Development of a consensus algorithm and data block structure based on digital blockchain technology for distributed systems for storing information about the state of power equipment

M M Sultanov, AA Smirnov, VA Yurov and VS Lunenko
1 Volzhsky Branch of MPEI, Volzhsky, Russian Federation

Annotation. The article considers the main directions of technological transformations in the Russian electric power industry, which performs an integrating function for the fuel and energy complex of the country. The methods of achieving and ensuring a high level of reliability and safety of power equipment for thermal power plants, hydroelectric power plants, and nuclear power plants at all stages of their life cycle from design to decommissioning are considered. The issues of creating a unified system of information support for power equipment of generating systems for thermal power plants, hydroelectric power plants, nuclear power plants and power complexes based on renewable energy sources, taking into account the technical condition during the entire life cycle, are studied. In order to improve the security and efficiency of planning and forecasting of power equipment operation modes, it is proposed to consider an information model consisting of a centralized data warehouse and a distributed registry based on blockchain technologies. The principle of operation of a distributed closed registry, the structure of data blocks, and the algorithm of consensus between private users of the registry are considered.

In the modern world, the variety of technologies in the electric power industry is increasing, which contributes to the acceleration of technological progress.

Let's consider the main directions of technological transformations in the world power industry.

In the gas heat power industry, the development of gas turbines of a wide range of single capacities has become a condition of technological progress.

Advanced steam-power technologies for generating electricity using super-supercritical steam parameters are being used abroad [1], and technologies for burning local solid fuels in the fluidized bed are being developed, which reduces emissions of harmful substances.

The direction of fast neutron reactors is developing in the nuclear power industry [2], which contribute to the transition of nuclear power to a fully closed fuel cycle. New technological solutions for low-power nuclear power plants (below 100 MW) are also being proposed and implemented [3], including mobile (floating) installations.

Technologies that use renewable energy, especially wind and solar energy, are actively gaining momentum. Over the past decade, these technologies have become more competitive than traditional ones in many countries. Such power plants allow you to implement local sources of low-power electricity-up to microgeneration.
Intensive development of gas-turbine, wind, solar power plants and electricity storage technologies in recent years has contributed to the development of distributed generation based on low-power sources (less than 25 MW) connected to the distribution grid. An important component of distributed generation is intelligent micro-networks, which create a technological basis for effective management of electricity generation and demand for electricity [4]. Distributed generation units can deliver power to a large electrical network or have connected consumers and operate as part of a local electrical network (micro-grid). The characteristics of the micro-grid (voltage levels, transmission capacity of power lines, etc.) are determined by the electrical power of the connected distributed generation units.

The growth of technological diversity in electricity production becomes an additional incentive for the technological transformation of the power grid complex, where the transition to new-generation electrical equipment is accompanied by active digitalization (automation, Informatization and intellectualization) at all levels of management of the network and power system as a whole, which allows you to move to maximum intensive use with an increase in the reliability and quality of power supply, while reducing the specific indicators of losses during transmission and distribution.

Smart management infrastructure in the power system creates opportunities for large-scale integration of all types of distributed energy sources, maximizing the potential of active consumers [5].

Creating new algorithms for collecting statistical data and modeling capital repair processes allows you to form the process of restoring equipment, obtain and analyze the corresponding reliability indicators during operation of equipment and on this basis make decisions aimed at optimizing the volume and timing of repairs, quality selection of operating modes and forecasting the operating time of power plant equipment.

1 Methods of forecasting and ensuring the reliability of generating system objects at all stages of the life cycle

Issues of reliability and safety of complex technical systems are particularly relevant at the current stage of creation, production and operation of power equipment for thermal power plants, hydroelectric power plants, and nuclear power plants. Over the past 30 years, the power equipment of TPP, HPP, NPP has gone beyond the established limits service life.

The reliability of objects changes and special methods must be used to calculate them to ensure a high level of reliability[6].

The process of creating and operating complex technical systems and the qualitative picture of changes in its reliability function at various stages of the life cycle are shown in figure 1.

