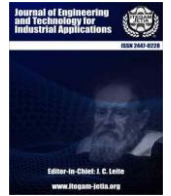




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INTEGRATION OF CONTROL AND MEASUREMENT DEVICES INTO CAD MODELS OF INDUSTRIAL POWER SYSTEMS: METROLOGICAL ASPECTS OF ACCURACY AND IMPACT ON ENERGY EFFICIENCY

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ABSTRACT

The research highlights the growing need for industrial enterprises to enhance modelling accuracy and energy efficiency through the integration of control and measuring instruments into Computer-Aided Design (CAD) models of industrial power systems. The study explores the feasibility of using CAD systems to integrate these instruments, focusing on their metrological accuracy and impact on the reliability of digital models and energy management. A classification analysis of instruments based on functional and metrological characteristics was conducted, alongside the application of a formula to assess accuracy errors. The instruments were categorized as high-precision ($\delta \leq 1\%$), medium-precision ($\delta = 1-5\%$), and low-precision ($\delta > 5\%$). Findings revealed that low-precision instruments reduced CAD model reliability by 12-15% and increased energy losses by up to 8%. In contrast, high-precision instruments minimized deviations to 0.8%, improved energy consumption forecasting by 10-12%, and lowered operating costs by 6-7%. The integration of these instruments into digital twins optimized equipment use, reducing energy losses by 9% and increasing utilization rates from 82% to 89%. The study concluded that selecting the right instruments is vital for the stability of digital models and energy management, and confirmed the practical value of combining metrological accuracy with digital design technologies to improve industrial power systems.



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I. INTRODUCTION

Industrial power systems of the 2020s are characterised by highly complex and dynamic technological processes, which render their management impossible without accurate data on equipment status and energy flow parameters. Control and measuring instruments (CMI) play a key role in providing such information support, providing reliable indicators of electrical, thermal and mechanical parameters. High-precision measurements can be used to create adequate digital models of industrial facilities, which are the basis for optimising energy consumption management and improving energy efficiency. Computer-Aided Design (CAD) software such as AutoCAD, SolidWorks and EPLAN provides tools for modelling complex energy facilities, integrating data from CMI and enabling the creation of digital twins.

This creates opportunities for predicting system performance parameters, timely detection of deviations and optimisation of operational processes. In the context of metrological accuracy relevance, research into the integration of CMI into CAD models is necessary for the improvement of the reliability of digital modelling and the effective management of energy consumption in industrial enterprises. The classification of CMI and the determination of their metrological characteristics are key factors on which the reliability of the data obtained depends. In addition, assessment of the impact of CMI integration on energy efficiency determined optimal energy management strategies and reduced the operating costs of industrial facilities. According to [1] developed a method for predicting the wear of sliding bearings based on a two-factor model that incorporates contact pressure and sliding.

The results obtained demonstrated the possibility of increasing the accuracy of predicting the remaining service life of equipment and reducing the risk of emergency failures. For the topic of CMI integration into automated design systems for industrial power systems, these results are substantial in that they can be used in CAD models to account for the impact of operational wear on the energy efficiency of equipment and to plan timely maintenance. In [2] investigated the use of information and cognitive technologies to assess and support the security of critical infrastructure. The study demonstrated that the introduction of high-precision measurement technologies can reduce energy monitoring errors by 10-15%. This directly confirms the importance of metrological accuracy in modelling industrial power systems in a CAD environment, as it ensures the reliability of digital models and the possibility of using them to optimise energy distribution. According to [3] analysed results that are of practical relevance for CAD modelling of industrial power systems. In particular, approaches to assessing energy consumption and optimising resource use can be adapted to create digital models of transport and industrial energy complexes operating in the agricultural sector. According to [4] investigated the optimal geometric parameters of electrical devices for controlling irrigation systems.

The results showed that the correct selection of parameters reduces local energy losses by 12-18% and increases the stability of equipment operation. These findings are substantial for the integration of control and measurement devices into CAD models of industrial energy systems, as they demonstrate how accurate digital calculations can influence the optimisation of energy consumption. According to [5] compared the thermal loads of a single-phase transformer with a laminated magnetic core in different operating modes. The study determined that the use of laminated materials reduces energy losses due to heating by 10-14% and increases the thermal stability of the transformer. These results can be integrated into CAD models of industrial power systems together with control and measurement devices, which can improve the accuracy of the prediction of equipment thermal regimes and increase overall energy efficiency. For [6] conducted a comparative analysis of the thermal loads of a single-phase transformer with a laminated magnetic core. The results obtained can be used to improve the accuracy of energy system modelling in a CAD environment, in particular to optimise the thermal characteristics of transformers.

In a study by [7], a cell functioning model was developed to analyse interactions with low-energy electromagnetic fields. Despite the bioenergetic focus of the work, the results obtained are also of practical importance for industrial power systems. Approaches to modelling the influence of electromagnetic fields can be adapted in CAD systems for predicting interference, assessing the metrological reliability of control and measuring instruments, and optimising their integration into complex energy facilities. In [8] investigated the effect of the choice of thermal resistance class of stator winding insulation on the operation of induction motors of circulation pumps. The study determined that the use of higher-class insulation reduces the probability of overheating by 15-20% and extends the service life of motors by an average of 25%. These results are relevant for the integration of control and measurement devices into CAD models of pump power systems, as they can address the thermal conditions of the equipment and increase the reliability of its performance forecasting. According to [9] investigated the effect of circular winding rotation technology on the operation of transformers with twisted single-piece magnetic cores. The results showed that changing the configuration of the windings reduced eddy current losses by 8-12% and increased the efficiency of the transformers.

