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Automated Monitoring of Time Synchronisation Devices and Digital Processing of Vector Measurements of Dynamic Characteristics of SMART Grid Power Systems

Abstract. Currently, customers of energy companies use devices to generate electricity (solar panels, windmills, etc.) and return energy to the grid to save costs or generate income. Therefore, it is urgent to solve the problem of creating an automated system for diagnosing the quality of electricity for consumers who use renewable sources of electricity. The purpose of this study was to improve the efficiency of management in intelligent SMART Grid power systems. To fulfil the said purpose, it was proposed to use an automated system for monitoring synchro signals of PMU microprocessor equipment and software tools for digital processing and statistical analysis of the results of synchronised vector measurements of dynamic characteristics of power grids. Software tools for digital processing and statistical analysis of the obtained vector measurement data were developed. Linear regression, Random Forest Regression, and Ridge regression methods were employed to analyse and predict electricity quality indicators. The results of a comparative analysis of the obtained results of the predictive model were presented. To conduct experimental studies, a laboratory sample of a quality control device for generating synchro signals was developed and manufactured, which directly affects the reliability of digital data from distributed synchronised vector measurements in transient modes (in real time). The multichannel nature of the device increases the performance and reliability of the automated monitoring system. The paper presents the results of experimental studies of the device as a part of the developed laboratory stand, which is connected to the current local IP network of the National University of Life and Environmental Sciences of Ukraine. The practical significance of the conducted experimental studies lies in the establishment of the technical possibility of simultaneous monitoring of time synchronisation signals generated by two GPS receivers. In this case, it is obvious to increase the performance of the developed and manufactured device for monitoring the quality of clock signal generation, compared to a single-channel one. This material can be useful for engineers who design electrical systems connected to renewable energy sources

Keywords: renewable energy sources, synchronised vector measurements, multichannel device, quality control of synchro signal generation, monitoring of synchro signals, Ridge regression model, forecasting of electricity indicators

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INTRODUCTION

At present, energy efficiency is one of the main technical indicators that characterise the competitiveness of products, innovative development of the economy, and national security. The need to adapt the Ukrainian economy, including the agro-industrial complex, as one of the main subjects of

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the export-forming function, to market energy prices has led to the need to solve the problems of highly efficient use of energy resources. Apart from energy consumption in the electric power industry, the problems of improving the energy efficiency of electricity production and supply are no less relevant. The joint solution of these issues in electric power SMART and MicroGrid systems through the introduction of digital intelligent control tools that operate in real time ensures a positive effect [1-3]. These problems are directly related to the level of automation of electric SMART Grid power systems. In turn, the quality of operation of automated control systems of electric power networks of SMART technologies directly depends on the characteristics of time synchronisation signals used for conducting synchronised vector measurements, as well as on the effectiveness of methods for digital processing and analysis of measurement results data. To find the factual characteristics of time synchronisation signals, it is necessary to have hardware and software tools that ensure their continuous monitoring and processing of the received digital data [1; 4; 5]. The use of distributed synchronised vector measurements in transient modes (in real time) in SMART Grid power systems necessitates the development of software tools for digital processing and statistical analysis of measurement results for the implementation of effective power supply management in the field of intelligent energy [6; 7].

The construction of modern computerised power supply management complexes and networks for the field of intelligent energy based on monitoring the main characteristics in transient modes (in real time) involves the use of synchronised vector measurements [8-10]. The widespread use of functionally oriented PMU microprocessor equipment in the system of distributed synchronised vector measurements provides synchronous measurements of the main characteristics for various sections of the power network distributed in space, values of phase angles of voltages and currents synchronised with a single astronomical time [11; 12].

Thanks to the widespread use of GPS technology, it has become possible to create and implement distributed synchronised vector measurements (which ensure synchronisation of measuring instruments with an accuracy of the order of hundreds of nanoseconds). Information on the instantaneous values of the amplitude and phase, respectively, of voltage and current, registered in the same period (or moment) of time for different sections of the power grid, values of the speed of change of the phase angle of adjacent nodes of the power grid, and a list of other characteristics provides a modern level of knowledge about the properties of power networks and the specific features of the course of dynamic processes, as well as the possibility of direct observations of dynamic characteristics of power supply systems [7; 12; 13]. Notably, one can currently observe the increasing use of distributed synchronised vector measurements, an increase in the range of tasks for which they are used, namely the development of power grids with adaptive relay protection and automation, the detection of “hidden damage” in power grids with adaptive relay protection, the production of online control signals for automated prevention of a decrease in the level of stability in power grids and the elimination of asynchronous modes.