![Figure 1. Graph of changes in the reliability function at all stages of the complex lifecycle technical systems](image-url)
– (t3–t4) - from 1st to 2nd major repairs; (tn-1-tn) - from (n-1) to n-th major repairs (approximately every 5 years);
– (tn – tn+1) - aging and wear after 30 years of operation with the possibility of further extension of the service life.
RTR(t) - the required level of reliability and security of the technical system;
Rned(t) - an unacceptable level of reliability and security of the technical system.
We will consider ways to achieve and ensure a high level of reliability and safety of power equipment for thermal power plants, hydroelectric power plants, and nuclear power plants at all stages of their life cycle from design to decommissioning.

1.1 Methods for evaluating control actions for predicting the reliability of generating facilities
The method of finding control actions [9] at the stage of creating complex systems is reduced to the following:
1) make up a matrix $u$=[$u_{ij}$] of the initial data – design, technological and operational parameters $u_{ij}$, failure rates or failure rates, or the probability of failure-free operation for a given time $t$ for the corresponding $i$-th stage of the product life;
2) according to the original matrix $u$=[$u_{ij}$] in accordance with the selected control law and the desired dynamics of the output characteristic development, the transposed matrices of control parameters and output characteristics [$u^T$], [$y^T$];
3) using a well-known formula using standard Microsoft Excel functions, determine the transposed pseudo-return matrix [$y^+^T$];
4) calculate the estimate of the pseudo-return matrix $B^+=[u^T][y^+]^T$, which is subsequently applied as a constant;
5) the final stage is the determination of the control effect according to the formula obtained in accordance with the selected desired control law and the specified dynamics of the output characteristic development.
The considered method allows to take into account active control actions when creating expensive objects and thus solves the problem of controlling the process of product improvement in the active formulation with the directed improvement of its characteristics.

1.2. Methods for improving the reliability and safety of power equipment
To increase the level of reliability at the design stage, it is proposed to use the method of control actions, expressed in the form of design, technological and operational parameters [6], laid down in the regulatory documentation.
The basis of the method is to create a model for the design calculation of reliability in the form of a system that has an input and output and characterizes the state shown in figure 2.

Figure 2. Model for calculating and improving reliability at the design stage
Method of design calculation and achievement of the required level of reliability and safety is a closed loop, as shown in figure 3.

![Figure 3. Methodology for calculating and achieving the required level of reliability and safety](image_url)

If the output characteristic does not reach the required value during the design process, then measures are developed to correct the design, technological and operational documentation, and this adjustment is carried out until the output characteristic reaches the required value.

Managing such data requires several conditions to be met:
1) data availability for all subjects of the power equipment market, as well as for software providers who should be interested in developing products to improve economic and energy efficiency;
2) data received from power companies, power equipment manufacturers and consumers must be reliable and unchangeable throughout the life of power equipment;
3) the speed of data movement between the collection from power equipment and their analysis of data should be high enough for operational monitoring and decision-making.

2. A method for detecting possible malfunctions of process equipment at an early stage of their occurrence and storing data on operating modes of power-generating equipment

2.1 Model for early detection of emergency situations on power plant equipment
Active use of technological equipment is accompanied by events (accidents) that can have a negative impact on its operation or lead to failure. A model that predicts a future emergency situation would allow timely measures to be taken to eliminate it and thus improve the efficiency of the use of technological equipment. The authors [10] consider a method for early detection and prediction of anomalies in the operation of technological equipment of power units on the example of a feed turbopump PTN 1100-350-17-4 of a 300 MW power unit.