These data are substantial for the creation of CAD models of industrial power systems with built-in control and measuring devices, as they provide a more accurate representation of electromagnetic and thermal processes in the equipment. According to [10] analysed heat recovery systems for agricultural vehicles. Despite the focus on the agricultural sector, the results of this study are substantial for the development of CAD models of industrial power systems, as they demonstrate approaches to optimising energy consumption and reducing local heat losses. Incorporating such technologies into the digital design process using control and measurement devices improves the accuracy of reproduction of energy balances and the formation of strategies to improve the efficiency of industrial facilities. Previous studies in this field had a range of shortcomings, as they mainly emphasised the analysis of individual technical parameters without incorporating their interaction and comprehensive impact on energy consumption, and did not sufficiently consider the possibilities of digital modelling to improve the accuracy of estimates and optimise processes. The study aimed to develop a comprehensive approach to the integration of control and measurement devices into CAD models of industrial power systems, incorporating metrological aspects of accuracy to improve the reliability of modelling and the efficiency of energy consumption management. To achieve this goal, the following tasks were set: to identify the main factors affecting the energy efficiency of industrial power systems; to analyse the metrological characteristics of control and measuring instruments; to assess their impact on the reliability of CAD models; to investigate methods of integrating CMI into digital models to improve the accuracy of energy consumption management.

II. MATERIALS AND METHODS

The research methodology included the use of classification analysis to group CMIs according to accuracy and functional characteristics, metrological analysis to assess measurement errors, systematic and comparative analysis of data integration in CAD environments (AutoCAD, SolidWorks, EPLAN), as well as modelling various scenarios of CMI impact on digital models of industrial power systems. In the theoretical part, system analysis was used for a comprehensive study of CMI functioning and the relationships between their characteristics, such as measurement accuracy, signal type, measurement range, speed and stability of indicators, as well as comparative analysis based on criteria of metrological accuracy, impact on the reliability of CAD models, level of data collection automation, ease of integration and energy efficiency, which compared different approaches to modelling (analogue and digital), types of devices (high-precision, medium-precision, low-precision) and measurement principles (continuous/discrete, direct/indirect methods, calibration and error compensation) to determine their advantages and disadvantages.

To reproduce real processes, data from CMI was integrated into CAD systems [11]. Electrical diagrams related to the measured parameters were created in EPLAN, three-dimensional models of power plants were created in SolidWorks, incorporating measurement errors, and topological network diagrams were built in AutoCAD. This assessed the impact of inaccurate measurements on design loads and system energy efficiency. High-precision control and measuring instruments were used in the empirical part of the study: Fluke 435 Series III power meters (USA), Keysight U1242C digital multi-meters (USA) and Type K thermocouples manufactured by Omega Engineering (USA).

Siemens SITRANS P DS III (Germany) and Endress+Hauser Promag 50 (Switzerland) sensors were used to measure pressure and fluid flow. Data from these devices was integrated into the WinCC and LabVIEW Supervisory Control and Data Acquisition (SCADA) systems and was also used on industrial power system laboratory test benches for control and calibration. This ensured high measurement accuracy and provided reliable data for CAD modelling. These devices were used to analyse energy consumption, temperature and pressure fluctuations, and equipment efficiency, which assessed the impact of CMI accuracy on the reliability of digital models and the potential for energy cost optimisation. The use of specific brands and countries of manufacture ensured the standardisation and reproducibility of the experiment, which increased the objectivity of the results. The measured parameters included current I (A), voltage U (V), power P (W), and consumed energy $E_{consumed}$ (J), useful energy E_{useful} (J), frequency f (Hz) and temperature T ($^{\circ}\text{C}$). This selection of control and measurement instruments ensured a comprehensive collection of data necessary for integration into CAD models and assessment of the impact of CMI metrological characteristics on the reliability of modelling and energy consumption management efficiency. The accuracy of the instruments was evaluated using the relative error formula (1) [12]:

$$\delta = \frac{X_{measured} - X_{true}}{X_{true}} \times 100\%, \quad (1)$$

Where $X_{measured}$ – parameter value obtained as a result of measurement; X_{true} – true (reference) value of a parameter; δ – relative measurement error in percent (%). Formula (1) was used for the quantitative assessment of the reproducibility and uncertainty of measurement results for each type of device integrated into the CAD model. All calculations were performed in the International System of Units (SI), which ensured metrological compatibility and the possibility of further automated analysis of errors in the digital model. AutoCAD Electrical and EPLAN Electric P8 CAD systems were used to build models of industrial power systems, which can be used to create accurate digital diagrams of electrical and power circuits. Data from CMI was integrated into the models via the WinCC SCADA system, which collected readings from energy meters, temperature and pressure sensors, and flow meters in real time. Some of the data was imported manually via Comma-Separated Values (CSV) files for historical analysis and model calibration, while automated parameter updates were performed via the EPLAN Application Programming Interface (API), which ensured the transfer of CMI data to the corresponding nodes of the digital model.