The widespread use of synchronised vector measurement technology in SMART Grid electric power systems can substantially reduce the uncertainty of primary information and improve the quality of processes for assessing the dynamics of electromechanical processes [7; 9]. Important in these processes is the use of software tools for digital processing and statistical analysis of the results of vector measurements, which determine the need for their further research, modernisation, and improvement for the implementation of effective power system management [10; 13].

It is problematic to use GPS signals as a reference sync signal for vector measurements [1; 5; 14]. Synchro signals generated solely by GPS signals cannot provide “high information survivability since they can be distorted, both in normal operation and in emergencies” [15]. The lack of sufficient reliability in providing SMART Grid time synchronisation signals to power systems leads to a decrease in the information reliability of the vector measurement process itself. To detect changes in time synchronisation signals, it is proposed to use computer-integrated systems that provide automated monitoring of time synchronisation devices [15; 16]. This approach will reduce the probability of accidents in smart grid power systems and, as a result, will help improve their energy efficiency. Modelling of dynamic energy consumption management scenarios using the inductive biclusterisation algorithm in the management of renewable energy sources is described in [6]. The web interface for an information system for diagnosing the quality of electricity consumers and monitoring synchronised vector measurements using cloud technologies is described in [17].

The purpose of this study was to develop and experimentally test the automated monitoring tools for time synchronisation devices and upgraded software tools for digital processing and statistical analysis of data from vector measurements of dynamic characteristics of SMART Grid power systems.

MATERIALS AND METHODS

To conduct experimental research in laboratory conditions and on the active IP networks, a developed laboratory stand with a quality control device for the formation of synchronous signals, two GPS receivers, and a reference high-stable thermostated quartz oscillator MXOCS were used. The study was performed in the problem-based research laboratory “Intelligent control systems in the agricultural industry” of the Department of Automation and Robotic Systems named after I. Martynenko (room 141, building 11, NULES of Ukraine). Experimental studies were performed according to the developed methods, structural and functional measurement schemes.

Automated monitoring of time synchronisation devices of distributed SMART Grid vector measurement tools of energy systems. Time synchronisation devices (TSD) of SMART Grid power systems are designed to generate sync signals that have prominent frequency stability. However, during their functioning, TSDs generate essentially quasi-periodic signals, to assess the quality indicators of which it is necessary to conduct measurements. Measurement of time characteristics is based on measurements of the relationships between the reference and controlled signal [18].

The parameter determined during the measurement process is a function called the time interval error function:

$$TIE_t(\tau)=TI_t(\tau)-TI_{REF}(\tau), \quad (1)$$

where the time interval function $TI_t(\tau)$ is found according to the equation $TI_t(\tau)=T(t+\tau)-T(t)$.

Function $TI_t(\tau)$ is a measure of the time interval τ, starting at the moment t, for the signal under study (provided that there is an ideal reference signal) [18]. Under such conditions, the time interval error function will have the following form:

$$TIE_t(\tau)=TI_t(\tau)-\tau. \quad (2)$$

In this case, the time interval function $TI_{REF}(\tau)$ of the reference signal $TI_{REF}(t)$ should be determined from the equation as follows:

$$TI_{REF}(\tau)=TI_{REF}(t+\tau)-TI_{REF}(t). \quad (3)$$

Automated monitoring lies in performing continuous (24/7) real-time measurements of the parameters of the TSD output signals, transmission, digital processing of measurement results and decision-making based on the obtained data.

The automated monitoring system includes sensors that provide the primary conversion of a physical quantity into an electrical signal. As a result, the time interval is converted into electrical digital signals, which should be represented as digital data of measurement results [5; 15; 16].

Further data processing provides calculation of indicators for comparison with normalised values defined by international recommendations, standards, and technical specifications. For instance, the maximum time interval deviation (TID) corresponding to one measurement period is calculated according to the following formula [18]:

$$MTIE(n\cdot\tau_0)=\max_{1\le k\le N-n}\left[\max_{k\le i\le k+n}x(i)-\min_{k\le i\le k+n}x(i)\right] \quad (4)$$

where τ_0 – is the sampling period; $\tau=n\tau_0$ – is the observation interval; $n=1,2,\ldots,N$; $\{x_i=x(i\tau_0), i=1,2,\ldots N\}$ –is a sequence of uniform discrete counts of the time error $x(t)$.

The operator solves the tasks of managing the work of SMART Grid energy systems based on the received data of the results of the measurements of the indicators of the time synchronisation signals and comparison with the normalised values. It is possible to increase the performance of the automated monitoring system by increasing the number of channels. Structurally, this possibility is implemented using the developed quality control device for synchronous signals formation (QCDSSF), the scheme of which is presented in Figure 1.