Their approach combines the MSET (Multivariate State Estimation Technique) method, in which the degree of abnormality in the technical condition is determined by exceeding the threshold level calculated by the algorithm automatically by the Hotelling criterion, and machine learning methods. An ensemble of regression models is used to determine the composition of the most informative features, based on the values of which early development of an emergency can be detected. The rationale for the method of selecting the modeled variable and the set of regressors is given. The method for calculating the anomaly index is based on the formation of an ensemble of linear regression models. The authors propose a method for generating an alarm for detecting anomalies in the operation of process equipment in power units. The model proposed by the authors allows us to identify the beginning of the development of an emergency situation, while individual parameters did not reveal the features of the pump functioning in the pre-accident time interval.
2.2. Methods for ensuring a high level of reliability of power equipment based on centralized and decentralized data storage

2.2.1 Possibilities of using block chains for information assurance of power equipment reliability.

One of the main criteria for ensuring the reliability of power equipment is the quality of information support, which reflects the current state of objects and their archived data. Data stored in the archive is used for predicting accidents and equipment failures, and making decisions about putting equipment into repair.

The current state of the energy system in the Russian Federation is a combination of large companies that produce electricity, system operators, and network companies. In the unified energy system (UES) of Russia, information management issues are handled by the UES system operator (SO UES) Russia and the administrator of the trading system (PBX). The volume of information includes qualitative and quantitative indicators of relations between participants in the wholesale electricity and capacity market (OEM) [11]. Despite the limited number of participants in the electricity generation and distribution market, the power system does not have a single information base that records the current state of power equipment and archived data on failures, planned repairs and accidents.

Increasing the share of small-scale generation, especially with the use of renewable energy sources, increases the relevance of creating a unified database for information support of the reliability of power equipment [12].

This system would include information about power producers and operators, as well as manufacturers of power equipment. In this way, it is possible to ensure control over the reliability and quality of power equipment throughout its entire life cycle – from the moment of production to decommissioning.

The developed methods of effective management of power equipment of generating systems to ensure a high level of reliability are based not only on processing a large amount of information, but also on the use of a complex mathematical apparatus [13]. These conditions require the creation of a unified information system for data storage and processing.

Creating a unified storage system for hardware status data involves the following tasks:

1) the need to allocate a subject of the energy market that would take over the function of collecting, storing and ensuring the reliability of data;
2) ensuring openness for each participant of the energy market-from equipment manufacturers to generation facilities;
3) ensuring continuous data filling from different market participants;
4) ensuring data integrity and security.

In turn, centralized storage, collection, and provision of access to large amounts of data carries serious financial costs, which will increase with the increase in data volume, and access to this information system is not possible on an open free of charge basis. This reduces the motivation for other market participants to share their information. On the other hand, almost all big data storage solutions that provide sufficient technical requirements for analysis have a centralized structure.

To solve the above tasks, we can use decentralized data storage technologies, for example, based on a blockchain (data chain), where each participant in the power equipment market can store this data, efficiently extract it from the system, and also contribute their own information [14].

But distributed registry technologies also have a number of disadvantages, such as:

1) the Complexity of storing a large amount of information. Distributed registry means that each of its participants has a copy of all data. If for large manufacturing companies, having such a data set may not incur significant data storage costs, then consumers will not be interested in spending resources to store such volumes of data.
2) the speed of extracting and adding data from distributed registries is too slow for operational analysis and will not allow for real-time monitoring and decision-making algorithms.
The service life of such an information system should be virtually unlimited, and the data structure may change over time. Based on this, the most important task is to ensure the reliability of data storage.

Distributed registry technology will improve the reliability of centralized data storage. Data security is guaranteed by a consensus algorithm between energy market participants. If one of the participants tries to send data to the blockchain that does not match the consensus algorithm, the other participants will not accept this data and such a block will not be embedded in the chain.

Therefore, in order to create a system for storing data on operating modes and reliability of power equipment, it is advisable to use a centralized and decentralized approach together.

A centralized cloud service for data storage will allow you to quickly record data and provide it to software providers. At the same time, the cost of supporting such a service can be recouped by providing paid access to SOFTWARE developers, and access to the system for power equipment manufacturers and companies operating it can be made free. In turn, all participants in the energy equipment market and energy consumers can use software services on the terms of the SOFTWARE provider.

A decentralized data storage registry will store not the data itself, but the hashes of this data – a unique fingerprint of data, of a fixed length, confirming the authenticity of data transmitted to a centralized database. Thus, a decentralized system is protected from uncontrolled growth of its volume, but it ensures the reliability and immutability of data transmitted to the centralized system.