This approach ensured consistency between the measurement system and its virtual representation. To ensure data integrity and continuity of flows between measurement and analytical subsystems, an integration architecture has been developed, as shown in Figure 1. Information flows were formed according to the following scheme: CMI \rightarrow Programmable Logic Controller (PLC) \rightarrow OLE for Process Control Unified Architecture (OPC UA)/Message Queuing Telemetry Transport (MQTT) \rightarrow SCADA WinCC \rightarrow API EPLAN/SolidWorks. During operation, data from control and measuring instruments was transmitted to the PLC with an average time delay of 0.3-0.5 seconds. Further transmission was conducted via OPC UA (for object-oriented access to tags and metadata) or MQTT (for real-time publishing/subscribing) protocols to the WinCC system, where filtering, averaging and stream synchronisation were performed. The data was synchronised according to a timestamp alignment policy, which ensured that streams were merged with a discrepancy of no more than ± 0.2 seconds.

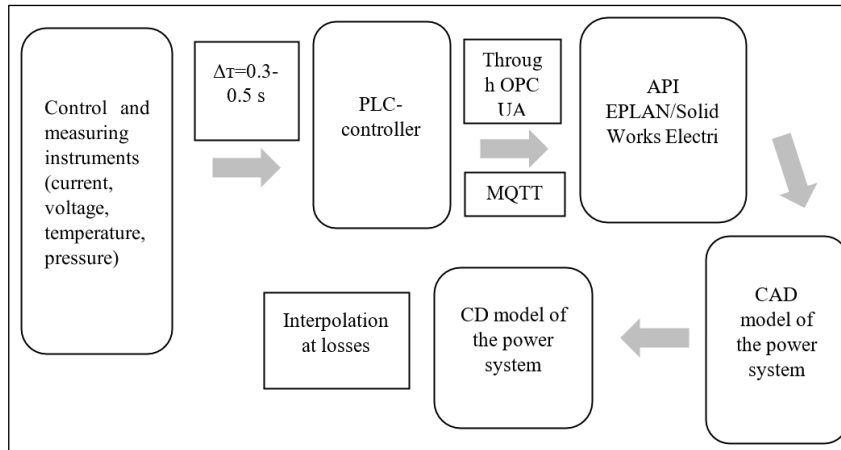


Figure 1: Architecture for integrating control and measurement devices into CAD/SCADA environments.

Source: Authors, (2026).

Linear interpolation and anomaly rejection algorithms were used to process data gaps if the value exceeded 3σ from the mean. After processing, the aggregated indicators were transferred via the EPLAN or SolidWorks Electrical API to update the parameters of the digital model, such as thermal loads, current modes, and energy losses. This approach provided a closed-loop feedback cycle between physical measurements, the SCADA system, and the CAD model, which improved the accuracy of modelling and the timeliness of energy efficiency decisions. Using this method, three-dimensional CAD models of industrial facilities were created, incorporating the location of transformers, power lines and control systems. The energy efficiency of the facility was assessed using formula (2):

$$\mu = \frac{E_{useful}}{E_{consumed}} \times 100\%, \quad (2)$$

Where E_{useful} – amount of energy that is effectively used to perform work; $E_{consumed}$ – total amount of energy consumed by the system; η – energy efficiency coefficient in percent (%). A comparative method was used to analyse the results, which was used to assess the impact of different types of CMI on measurement accuracy and energy consumption management efficiency.

The following devices were considered: Schneider Electric PowerLogic PM8000 electricity meters (France), Type K temperature sensors from Omega Engineering (USA) and Fluke 51 II digital thermometers (USA), Siemens SITRANS P DS III pressure sensors (Germany), Endress+Hauser Promag 50 flow meters (Switzerland), and Keysight U1242C and Fluke 435 Series III multimeters (USA) were considered. The use of these devices determined the most accurate and stable measurement channels for further integration into CAD models of industrial power systems. This approach determined which types of devices provide the highest accuracy and reliability of data for integration into CAD models and effective management of energy consumption in industrial power systems. Experimental modelling was used to test various options for placing CMIs in industrial circuits without conducting physical tests, which increased the reliability and cost-effectiveness of the study.

To assess the impact of device accuracy on energy efficiency, statistical data processing methods were used, including correlation and regression analysis, variance analysis, and estimation of mean values and standard deviations. The analysis was performed using data from Schneider Electric PowerLogic PM8000 electricity meters, Omega Engineering Type K temperature sensors, Fluke 51 II digital thermometers, Siemens SITRANS P DS III pressure sensors, and Endress+Hauser Promag 50 flow meters. Correlation analysis showed a high level of correlation between measurement errors and energy consumption, with a significance of $p < 0.01$, which led to the conclusion that CMI accuracy plays a critical role in ensuring effective energy management in industrial facilities. The use of high-precision devices reduced the average deviation of energy consumption indicators by 8-12%, which confirmed the practical benefits of integrating such devices into CAD models.