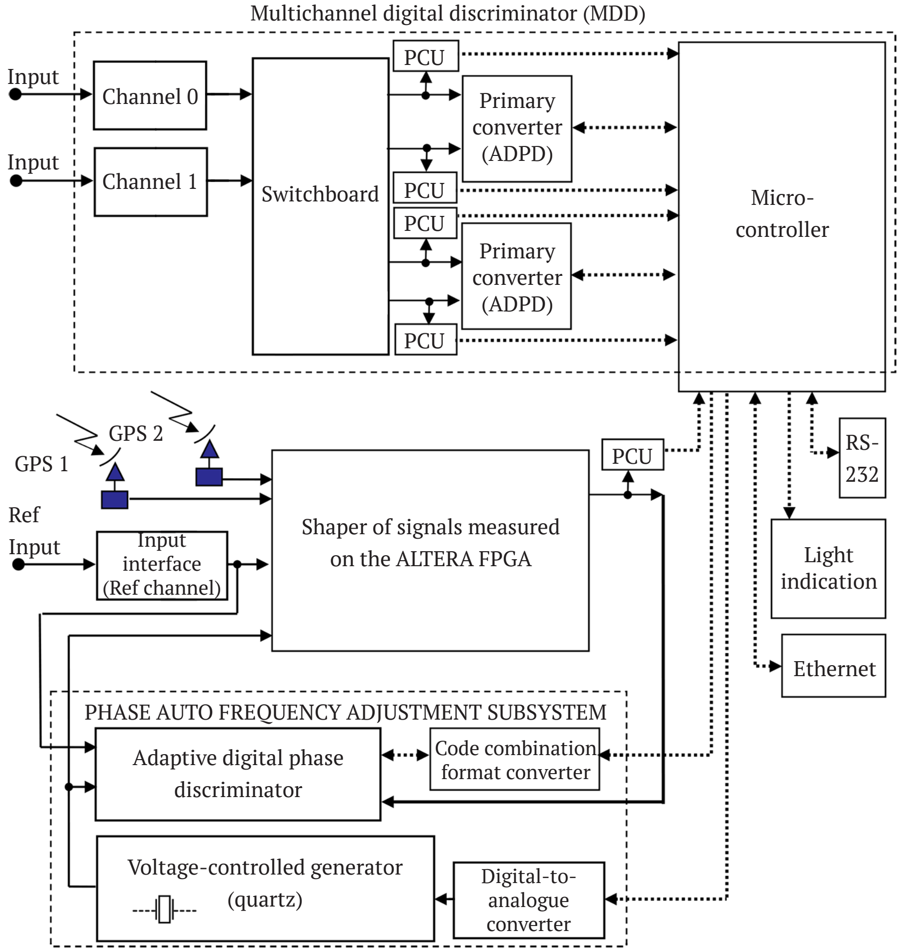


Figure 1. Block diagram of the quality control device for generating synchro signals

The device was built using a multichannel digital discriminator (MDD), the software and hardware implementation of which was performed using the Cyclone IV EP4CE10E22C8N programmable logic circuit. MDD performs the functions of a primary sensor, which provides the primary conversion of the error of the time interval (controlled indicator) into a digital signal in text format. Therewith, in the periodicity control unit (PCU) of the device (Fig. 1) the presence of pulse fronts on the clock interval of the controlled signal is checked. The results of these processes, which are presented in digital format, are processed by a microcontroller and prepared for transmission via RS-232 and Ethernet interfaces.

MDD is implemented using an adaptive digital phase discriminator (ADPD), which is protected by a Ukrainian patent for an invention [19]. The ADPD asynchronously, i.e., at any given time, without synchronising the measurement and reading processes, forms a code combination that determines the time ratio between the reference and controlled signal.

The developed QCDSSF device provides in an automated mode continuous monitoring of time synchronisation signals by performing simultaneous multichannel measurements of the instantaneous value of the deviation of the time interval relative to the reference synchronisation signal, which is formed by a voltage-controlled generator. The results of measurements of several time synchronisation signals (up to two simultaneously) are transmitted in text format via the IP network to a computer, where they are processed using software and presented to the SMART Grid operator of power systems for decision-making.

To conduct experimental studies of the automated monitoring system, a laboratory stand was developed with a quality control device for the formation of synchronous signals, two GPS receivers, and a MXOCS reference high-stable thermostated quartz generator were used. A photo of the laboratory stand is shown in Figure 2.