Creating a decentralized information base to ensure the reliability of equipment based on the technology of distributed closed registries is reduced to the following tasks:

1) creating a consensus algorithm;
2) creating the structure of information blocks.

2.2.2. The principle of operation of a decentralized information system for information security based on blockchain. Blockchain is a tool for storing and transmitting data. The main advantage of blockchain technology is that intermediaries that control and ensure the reliability and security of activities in this area disappear, shifting these functions to the system participants themselves. It is assumed that if 51% of the participants in the system adhere to the consensus algorithm, then the system is safe. Thus, with an increase in the number of participants in the system, its security increases.

For the proposed information system, all participants in the energy market – equipment manufacturers, large generation, small generation, and system operators – are equal participants in a decentralized data storage system based on blockchain. In the future, we will use the term "node", by which we mean the system participants described above.

The task of the information system itself is to confirm the authenticity of information about power equipment and changes in their lifecycle - problems, failures, planned repairs, unplanned repairs, changes in equipment loading, and equipment movement between nodes.

All information is stored as data blocks, where each block has a hash of the previous block. An individual block in the chain contains information about all previous blocks, and any change in the data chain is impossible.

Figure 4 shows the General scheme of the information system, which shows two blocks in the chain.
The data block consists of the following fields:

1) block number: specifies the number of the current block in the data chain (required field);
2) nodes: a public key unique to each node is used as the node address to uniquely identify it (required field);
3) data block: the block where data is stored, it can contain information about the equipment or its status. We will describe the structure of the data block below. (optional part of the block);
4) service field: since the system is designed to work for many years, some parameters of the data and the consensus algorithm may change. When changes need to be made to the operation of the blockchain, nodes can vote for these changes by sending empty blocks without data, indicating the results of their decision in the “Service information” field. Nodes can also use this field to signal any events, so that other nodes pay attention to this block (this field is optional, by default it is zero);
5) hash of the previous block: a mandatory field that ensures data integrity;
6) timestamp: time in Unix Timestamp format (required field);
7) block hash: the hash of all data contained in the current field, including the hash of the previous block;
8) EDS: an electronic digital signature of data that allows you to verify that the data was sent by a specific node specified in the “Node” field.

The hash of a block is a unique digital copy of the information contained in it. Any change to the information in the block will change its hash. The SHA-256 algorithm is proposed as the main algorithm for generating hashes [15].

2.2.3. Registration of network members. Let's consider the main conditions for creating a blockchain for effective management of energy equipment of energy systems.

Since energy is one of the main sectors on which the functioning of the state as a whole depends, it is impossible to make such a system completely decentralized. The state should take over the functions of access control in the information support system for various participants in the energy market.

This can be done by creating a state provider of electronic digital signatures (SE EDS). SE EDS is also a node in the information system, but it has exclusive rights to issue digital signatures to participants, the right to register participants in the blockchain, and the right to stop the activities of participants.

The first block in the chain is the GP EDS block, where its public key is published. All other participants can verify the electronic signature of the GP EDS, knowing exactly its public key published in the zero block of the blockchain.

Registration of a participant is based on the following principle:

1) the participant (equipment manufacturer, generating company) applies to the SE EDS, providing the necessary set of documents.
2) the SE EDS checks the participant for compliance with the possibility of participation in the system.
3) the SE EDS sends a new participant with its public key to the blockchain on its own behalf and signs this information with its digital signature.
4) Other nodes verify the digital signature of the GP EDS and accept the block in the chain.
5) The Participant is given a private key with which they can sign their data and send it to the blockchain.

The EDS GP can also stop a node from participating in the network by sending information about it to the network.

2.2.4. Consensus algorithm. Any decentralized blockchain system is clearly defined by the consensus algorithm, i.e. the operating conditions of the node in the network. If the blocks that fall into the network do not meet these conditions, then the network participants do not accept these blocks, and they do not fall into the General chain with data. Thus, if the network has more than 51% honest participants, then the blocks that fall into the chain are considered reliable.