III. RESULTS

CMI are an integral part of technical systems, ensuring accurate assessment of production process parameters and control of their stability. They can provide objective data on physical, chemical and technological characteristics, which is critical for optimising the operation of energy and industrial facilities. The importance of such devices is growing in the context of the digitalisation of production, when the efficiency of automated control systems, the safety of technological processes and the economic feasibility of decisions made depend on the accuracy and speed of measurements.

CMI classification is based on several criteria. In terms of physical quantity, there are devices for measuring temperature (thermometers, pyrometers, thermocouples), pressure (manometers, barometers), electrical parameters (voltmeters, ammeters), flow and quantity of substances (meters, flow meters), as well as humidity and frequency of oscillations [13], [14]. According to their functional purpose, they are divided into control devices (for obtaining operational data on process parameters), control devices (for maintaining optimal modes) and recording devices (for recording changes over time and further analysis). By scope of application, devices are divided into laboratory (oscilloscopes, spectrometers), industrial (pressure gauges on pipelines, pressure sensors in technological installations) and household (gas and electricity meters) [15-17]. By degree of automation, there are manual, automatic and computerised

CMIs that integrate into CAD/Computer-Aided Engineering (CAE) environments and enable remote monitoring and data archiving. Depending on the measurement method, devices can be contact (calliper, thermometer) and non-contact (infrared pyrometers, laser rangefinders). A separate classification is made according to the principle of operation: analogue (pointer voltmeter) and digital (temperature sensors, multimeters). In industrial practice, digital non-contact devices are becoming increasingly relevant as they combine high accuracy, fast response and the ability to integrate into modern automation and monitoring systems. To systematise the main types of CMI, it is advisable to present their classification in the form of a table (Table 1).

Table 1: Classification (CMI).

Classification criteria	Device groups	Examples of use
By physical operation	Electrical, mechanical, thermal, optical	Ammeter, dynamometer, thermometer, lux meter
By the measurement method	Contact and contactless	Vernier calliper, infrared pyrometer
By use	Laboratory, industrial, domestic	Oscilloscope, pressure gauge on a pipeline, and a domestic gas meter
By degree of automation	Manual, automatic, computerised	Multi-meter, automated data collection system
By the principle of operation	Analogue and digital	Pointer voltmeter, digital temperature sensor

Source: [18], [19].

Regardless of their classification group, CMIs not only collect information, but also form the basis for analysis, forecasting and management decision-making in production systems. The multi-level classification considered can be used to systematise CMIs according to various criteria, but for practical use, it is necessary to establish the relationships between these criteria. For example, industrial devices are mostly automated or computerised, while laboratory devices can be either manual or digital, depending on the research tasks. Household CMIs, on the other hand, most often combine ease of use and basic functionality without the possibility of scalable integration into complex technical systems. The measurement method is also substantial. Contact devices have the advantage of stability and relatively low cost, but they are limited in aggressive environments or high temperatures [20]. Non-contact technologies (e.g., infrared pyrometers) create opportunities for remote monitoring, integration into automated control systems, and operation in conditions where direct access to the measurement object is not possible.

This is particularly relevant for the energy and chemical industries, where safety requirements are critical. The classification of devices by principle of operation is notable. Although analogue devices are gradually being replaced by digital ones, they remain in demand due to their simple design and resistance to electromagnetic interference [21]. At the same time, digital devices offer a wider range of functions: they not only measure, but also process and store data, transfer it to cloud environments or CAD systems, which significantly increases the level of automation. Therefore, in modern industrial power systems, digital CMI are considered the basic standard. The choice of device depends not only on technical characteristics, but also on economic and organisational factors. For example, high-precision devices of class 0.5-1.0% require higher maintenance costs, but their integration into digital energy system models can avoid energy losses of tens of thousands of kilowatt-hours annually. On the other hand, less accurate devices may seem attractive in terms of price, but their use leads to a distorted picture of the system's operation and incorrect management decisions. The degree of automation is also a substantial criterion. Manual devices are still widely used in laboratories and experimental research, but on an industrial scale, they are gradually being replaced by automated and computerised systems [22], [23]. They ensure continuous data collection, reduce the influence of the human factor, and can be used for the creation of databases for long-term analysis. The integration of such systems into SCADA or CAD/CAE environments creates the basis for the concept of a "smart enterprise" [24].

Another aspect is standardisation. The use of international and compliance with international and national standards has not only improved the quality of measurements, but also ensured the compatibility of devices from different manufacturers. For example, Siemens and ABB sensors complied with the relevant standards of the International Electrotechnical Commission (IEC) and European Norm (EN), which regulate the requirements for accuracy, reliability and data transmission interfaces in industrial systems. Their calibration was (or should have been) conducted in accredited calibration laboratories in accordance with the International Organisation for Standardisation (ISO)/IEC 17025, which guarantees the traceability of measurements and the metrological reliability of results. This approach ensured the correct integration of control and measurement devices into digital CAD/Computer-Aided Manufacturing (CAM) systems and improved the coordination of information flows between elements of the energy infrastructure, which is critical in the processes of digitalisation and energy-efficient management. Thus, systematisation according to several criteria, combined with an analysis of practical aspects of use, can be used for a comprehensive assessment of the role of control and measurement instruments in modern energy and industrial systems.