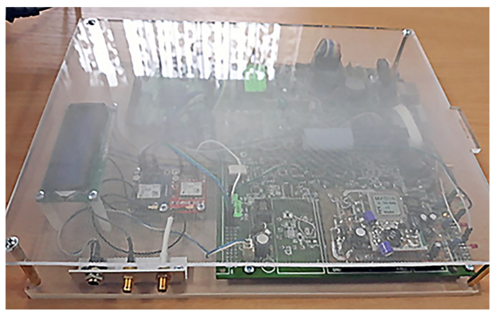


Figure 2. The appearance of a laboratory stand with a quality control device for the synchronous signals formation

The task of experimental studies was to check the technical specifications of the developed device for controlling the quality of clock signal generation. During the study, the accuracy of measurements of the deviation of the time interval of two time synchronisation signals of type 1-PPS (one pulse per second) relative to the reference sync signal, which is connected to the REF input, was checked (Fig. 1). Controlled time synchronisation signals of the 1-PPS type, formed by two GPS receivers, were connected to the corresponding inputs Input 1 and Input 2 of the device. Interaction of the developed laboratory stand with the computer was performed using the current local IP network of the NULES of Ukraine.

Digital processing of the obtained results of vector measurements of dynamic characteristics of SMART Grid power systems. The input information was an array of measured values of the vector format of electrical parameters [20] obtained from the ENIP-2 type PMU vector measurement device. This data was collected primarily for scientific purposes.

For further statistical processing and forecasting, a dataset containing 100 rows and 5 columns was created (Table 1). Digitised graphs are presented in Figure 3.

Table 1. Fragment of the generated data set

No.	f, Hz	I, A	U, V	I2, A
1	49.9803	2.0511	230.705	33.374
2	49.9669	2.0512	230.694	33.375
3	49.9942	0.0513	230.661	33.371
4	49.9982	2.0507	230.629	33.374
5	50.0154	2.0506	230.596	33.375
6	49.961	2.0508	230.552	33.373
7	50.0107	2.051	230.535	33.375
8	49.9887	2.0509	230.508	33.3735
9	49.9905	2.0512	230.469	33.3745
10	49.9715	2.0514	230.442	33.3735
11	49.9701	2.0512	230.42	33.369
12	49.9611	2.0514	230.409	33.375
13	49.9822	2.0513	230.381	33.372
14	49.9847	2.0513	230.359	33.3745
15	49.9821	2.0511	230.337	33.379

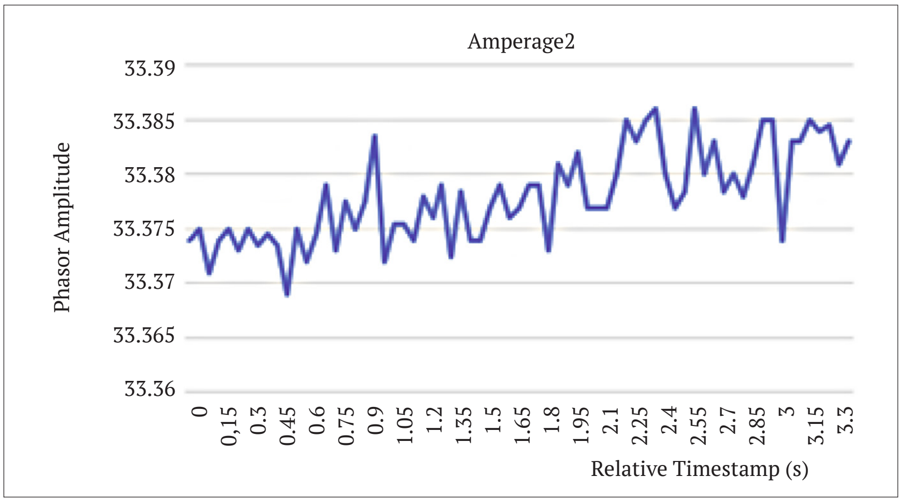


Figure 3. The appearance of a laboratory stand with a quality control device for the synchronous signals formation

Data structure. The data set is the characteristics of electricity (frequency, voltage, current). The dataset comprises a training dataset used to train and tune the model designed to predict values on the test data.

Eventually, the training set was divided into a training sample and a validation sample to evaluate the accuracy and quality of the models. The calculated statistical indicators for frequency, voltage, and current are presented in Table 2.

Table 2. Statistical characteristics of the measured parameters

Statistical characteristics	Frequency	Voltage	Current
Average values:	49.992	33.378	228.884
Median:	49.992	33.377	229.318
Maximum value:	50.024	33.386	230.705

For columns (1) and (2), the value of column (3) was predicted using two methods: KNN and Ridge regression.