The main consensus algorithm for the proposed system:
1) checking the block hash.
2) checking the sender's node as an active network participant. Verification is performed by finding the block from the GP EDS with the last record of the node and its status.
3) checking the electronic signature of the GP EDS in the found block.
4) checking the EDS of the node that sent the block.
5) checking the validity of information in the data block.
6) checking the timestamp: the timestamp must be greater than the previous block, but less than or equal to the current time.
7) the hash of the previous block must match.

If all checks pass, the consensus is considered found, and the notes add the block to the data chain.

2.2.5. The block with data. Validation of information in a data block depends on the type of data contained in the block. Different network participants should have their own structures in the data block. For example, consider a power equipment manufacturer and the structure of data that it can send to the network.

For example, the manufacturer produces transformers of the TSK-SVEL-25 brand.

The manufacturer can publish information about the manufactured equipment by sending a block with the content shown in figure 5 to the network.

![Figure 5. Registration of the equipment brand](image)

In the data, it specified the following fields:
1) type – the type of data to send. In this case, 34 is the registration code for the new brand. Required field in the data, if present. Based on this code, nodes check the validity of the data block;
2) id – a unique 256-bit identifier. The task of the node when receiving such a block is to check its uniqueness (required field);
3) name – in this field, the manufacturer must specify the name of the equipment brand (optional field);
4) data–optional field where you can specify technical characteristics.
The type field can be followed by an array of data listing several brands. Thus, the manufacturer, having registered the brand of equipment in the blockchain, can now register the equipment produced directly. For example, when three transformers are released, it sends the block shown in figure 6 to the network.

**Figure 6. Registration of manufactured equipment**

| Number of block: 543102 |
|-------------------------|
| Node: 730f75da073e047b86ac2d8d74e57db9.. |
| Type: 34 |
| mark: 0627985b676dcdcf6374dfb6d34d2d.. |
| list: { id: 2446efb484a25bba4c17ae6f, id: 25694d4844a25bbd5f6 } |
| Data: {Technical information} |

Service: 0
	TimeStamp: 14582938042
	Previos Hash: 084a988248f2341aa1abb65bbba...
	Hash: 1cd1f65f2246efb484a25bbd6c17ae67...
	Digital signature: c17ac677843daffe244c151fc..

When registering equipment, the manufacturer, as well as when registering a brand, assigns each sample of equipment a unique 256-bit key and sends the information to the network. Thus, the following information is available in the network:

1) information about the hardware manufacturer that the EDS GP added to the blockchain;
2) brands of equipment produced by this manufacturer;
3) directly samples of equipment issued by the manufacturer.

Then the manufacturer supplies the equipment to a certain energy company, which is also registered in the system. To do this, it needs to create a block containing the transaction (figure 7). Next, for convenience, we will only give the structure of the data block. the information in the main block is formed according to the same principles.

**Figure 7. The transaction between the two parties**

```
| type: 3 |
| to: 35d33e5fabc7e424371f56d7796ad9597df169af0222c43167... |
| list: { id: ae8f35f877e1782f600a635... } |
| data: {Сопроводительная информация} |
```

1) type = 3 means the outbound transaction;
2) to-node that the hardware is sent to;
3) list – a list with unique hardware IDs that must have been previously registered by the manufacturer.
4) data-field for accompanying information.

This transaction can be made not only by the manufacturer, but also by any other owner of the equipment. Unlike digital assets, when it comes to real equipment, it is not possible to transfer it in real time, and a transaction sent to the node of an energy company does not mean that the company already has this equipment.

Therefore, this hardware is marked as reserved in the network. When the equipment is actually delivered, the power company must send a similar transaction with type = 4, which confirms receipt of the sample equipment data.
Then the company that operates the power equipment, using its unique identifier, sends data such as output to work, failures, repairs, output to the reserve sends data to the centralized system, and a unique impression of this data to the blockchain system.