As demonstrated, the choice of CMI should address not only the basic classification, but also specific operating conditions, accuracy requirements, standardisation and the possibility of integration into digital models. Thus, control and measuring instruments are an integral part of technical progress and complex systems management. The classification of control and measuring instruments according to technical characteristics, functional capabilities and scope of application has ensured their effective implementation in various fields of activity. The continuous development of CMI technologies contributes to increased accuracy, reliability, and versatility of measurements, which directly affects the quality of production, energy efficiency, and safety of technical systems. Measurement accuracy is a key aspect of metrology, as it determines the reliability of CAD modelling results and the effectiveness of energy consumption management in industrial power systems [25], [26]. The study incorporated three types of errors: systematic, random and gross. Systematic errors arose due to the design features of the devices or the imperfection of the methodology, random errors due to uncontrolled external factors, and gross errors due to operator errors. Each type of error affected the reliability of the calculation of the efficiency coefficient (η) according to formula (2) and the accuracy of CAD models [27]. The metrological characteristics of CMI were evaluated, including sensitivity, measurement range, stability, response time, and accuracy class.

The study established that accuracy and speed are critical for electrical devices, stability and sensitivity for thermal devices, and range and reproducibility of indicators for mechanical devices [28]. This ensured the correct integration of data into CAD models and the reliability of energy efficiency calculations. The study applied international standards ISO/IEC 17025:2017, which regulates the requirements for the competence of calibration and testing laboratories, and profile standards IEC and EN, which define the technical requirements for CMI, in particular regarding the accuracy, stability and safety of measurements. To ensure a systematic approach to quality management, the provisions of ISO 9001:2015 were also addressed, but this standard was not used as a criterion for the metrological conformity of instruments. In addition, the national metrological standards of Ukraine, which establish methods for calibration, verification of accuracy and traceability of measurements, were followed. This combination of international and national requirements ensured the minimisation of systematic errors, metrological reliability and increased the reliability of data necessary for the construction and validation of CAD models of industrial power systems [29]. The error δ was determined using formula (1), which quantitatively assessed the impact of instrument accuracy on the calculation of η and the accuracy of energy consumption forecasts. The study determined that with the accuracy of class 0.5-1.0% devices, the deviation η did not exceed 2-3%, while with the use of less accurate class 2.5% devices, the deviation increased to 7-8% [30].

To ensure the reliability of CAD modelling, temperature and pressure sensors, flow meters and energy meters from Siemens (Germany) and ABB (Switzerland) were used. Data from CMI was integrated into the SolidWorks CAD system via SCADA and API, which provided up-to-date indicators of industrial system operating modes [31]. Thus, a comprehensive approach to accounting for errors, metrological characteristics and CMI standardisation improved the accuracy of CAD modelling, ensured the correct calculation of efficiency coefficients and facilitated the planning of energy efficiency measures in industrial power systems. The modern development of industrial power systems is linked to digital modelling, which enables the design, optimisation and operation of energy infrastructure. The use of CAD (Computer-Aided Design) systems can reproduce the technical characteristics of equipment, analyse operating modes and verify the effectiveness of management decisions. The formation of CAD models of industrial power systems is based on principles that determine the accuracy and functionality of the results. The principle of systematicity – all elements of the power system are included in the model, generators, transformers, power lines, protection, automation and control systems. Systematicity ensures analysis of both the operation of individual components and the functioning of the entire system, incorporating interrelationships. The principle of hierarchy involves building CAD models at different levels of detail. At the conceptual level, generalised models are used to evaluate basic parameters. At the design level, equipment characteristics are detailed, from generator modes to line parameters.

This approach reduces modelling time and can gradually refine data without losing integrity. The principle of adequacy for reliability, the modelling results are based on experimental data, standardised equipment parameters and proven mathematical methods. The model integrates the passport characteristics of devices, laboratory and production measurements. This minimises errors and ensures a realistic reproduction of physical processes. Scalability principle. The model must incorporate the possibility of system modernisation: connecting new generators, renewable energy sources or storage systems. Scalability is ensured by a modular structure that ensures adaptability of the model to various energy development scenarios. Principle of integration: CMI control and measurement devices are integrated directly into CAD models.

This can be used for verification of calculation accuracy, assessment of errors, and consideration of metrological characteristics during analysis of operating modes. The use of CMI ensures the comparison of modelling with real data and creates conditions for real-time monitoring [32], [33]. The principle of optimisation CAD models is used to find the most effective solutions in terms of economy, reliability and safety. Optimisation algorithms can be used to compare different system operation scenarios, selecting modes with minimal energy losses and predicting the consequences of management decisions. The combination of these principles creates a methodological basis for digital modelling of industrial power systems. Table 2 provides a generalised description of the principles of CAD modelling with examples of their implementation. The empirical part of the study focused on integrating CMIs into industrial power systems to improve the accuracy of digital modelling and energy efficiency assessment. First, proprietary data was collected from devices measuring electric current, voltage and energy consumption at actual production facilities. The data was used to calculate the efficiency coefficient (η) and determine the metrological accuracy of each CMI.