The Predict matrix for data processing is presented in Table 3.

Table 3. Matrix for data processing

f, Hz	U, V
50.0228	228.569
49.9793	228.492
50.0041	228.404
50.0248	228.332
50.0233	228.272
49.9803	228.195
49.9734	228.113
49.9666	228.041
50.0249	227.926

Features of software implementation.

Features of the software implementation include:

– data reading and primary processing using the Pandas library;

– plotting graphs using the Matplotlib and Plotly express libraries;

– building a correlation table using the Seaborn library;

– data standardisation, splitting the training set into a training sample and validation sample, implementing classification models using the Scikit-Learn library.

Initially, the data was normalised for the highest accuracy of the calculation. An example of calculation based on normalised data is presented in Figure 4, without normalisation for Ridge regression – in Figure 5.

```
In [208]: from sklearn.linear_model import Ridge
          model = Ridge()
          model.fit(X_train_norm, Y_train)
          model.score(X_train_norm,Y_train)
Out[208]: 0.4774677178673772
```

Figure 4. Code snippet of the programme and calculation based on normalised data

```
In [209]: model.fit(X_train, Y_train)
          model.score(X_train,Y_train)
Out[209]: 0.45478502803711784
```

Figure 5. Code snippet of the programme and calculation based on data without normalisation

According to the normalised data, the accuracy of the model is higher. Columns (1), (2) are frequency and voltage, respectively. Predicted column (3) – current. The results of forecasting using the k-nearest neighbours algorithm (KNN) and the calculation accuracy of the method are presented in Figure 6, the predicted model is presented in Figure 7.

```
In [206]: model.score(X_train_norm, Y_train)
Out[206]: 0.6012872304007943
```

Figure 6. Code snippet of the programme and prediction results using the KNN method

```
In [207]: model.predict(X_prednorm)
Out[207]: array([33.3764, 33.3723, 33.3761, 33.3794, 33.383 , 33.38   , 33.3798,
                 33.3798, 33.3815])
```

Figure 7. Predictive model based on the KNN method

The Ridge regression method and the calculation accuracy of the method are presented in Figure 8. The predicted model is presented in Figure 9. The digital monitoring data obtained during experimental studies was stored in the computer's memory.

```
In [208]: from sklearn.linear_model import Ridge
          model = Ridge()
          model.fit(X_train_norm, Y_train)
          model.score(X_train_norm,Y_train)
Out[208]: 0.4774677178673772
```

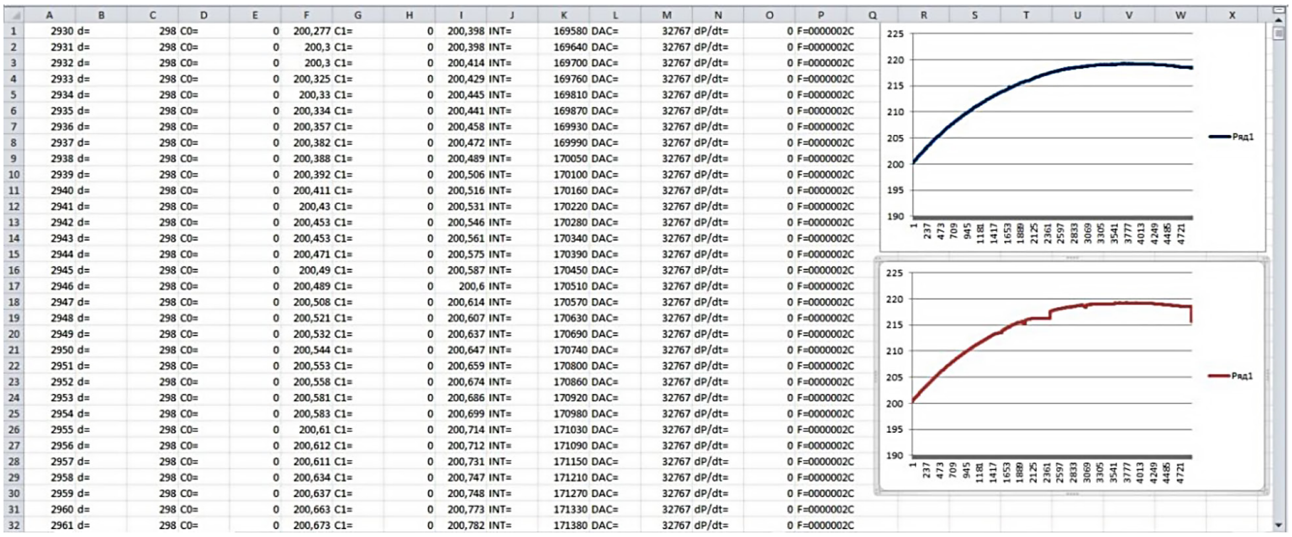
Figure 8. Code snippet of the Ridge regression method and method calculation accuracy

```
In [210]: model.predict(pred)
Out[210]: array([33.38373138, 33.38404514, 33.38446656, 33.38480939, 33.38508349,
                 33.3853977 , 33.38576735, 33.38608706, 33.38666182])
```