For convenience, manufacturers or users of equipment can equip it with RFID tags, which will contain the equipment ID, and use a programmable tag reader to quickly send information to the network.

Conclusion
The proposed new model of information management system for power equipment of modern generating systems based on centralized and distributed registers allows using the advantages of each system and minimizing their disadvantages. This approach allows you to create a system that will be open and transparent to all participants in the power equipment market, and on the other hand meet the requirements for security and trade secrets. Since a distributed registry uses a public key as node IDs, and instead of direct data, it stores a hash that cannot be used to restore data, but can be verified for authenticity, all participants should be able to use this registry.

The research is funded by Russian Federation public contract №0720-2020-0025 "Technique development and method analysis for ensuring power system object security and competitiveness based on the digital technologies"

References
[1] A.G. Tumanovsky, A.L. Schwartz, E.V. Somova, E.Kh. Verbovetsky, G.D. Avrutsky, S.V. Ermakova, R.N. Kalugin, M.V. Lazarev Pulverized coal power units for super- and ultra-supercritical parameters of steam (Thermal Engineering. 2017. No. 2) p. 3–19.
[2] E.O. Adamov, A.A. Kashirsky, E.V. Muravyov, D.A. Tolstoukhov Structure and parameters of two-component nuclear energy during the transition to the closure of the nuclear fuel cycle (Izv. RAS. Energy. 2016. No. 5) P. 14–32.
[3] NEA/OECD small modular reactors: nuclear energy market potential for near-term deployment, Nuclear Development (OECD Publishing, Paris) 2016.
[4] O. Erdinc, N.G. Paterakis, I.N. Pappi, A.G. Bakirtzis, J.P.S. Catalao A new perspective for sizing of distributed generation and energy storage for smart households under demand response (Appl. Energy. 2015. V. 143) P. 26–37.
[5] Yu.N. Kucherov, A.V. Ivanov, D.A. Korev, N.A. Utkin, A.Z. Beetle. Development of active consumer technologies and their integration into the public electricity network (Energy Policy. 2018. No. 5) P. 73–86
[6] Sultanov M.M. Reliability assessment, resource extension and optimization of repair of TPP equipment and energy systems: textbook. The allowance (Volzhsky branch of NRU "MPEI" 2016).
[7] Trukhanov V.M. Reliability in technology (2nd ed., Moscow: LLC Spektr Publishing House, 2017) 656 p.
[8] Gartung, Yu. A. Investigation of the development of dynamical systems caused by some differential programs (Moscow: Nauka, 1984) 59 s.
[9] TRUHANOVA N.V., SULTANOV M.M. Estimation technique of corrective effects for forecasting of reliability of the designed and operated objects of the generating systems (journal of physics: conference series 2017)
[10] Korshikova, A. A. and A. G. Trofimov A model for the early detection of emergencies in the equipment of power plants based on machine learning methods (Thermal Engineering, 2019, No. 3) p. 49–56
[11] Modern Market Energy of the Russian Federation (AHO Training Center NP Market Council) 368 p.
[12] A.Vaskov, M.Tyagunov, T.Shestopalova, G. Deryugina, I. Ishchenko *Structure and Parameter Optimization of Renewable-Based Hybrid Power Complexes* (Handbook of Research on Renewable Energy and Electric Resources for Sustainable Rural Development. Ed. V.Kharchenko (Russia) and P.Vasant (Malaysia), - Hershey, Pennsylvania, IGI Global, 2018) P. 352-382

[13] M.M. Sultanov, V.M. Trukhanov, E.K. Arakelyan, M.A. Kulikova Methods to achieve and ensure a high level of reliability and safety of power equipment of TPPs, HPPs, NPPs at all stages of the life cycle (Monthly Scientific and Technical Electronic Journal; No. 3, March 2018) 6-15 cc.

[14] Fedotova V.V., Emelyanov B.G., Tipner L.M. The concept of blockchain and the possibility of its use (European Science. - 2018. - No. 1.) P. 40-48.

[15] Salomon D., Motta G. *Handbook of data compression* (Springer Science & Business Media, 2010).