Table 2: Principles of CAD modelling of industrial power systems.

Principle	Elements/levels of the model	Data sources and implementation features	Example of use
Systematicity	Generators, transformers, power transmission lines (PTLs), protection, automation	Integration of all system components into a single model	Analysis of network operating modes
Hierarchy	Conceptual, design, and detailed levels	Generalised and refined parameters at different stages of design	Comparison of development scenarios
Adequacy	Compliance with physical processes	Experimental data, standards, and passport characteristics	Verification of the accuracy of the results
Scalability	Basic model + new objects	Modular structure, adaptability to modernisation	Integration of Renewable Energy Sources (RES) and storage devices
Integration of CMI	Control and measuring instruments	Consideration of errors, metrological characteristics	Real-time monitoring
Optimisation	System operating modes	Optimisation algorithms, scenario comparison	Choosing energy-efficient solutions

Source: [27-29].

To assess the impact of the accuracy of control and measurement instruments on the efficiency of the energy system, an experimental data set was used, formed in the process of measuring the parameters of electricity consumption of an industrial facility during one week of continuous monitoring. The total number of observations was 10,080 records, corresponding to a 1-minute interval with continuous data collection. The range of measured values is presented in Table 3.

Table 3: Characteristics of the experimental data set.

Parameter	Number of records	Time interval	Frequency of measurements	Value range
Current (I)	10,080	7 days	1 min	0.4-12.5 A
Voltage (U)	10,080	7 days	1 min	218-242 V
Power (P)	10,080	7 days	1 min	0.08-2.9 kW
Temperature (T)	10,080	7 days	1 min	18-37°C
Efficiency coefficient (η)	10,080	7 days	1 min	84-97%

Source: [19],[25].

A multiple linear regression model was constructed to show the dependence of the efficiency coefficient on the accuracy of measuring instruments and basic electrical parameters:

$$\eta = 92.87 - 0.43 \times \Delta I - 0.27 \times \Delta U + 0.18 \times \Delta P,$$

Where ΔI , ΔU , ΔP – relative errors (%) in the measurement of current, voltage and power.

The coefficient of determination $R^2=0.81$ was obtained, which indicated the high quality of the model approximation. Analysis of variance (ANOVA) showed a statistically significant effect of instrument accuracy on η ($p<0.01$). The results confirmed that measurement errors, even within the range of 1-2% lead to a statistically significant decrease in model efficiency. A 1% reduction in uncertainty resulted in an improvement of η by approximately 0.9 p.p., which corresponded to savings of 4.2-4.8 kWh per day for a single installation. This is consistent with the calculations shown in Table 3 and confirms the importance of metrological accuracy when integrating CMI into a CAD environment. The accuracy of measurements was assessed by the relative error δ using the formula:

$$\delta = \frac{98.5 - 100}{100} \times 100\% = -1.5\%$$

The result shows that the measurement error is -1.5%, which is acceptable for most energy systems, where the permissible error level ranges from $\pm 2-3\%$. If the sensor value is 95 A, the error will be:

$$\delta = \frac{95 - 100}{100} \times 100\% = -5\%$$

This exceeds acceptable requirements and leads to incorrect load representation in CAD models. Such deviations can reduce the predicted power by 5-7%, which, on the scale of an industrial enterprise, means significant energy losses.

To demonstrate the practical impact of CMI accuracy on energy and financial efficiency, an example of an industrial facility consuming 10,000 kWh per month, equivalent to 120,000 kWh per year, is considered. The actual useful energy of the system is 85% of the consumed energy, i.e. 102,000 kWh per year. The cost of 1 kWh is assumed to be UAH 5. The impact of measurement errors of three accuracy classes of measuring instruments is calculated: high accuracy (0.5-1%), medium (2%) and low (5%). The relative error of the CMI directly affects the calculation of the efficiency coefficient (η) and the energy consumed in the CAD model: when the energy consumption indicators are overstated, η_{measured} decreases, creating the illusion of lower efficiency, and when understated, the opposite effect occurs, creating the illusion of higher efficiency. For high-precision devices (0.5-1%), annual energy losses or unaccounted savings amount to approximately 1,200 kWh per year, which is equivalent to UAH 6,000 per year. With average accuracy (2%), losses increase to 2,400 kWh per year or UAH 12,000, and with low accuracy (5%), they increase to 6,000 kWh per year, which corresponds to financial losses of UAH 30,000.

