V, fits linear corrections (k , b) for each channel into the firmware, and records the residual error. Stage 2 produces bench unbalance states at $K_2U = 0.5, 1, 2, 3$, and 4% and records the deviation $|\Delta K_2U|$ against an IEC 61000-4-30 Class A analyzer at every set point. Stage 3 runs the node for seven days beside that analyzer on a live network and compares the paired 10-minute aggregates using the Bland–Altman method—bias and 95 % limits of agreement—rather than correlation, which measures association, not agreement, with both instruments’ windows aligned to the same clock boundaries. A methodological caveat governs Stage 2: an autotransformer bench produces only magnitude unbalance, exactly the class in which the magnitude-based method is already correct; therefore, passing this test proves nothing about angle blindness. Gen-2 must therefore also be exercised with a three-phase programmable source generating angular cases (for example, $120^\circ \pm 2^\circ$ at equal magnitudes), in which Gen-1 reads near zero by construction. Because the ATM90E32AS derives its angles from zero crossings—making them sensitive to distortion in a way that an RMS magnitude is not—the protocol also injects differential harmonics at levels permitted by GOST 32144-2013 (fifth harmonic up to 6 %, unequally distributed) and records the resulting K_2U deviation.

Results. A worked example makes the identifiability limit concrete and quantifies why the two-generation split is necessary. Set all three phase magnitudes to 220.0 V, with angles $0^\circ/-110^\circ/+125^\circ$: the complex symmetrical components yield the true $K_2U = 5.17\%$, which exceeds even the 4 % maximum limit, whereas any method based on the three phase-to-neutral RMS magnitudes returns 0.000 %, since the magnitudes are identical. A second case lies exactly at the normative boundary: 230 V on all phases at $0^\circ/-118^\circ/+118^\circ$ yields a true $K_2U \approx 2.0\%$, yet reads 0 %. To first order, a 1° angular deviation in one phase corresponds to approximately 0.58 percentage points of K_2U —a large value relative to a 2% limit.

A Monte Carlo propagation of distributions following GUM Supplement 1 [16] (200,000 random unbalanced states) separates the two error

contributions in the Gen-1 chain. Channel gain errors are drawn independently from a normal distribution whose $\pm 0.5\%$ class limit is taken as 2σ ; states are drawn uniformly over magnitude unbalance with nominal angles. Under these assumptions, the estimate is practically unbiased away from zero: the mean deviation is $+0.004$ pp, with a 95 % coverage interval of ± 0.20 pp. Near a balanced state, however, the non-negativity of K_2U produces a small positive offset. Reading the class limit instead as a rectangular distribution, the GUM default for a manufacturer's accuracy class, widens the interval to approximately ± 0.23 pp; the script and its seed are published with the firmware. Adding angular deviations of up to $\pm 2^\circ$ produces systematic underestimation. On a real feeder, this deficit is deterministic, not noise: with a dominant single-phase load, the magnitude method recovers only the fraction $\cos(\psi - \varphi)$ of the true K_2U —an acknowledged systematic effect in the sense of GUM clause 3.2.3 that must be corrected here by the Gen-2 phasor measurement, not absorbed into an uncertainty budget. This behavior is consistent with the underestimation of magnitude-based metrics reported for LV networks by Hashmi et al. [5].

The symmetrical-components module is hardware-independent and was checked on the host against a complex-arithmetic reference over seven cases: pure magnitude unbalance, pure angular unbalance, combined cases, and complete phase loss. Two arithmetic paths must be distinguished. The double-precision implementation of the shared K_2U core reproduces the reference to [value not provided], whereas the node-side C module computes in single precision to match the ESP32 floating-point unit and agrees with the same reference to within [value not provided] percentage points of K_2U over those cases. Both are round-off effects, six orders of magnitude below the 2% limit; therefore, the implementation introduces no error of practical significance. This constitutes a numerical verification of the computation chain, not a metrological validation, and no statement about measurement accuracy follows from it. The test bench is included in the repository and runs in CI. Six functional scenarios verify system behavior against stated criteria: normal operation (telemetry freshness ≤ 30 s), unbalance $\geq 2\%$ and $\geq 4\%$ (advisory within 15 s), a 30-minute Wi-Fi outage