Figure 9. Predictive model using the Ridge regression method

RESULTS AND DISCUSSION

Figure 10 presents digital monitoring data for time synchronisation signals of two GPS receivers, which were processed using Excel software. Based on the results of experimental studies, graphs of the dependence of time interval deviations (TID) of controlled time synchronisation signals generated by two GPS receivers were constructed. The upper graph presented in Figure 10 displays the results of monitoring the signal generated by the first GPS receiver, and lower graph – the second GPS receiver.



	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P
1	2930	d=	298	C0=	0	200,277	C1=	0	200,398	INT=	169580	DAC=	32767	dP/dt=	0	F=0000002C
2	2931	d=	298	C0=	0	200,3	C1=	0	200,398	INT=	169640	DAC=	32767	dP/dt=	0	F=0000002C
3	2932	d=	298	C0=	0	200,3	C1=	0	200,414	INT=	169700	DAC=	32767	dP/dt=	0	F=0000002C
4	2933	d=	298	C0=	0	200,325	C1=	0	200,429	INT=	169760	DAC=	32767	dP/dt=	0	F=0000002C
5	2934	d=	298	C0=	0	200,33	C1=	0	200,445	INT=	169810	DAC=	32767	dP/dt=	0	F=0000002C
6	2935	d=	298	C0=	0	200,334	C1=	0	200,441	INT=	169870	DAC=	32767	dP/dt=	0	F=0000002C
7	2936	d=	298	C0=	0	200,357	C1=	0	200,458	INT=	169930	DAC=	32767	dP/dt=	0	F=0000002C
8	2937	d=	298	C0=	0	200,382	C1=	0	200,472	INT=	169990	DAC=	32767	dP/dt=	0	F=0000002C
9	2938	d=	298	C0=	0	200,388	C1=	0	200,489	INT=	170050	DAC=	32767	dP/dt=	0	F=0000002C
10	2939	d=	298	C0=	0	200,392	C1=	0	200,506	INT=	170100	DAC=	32767	dP/dt=	0	F=0000002C
11	2940	d=	298	C0=	0	200,411	C1=	0	200,516	INT=	170160	DAC=	32767	dP/dt=	0	F=0000002C
12	2941	d=	298	C0=	0	200,43	C1=	0	200,531	INT=	170220	DAC=	32767	dP/dt=	0	F=0000002C
13	2942	d=	298	C0=	0	200,453	C1=	0	200,546	INT=	170280	DAC=	32767	dP/dt=	0	F=0000002C
14	2943	d=	298	C0=	0	200,453	C1=	0	200,561	INT=	170340	DAC=	32767	dP/dt=	0	F=0000002C
15	2944	d=	298	C0=	0	200,471	C1=	0	200,575	INT=	170390	DAC=	32767	dP/dt=	0	F=0000002C
16	2945	d=	298	C0=	0	200,49	C1=	0	200,587	INT=	170450	DAC=	32767	dP/dt=	0	F=0000002C
17	2946	d=	298	C0=	0	200,489	C1=	0	200,6	INT=	170510	DAC=	32767	dP/dt=	0	F=0000002C
18	2947	d=	298	C0=	0	200,508	C1=	0	200,614	INT=	170570	DAC=	32767	dP/dt=	0	F=0000002C
19	2948	d=	298	C0=	0	200,521	C1=	0	200,607	INT=	170630	DAC=	32767	dP/dt=	0	F=0000002C
20	2949	d=	298	C0=	0	200,532	C1=	0	200,637	INT=	170690	DAC=	32767	dP/dt=	0	F=0000002C
21	2950	d=	298	C0=	0	200,544	C1=	0	200,647	INT=	170740	DAC=	32767	dP/dt=	0	F=0000002C
22	2951	d=	298	C0=	0	200,553	C1=	0	200,659	INT=	170800	DAC=	32767	dP/dt=	0	F=0000002C
23	2952	d=	298	C0=	0	200,558	C1=	0	200,674	INT=	170860	DAC=	32767	dP/dt=	0	F=0000002C
24	2953	d=	298	C0=	0	200,581	C1=	0	200,686	INT=	170920	DAC=	32767	dP/dt=	0	F=0000002C
25	2954	d=	298	C0=	0	200,583	C1=	0	200,699	INT=	170980	DAC=	32767	dP/dt=	0	F=0000002C
26	2955	d=	298	C0=	0	200,61	C1=	0	200,714	INT=	171030	DAC=	32767	dP/dt=	0	F=0000002C
27	2956	d=	298	C0=	0	200,612	C1=	0	200,712	INT=	171090	DAC=	32767	dP/dt=	0	F=0000002C
28	2957	d=	298	C0=	0	200,611	C1=	0	200,731	INT=	171150	DAC=	32767	dP/dt=	0	F=0000002C
29	2958	d=	298	C0=	0	200,634	C1=	0	200,747	INT=	171210	DAC=	32767	dP/dt=	0	F=0000002C
30	2959	d=	298	C0=	0	200,637	C1=	0	200,748	INT=	171270	DAC=	32767	dP/dt=	0	F=0000002C
31	2960	d=	298	C0=	0	200,663	C1=	0	200,773	INT=	171330	DAC=	32767	dP/dt=	0	F=0000002C
32	2961	d=	298	C0=	0	200,673	C1=	0	200,782	INT=	171380	DAC=	32767	dP/dt=	0	F=0000002C