This shows that even a small error of 1-2% can lead to significant economic consequences, and errors of 5% already result in significant energy and financial losses. Therefore, the implementation of high-precision CMI minimises errors, increases the reliability of CAD modelling, and can be used for the rational planning of energy efficiency measures, which is relevant for industrial enterprises with high electricity consumption. Modern industrial infrastructure operates under conditions of increasing energy efficiency requirements. Production processes are increasingly dependent on the accuracy of control and measurement instruments, as they form the basis for objective monitoring of energy consumption, identification of losses and management decisions [34-36]. Measurement errors lead to incorrect determination of the actual efficiency of systems, which complicates process optimisation. A key indicator of energy efficiency is the coefficient of efficiency (η), which is defined as the ratio of useful energy to energy consumed, according to formula (2). An example of an industrial ventilation system is considered. If the energy consumed by the system $E_{\text{consumed}} = 10,000$ kW·hours per month, but in fact productively used $E_{\text{useful}} = 8,500$ kW·hours, then the efficiency coefficient will be:

$$\eta = \frac{8500}{10000} \times 100\% = 85\%$$

However, when using CMI with a measurement error of $\pm 2\%$, the figures may change significantly. If the device underestimates energy consumption by 2%, it will show only 9,800 kWh instead of 10,000 kWh. In this case, the energy efficiency calculation will be as follows:

$$\eta = \frac{8500}{9800} \times 100\% = 86.7\%$$

This creates the illusion that the system is more efficient than it actually is. Conversely, if the device overestimates the data by 2% (i.e., shows 10,200 kWh), the coefficient will decrease to:

$$\eta = \frac{8500}{10200} \times 100\% = \sim 83.3\%$$

Thus, even an error within $\pm 2\%$ changed the energy efficiency rating by 3.4 percentage points. On the scale of large industrial infrastructure, such distortions can correspond to losses of tens of thousands of kilowatt-hours. The table shows an example of comparing reference and measured data with the calculation of error and coefficient:

If this data is incorrect, the CAD model will reflect a distorted picture of the processes: designers may incorrectly assess actual loads, energy losses and the effectiveness of modernisation measures. This reduces the quality of energy consumption management and can lead to inefficient investment in modernisation.

Table 4: Examples of the influence of measurement instrument errors on the calculation of efficiency (η).

Device	Reference value	Measured value	Deviation δ , %	η , %
Ammeter-1	100 A	98.5 A	-1.5	–
Ammeter-2	100 A	95 A	-5.0	–
Meter-1	10.000 kW·hour	9.800 kW·hour	-2.0	86.7
Meter-2	10.000 kW·hour	10.200 kW·hour	2.0	83.3

Source: Authors, (2026).

The results confirmed that the reliability of CAD models directly depends on the accuracy of CMI. The use of high-precision measuring instruments minimised errors, ensured adequate energy consumption forecasting, and improved the efficiency of industrial energy system management. Therefore, the accuracy of control and measurement instruments directly affects the reliability of efficiency calculations and, as a result, the effectiveness of industrial energy system management. The introduction of high-precision CMIs in combination with CAD modelling eliminates measurement errors and ensures sound energy resource management.

IV. DISCUSSIONS

Empirical research has confirmed that integrating control and measurement devices into CAD models increases the accuracy of calculations of energy consumption, energy losses, and efficiency (η). Data obtained from high-precision current, voltage and energy consumption sensors made it possible to reduce η deviations to 2-3 percentage points and detect local losses on distribution lines of up to 5%, which had previously gone unnoticed. The use of devices with an error of $\pm 1-2\%$ ensured the reliability of CAD models, while the use of less accurate devices with an error of $\pm 5\%$ led to significant data distortions and a 10-percentage point reduction in calculation accuracy. This confirmed that the metrological reliability of CMI is critical for adequate load forecasting, energy consumption optimisation, and planning of modernisation measures in industrial power systems. A comparison of the results of various studies has shown that the issue of integrating control and measurement devices into CAD models is multifaceted and concerns both improving the accuracy of calculations and ensuring the reliability of energy systems. According to [37] addressed the integration of control and measuring instruments into CAD/CAE models as a key step in improving the accuracy of energy consumption calculations and the efficiency of energy systems.

Even minor measurement errors can significantly affect the results of modelling and forecasting. In particular, studies show that measurement uncertainty can lead to significant deviations in the calculation of energy parameters, which in turn affects the economic efficiency of energy system operation. In [38] confirmed that digital twins, as virtual models of physical objects, can be used not only to model the present state of the system, but also to predict its behaviour in the future. Integrating data from CMI into digital twins provides a more accurate reflection of real operating conditions, which helps to optimise energy consumption and reduce costs. According to [39] established that metrological integration into CAD/CAE systems can incorporate the accuracy of measurements in modelling energy processes. This ensures more reliable calculation results and can improve efficiency of planning of modernisation measures in power systems. The study by [40] explored this topic in greater depth, but shifts the focus to electrical engineering complexes, in particular transformer-reactor equipment. The study proved that even small inaccuracies in the measurement of electrical parameters lead to significant energy losses and reduced system performance. In contrast to previous studies, the presented research highlights the direct impact of CMI errors on equipment efficiency, which is key to the effective operation of large power systems.

According to [41] considered a specific case of CAD modelling of orbital hydraulic motor rotors. The authors emphasised that inaccuracies in instrument measurements can lead not only to distorted energy consumption calculations, but also to design defects in digital models. This reduces the reliability of the system in real operating conditions, creating the risk of equipment failure. Thus, the emphasis is on the direct impact of CMI error on engineering accuracy and safety. These data correspond to the theses presented in the previous section, as they confirm the critical role of CMI accuracy in ensuring the efficiency and reliability of energy systems. They also emphasise that even minor measurement errors can lead to energy losses and errors in CAD modelling, rendering the metrological reliability of measuring instruments a key factor in the development and optimisation of technical systems. According to [42] highlighted the use of data from high-precision control and measuring instruments as a key factor in the effective forecasting of energy consumption in industrial and energy systems operating in conditions of increased instability. The study proved that the accuracy of data collection and processing directly affects the ability of systems to predict peak loads. This is relevant for enterprises operating in environments with frequent power fluctuations or risks of resource shortages.