(aggregate loss $\leq 0.1\%$ via store-and-forward), broker failure (recovery ≤ 2 min), and power interruption (restart with time resynchronization ≤ 60 s). These advisories act on instantaneous values and are deliberately distinct from a GOST assessment, whose normative test is the weekly 95th percentile of 10-minute values. $2.3 \cdot 10^{-13} 2.9 \cdot 10^{-6}$

Discussion. Several limitations bound the present results. First, Gen-1 is not compliance-capable by design: its outputs are labelled as screening data, and no conformity statement under GOST 32144-2013 may be based on them. Second, the key validation values are pending: the voltage residual error, the K_2U deviation against the Class A analyzer, and the 7-day agreement will be reported when the laboratory and field campaigns are complete, with the calibration protocols published alongside. Third, the work is at the single-prototype stage: one unit of each generation has been built and operated on a bench, while unit-to-unit spread, long-term drift, and the temperature behavior of the ATM90E32AS angle channels remain to be characterized on a small batch. Fourth, the cost comparison rests on component list prices, will be finalized from purchase invoices, and covers hardware only. Fifth, the angle accuracy bound is inferred from a fiducial-error specification whose applicability to the U_{angle} registers is not stated; angle-zero calibration mitigates offset but not gain, harmonic, or temperature effects, which the programmable-source tests must bound.

A further limitation is legal rather than technical. Where GOST 32144-2013 applies, an instrument used for a conformity assessment must hold type approval and undergo periodic verification. K_2U -Node has neither; therefore, its readings—however accurate the pending characterization shows them to be—support engineering diagnosis, exposure mapping, and maintenance decisions, but not a formal determination of compliance. This is the intended role: in Uzbekistan, as in comparable networks with rapidly growing single-phase rooftop generation, the certified analyzers available to a utility number in the dozens, whereas the sites that would benefit from continuous monitoring number in the thousands. It is this coverage gap that an open device can close.

A safety note applies to any reproduction of this work. The device connects to a live 380/220 V three-phase network; all mains-side wiring must be performed by a qualified, authorized electrician on de-energized, locked-out equipment, with the absence of voltage verified on every conductor before it is touched, in compliance with local electrical safety regulations. The design provides galvanic isolation between the mains and the logic/user side (an isolated PZEM-004T front end in Gen-1, one voltage transformer per phase in Gen-2, and an HLK-PM01 isolated supply), and the voltage taps must be rated for the installation category of a distribution panel (CAT III/IV). No USB connection may be made to the node while the taps are live. Fused voltage taps, an upstream three-pole MCB, and an IP₆₅ enclosure do not substitute for safe working procedures: the enclosure interior contains lethal voltages whenever the taps are connected, and firmware should be developed and debugged on a low-voltage bench before any live connection.

Conclusion. K2U-Node shows how standards-referenced monitoring of the negative-sequence voltage unbalance factor—the line-voltage computation, RTC-aligned 10-minute quadratic aggregation, and two-level 2%/4% evaluation specified by GOST 32144-2013 and IEC 61000-4-30—can be implemented on open, commodity hardware. A Gen-1 screening node costs about 74 USD in single units, compared with several

thousand USD for a certified Class A analyser; the Gen-2 node, which computes the standard quantity, is being costed from purchase invoices. The comparison covers hardware only, and a certified analyser additionally carries an approval that an open device does not claim. The two-generation architecture turns a measurement-theory limitation into a deployment strategy and mirrors the Class S/Class A tiering of the standard itself: Gen-1 is confined to wide-area screening and exposure mapping, whereas the Gen-2 phasor node—reading the Uangle registers that no published driver exposes as a sensor, applying mandatory angle-zero calibration, and logging to an SD card as the primary record for 30-day campaigns—delivers K_2U , K_0U , and φ_2 at the decisive points. Its single-precision embedded implementation agrees with a double-precision complex-arithmetic reference to within [value] percentage points of K_2U , providing numerical verification rather than metrological verification, and the three-stage methodology—including the angular and harmonic cases that a magnitude-only bench cannot produce—defines the path to metrological characterisation. All designs, firmware, and test benches are openly licensed, so the device can be reproduced, audited, and extended $3 \cdot 10^{-6}$.

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