Figure 10. The results of experimental studies of the time synchronisation signals of two GPS receivers using a laboratory sample of the device for quality control of the formation of synchronous signals

Analysis of the results obtained confirms the technical capability of the device to perform simultaneous primary conversion of the deviation of the time interval of two controlled signals into a digital code with a quantisation step of less than 1 nanosecond. This result is sufficient for the practical implementation of the tasks of monitoring SMART Grid time synchronisation signals of power systems, which, according to the international standards IEEE C37.118.1-2011, IEEE C37.118.2-2011, must provide an accuracy of ±1 microsecond for synchronised vector measurements using synchrophasors [5].

Analysing the resulting forecast graph (Fig. 11), according to the normalised data, the accuracy of the Ridge regression model is 10-15% higher than the KNN method.

A diagram of the calculated predicted voltage values compared to the factual values is presented in Figure 12.

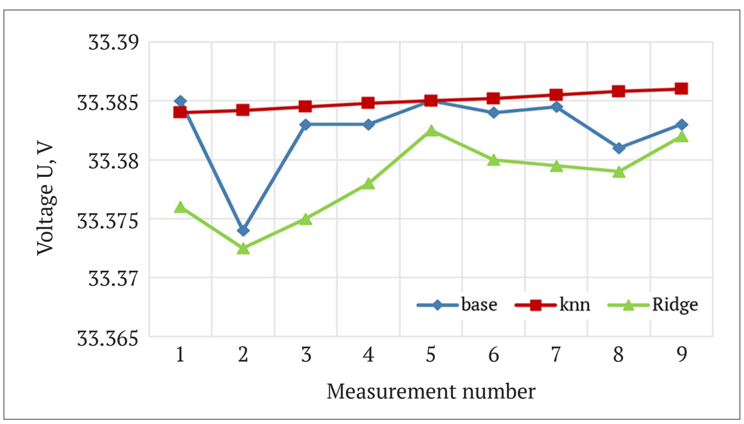


Figure 11. Graphical representation of output and projected data using KNN and Ridge regression methods

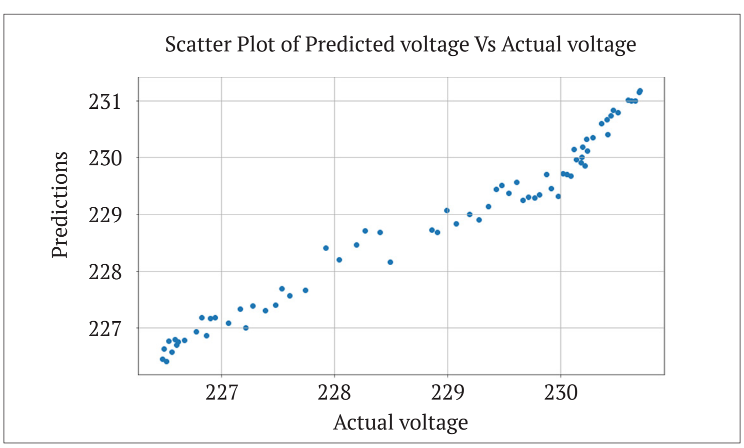


Figure 12. Graphical representation of output and projected data using KNN and Ridge regression methods

Analysing the resulting forecast graph (Fig. 12), according to the normalised data, the accuracy of the Random Forest Regression model is 5-10% higher than linear regression.