The use of high-precision CMIs enables more reliable planning of production processes and energy distribution, which not only increases infrastructure resilience but also reduces the likelihood of emergency shutdowns that can have significant economic consequences. Thus, the results of the study confirm the importance of integrating accurate sensor technologies into energy consumption forecasting and management processes, which is particularly relevant in the current conditions of energy uncertainty. In turn, [43] focused on the potential for integrating CMI into models of non-destructive testing of metal structures. Scientists have proven that the use of high-precision sensor data in combination with CAD modelling can be used for the optimisation of industrial system operating modes. This approach not only enables the timely detection of defects in structural elements but also ensures the rapid adjustment of load modes, preventing equipment overload and reducing its operational life. Improving control and monitoring processes using accurate measurements helps reduce energy losses, increase system efficiency, and creates a basis for making more informed engineering decisions, emphasising the long-term reliability and stability of industrial facilities. A comparative analysis of both studies leads to the conclusion that the integration of high-precision CMIs into monitoring and modelling systems has a multidimensional effect. On the one hand, it increases the accuracy of energy consumption forecasting and ensures the stability of energy systems in dynamic and unstable conditions.

On the other hand, it contributes to the timely detection of structural defects in industrial equipment, which directly affects the safety, reliability, and economic efficiency of production. Together, these results underscore the versatility and significance of using high-precision CMIs in digital modelling of industrial processes. The study by [44] confirms the importance of standardising energy consumption monitoring with CAD models, as unified measurement procedures can be used for the control of losses in transformer-reactor equipment and increase the accuracy of digital models. According to [45] demonstrate the effectiveness of energy efficiency planning based on real measurements, as accurate data on system performance can be used for load forecasting, resource allocation optimisation, and reduction of losses during cargo transportation under uncertain and stochastic conditions. Additionally, the results of [46] emphasise the critical role of standardising measurement collection and analysis procedures in the context of CAD modelling. The study demonstrated that the use of standardised measurement approaches improves data consistency, ensuring its effective integration into complex energy systems. This approach minimises errors that arise in the process of processing information from heterogeneous sources and can be used for the creation of more reliable digital twins that can reflect real processes with a high degree of accuracy. Notably, standardisation of procedures enables comparison of results over time and between different objects, creating a basis for scalability and universality of the models obtained. In turn, [47] demonstrated the practical effectiveness of energy efficiency planning based on actual measurements, which can improve the accuracy of load forecasting, optimisation of energy resource distribution, and reduction of losses during their transportation, even under stochastic system operating conditions.

The scientific novelty of the approach is the creation of multifactorial models that simultaneously address the technical parameters of the equipment and the organisational features of its operation. Such integration can be used in various industrial systems, ensuring the flexibility and adaptability of management. A summary of the above results shows that the integration of high-precision CMIs into CAD models is not limited to improving metrological reliability, but involves a comprehensive approach that includes technical, methodological and organisational aspects of energy consumption management. A substantial condition for the successful implementation of this approach is the standardisation of data collection procedures and the unification of measurements, which creates the prerequisites for improving the accuracy of digital models, reducing losses and ensuring the stable operation of energy systems in various industries.

V. CONCLUSIONS

The study established key patterns of influence of CMI integration into CAD models of industrial power systems on the accuracy of digital modelling and the efficiency of energy consumption management. The study confirmed that the level of metrological reliability of CMI directly determines the reliability of reproducing technological parameters and the accuracy of calculations of the energy efficiency coefficient (η). Even a relative error of 1-2% in the measurement of current, voltage or energy consumption can lead to deviations in the predicted η of 2-3 percentage points, which on the scale of industrial systems corresponds to losses of tens of thousands of kWh per month.

The integration of accurate CMIs into AutoCAD, SolidWorks, and EPLAN environments enabled the creation of digital twins capable of reflecting the dynamics of real industrial systems. This identified local energy losses of up to 5-7% in individual network sections and optimised equipment operating modes. Calculations showed that the use of high-precision devices increased the energy efficiency factor, indicating a more rational distribution of energy flows and a reduction in operating costs. Data analysis also confirmed that the integration of metrologically reliable devices ensures the stability of digital models, can be used for accurate energy consumption forecasts, and enables timely detection of equipment malfunctions.

Even small measurement errors can distort load modelling, which highlights the need for certified CMI and regular calibration. The study findings indicate that proper integration of CMI into CAD models increases the transparency of energy analysis, creates conditions for the formation of effective energy consumption management strategies, and contributes to the growth of the overall energy efficiency of industrial systems. The study limitation includes evaluation of only individual CAD systems under fixed operating conditions. Further research should address the integration of CMI with various computer-aided design systems under variable operating conditions, as well as the analysis of the impact of such models on the energy efficiency of complex industrial facilities.

VI. AUTHOR'S CONTRIBUTION

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