This study combined two tasks of diagnosing the quality of electricity vector measurements of SMART Grid power systems:

– conducting experiments on time synchronisation of two GPS receivers based on a previously developed laboratory stand;

– generating a dataset based on the results obtained and digitally processing the dynamic characteristics of electricity quality indicators.

In contrast to the publications [1; 17; 19] that were reviewed, this study presents the created software and hardware for automated diagnostics of digital signal synchronisation devices, which is an advanced system developed in Ukraine and tested in the current network of the National University of Life and Environmental Sciences of Ukraine. With the obtained real data, statistical processing was performed using various methods – KNN and Ridge regression, Random Forest Regression and linear regression, from which the best ones were selected – Ridge regression and Random Forest regression.

CONCLUSIONS

Based on the results obtained the following conclusions can be drawn:

1. Software tools were developed for digital processing and statistical analysis of a training data set in vector format of electrical parameters of SMART Grid energy systems, which provide the construction of a predictive model of electricity parameters, which is necessary for further decision-making.

2. The analysis of the obtained forecast graphs was performed, and it was concluded that according to the normalised data, the accuracy of the Random Forest Regression model is higher by 5-10%, while the accuracy of the Ridge regression model is higher by 10-15%.

3. As a result of experimental studies of the developed and manufactured device for quality control of the formation of synchronising signals as part of a laboratory stand, which is connected to the active local IP network of the NULES of Ukraine, the technical possibility of simultaneous monitoring of time synchronisation signals generated by two GPS receivers has been established. In this case, it is obvious to increase the performance of the developed monitoring device, compared to a single-channel one.

4. A comparative analysis of the obtained values of the deviation of the time interval with a quantisation step of 1 nanosecond and the norm of ±1 microsecond, which is set to the accuracy of the synchronising signals of vector measurements, indicates the practical possibility of solving the problems of monitoring time synchronisation signals with the manufactured device.

In the future, it is planned to develop the project, namely:

– within the framework of the research project, to purchase and connect several types of devices for vector measurements of PMU (synchrophasors) and integration into the information collection system at various facilities;

– to apply optimisation and decision-making methods for quality management at points where renewable generation sources are connected.

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Автоматизований моніторинг пристроїв синхронізації часу та цифрова обробка векторних вимірювань динамічних характеристик SMART Grid енергосистем

Анотація. В теперішній час клієнти енергокомпаній використовують пристрої для вироблення електроенергії (сонячні панелі, вітряки та ін.) і для економії витрат або для отримання доходу повертають енергію в мережу. Тому актуальним є вирішення задачі створення автоматизованої системи діагностування якості електроенергії споживачів, які використовують відновлювальні джерела електроенергії. Мета дослідження – підвищення ефективності керування в інтелектуальних SMART Grid енергосистемах. Для її реалізації запропоновано використання автоматизованої системи моніторингу синхросигналів мікропроцесорного обладнання PMU та програмних засобів цифрової обробки і статистичного аналізу результатів синхронізованих векторних вимірювань динамічних характеристик енергомереж. Розроблено програмні засоби цифрової обробки та статистичного аналізу отриманих даних векторних вимірювань. Для аналізу та прогнозування показників якості електроенергії використовуються методи лінійної регресії, Random Forest Regression та Ridge regression. Наведено результати порівняльного аналізу отриманих результатів прогнозної моделі. Для проведення експериментальних досліджень розроблено та виготовлено лабораторний зразок пристрою контролю якості формування синхросигналів, від яких безпосередньо залежить достовірність цифрових даних розподілених синхронізованих векторних вимірювань у перехідних режимах (в реальному часі). Багатоканальність пристрою забезпечує підвищення продуктивності та надійності системи автоматизованого моніторингу. Наведено результати експериментальних досліджень пристрою у складі розробленого лабораторного стенду, який підключено до діючої локальної IP-мережі НУБіП України. Практична значущість проведених експериментальних досліджень полягає у встановлені технічної можливості одночасного моніторингу сигналів синхронізації часу, що формуються двома приймачами GPS. У цьому разі очевидним є збільшення продуктивності розробленого та виготовленого пристрою контролю якості формування синхросигналів, в порівнянні з одноканальним. Матеріал може бути корисним інженерам, які проектують електричні системи з підключенням відновлювальних джерел енергетики

Ключові слова: відновлювальні джерела електроенергії, синхронізовані векторні виміри, багатоканальний пристрій, контроль якості формування синхросигналів, моніторинг синхросигналів, модель Ridge regression, прогнозування показників електроенергії