Internet of distributed energy architecture

Version 2.0

Transactive energy

Internet of things

Neural grid

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INTERNET OF DISTRIBUTED ENERGY ARCHITECTURE (IDEA)

Version 2.0

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Contents

Basics of IDEA

1 **Internet of Distributed Energy Architecture (IDEA)** is the cyber-physical infrastructure for decentralized smart control of power systems and for plug & play integration of active consumers, power sources and flexibility sources.

2 The IDEA is aimed at eliminating the following types of costs that arise when integrating distributed energy resources into power systems:

— Transaction costs;
— Costs of users' integration into the information and control systems;
— Costs of integrating power units into the grid.

3 Decentralized smart control of power systems in the Internet of energy is provided by **energy transactions**. An energy transaction is an interaction between two users of the Internet of energy and their assets, in which power is transferred over the grid as a result of a contract in the transaction system and the machine-to-machine interaction of the users' equipment.

4 Two types of energy transactions are available in the Internet of energy, which are the main **use cases** of the IDEA:

— Peer-to-peer (P2P) energy transaction between two power cells;
— Mixed or peer-to-operator (P2O) energy transaction between a power cell and an operator of some service of the Internet of energy.

5 One of the participants (parties) of energy transactions and the structural unit of the power system controlled by the Internet of energy is the **power cell.** A power cell is a set of power units (generators, energy storage systems, electric loads) that is connected to distribution electric grids, has a single **interface** for connecting to the Internet of energy, and acts as a single actor in energy transactions with other power cells and services of the Internet of energy. Another type of energy transaction participant is the service operator of the Internet of energy.

6 Each power cell is provided with a **software agent**, which serves for representing the power cell on the Internet of energy, coordinated control over interaction of the power cell with all systems of the Internet of energy, its participation in the services of the Internet of energy, dispatching of this participation in order to avoid a conflict of services for the resources of the power cell, interaction of the power cell with other power cells via their software agents, data exchange with the local automation of the power cell equipment or its local control system, sending control signals and commands to this local

automation of the power cell equipment or to its local control system.

7 To ensure interoperability in the interaction between power cells (their software agents) and to implement energy transactions, three systems operate within the Internet of energy:

— **Transactive Energy (TE)** is the system for implementing the commercial component of energy transactions which performs fully automatic formation and protected hosting of smart contracts that fix the parameters of energy transactions, verification of their execution, financial settlement of fulfilled obligations, fixing discrepancies and disputes, usage of data for their settlement and performing clearing functions. In particular, the system implements the meter-to-cash function – fully robotized electric power billing and processing.

— **Internet of Things (IoT)** is the system for implementing the informational component of energy transactions in which machine-to-machine (M2M) interaction is performed, as well as the exchange of all informational and control signals necessary for energy transactions between power cells and their software agents, access of software agents to the local automatic devices of the equipment and/or local control systems of power cells, as well as the creation, hosting and provision of digital twins and digital shadows of power cells and their equipment, operation of auxiliary software for machine-to-machine interaction.

— **Neural Grid (NG)** is the system for implementing the physical (electrical) component of energy transactions which provides, if necessary, the decentralized power-frequency control, power flows control in the power system in order to form the power transmission mode necessary for energy transactions realization and maintaining static and dynamic stability in the conditions of simultaneous performance of many energy transactions. The system provides the functions of adaptive relay protection and automation – technological protection of power cells and power grid in the conditions of bidirectional power flows caused by energy transactions, as well as the integration of certain types of power cells with electric networks (connection to power grids).

Introduction

The Internet of Distributed Energy Architecture (IDEA) was developed to meet the demand of rapidly developing distributed energy sector and new business practices related to this energy sector for a new approach to the formation and management of power systems.

The development of the IDEA was carried out in the context of the EnergyNet National Technological Initiative project. The first, preliminary version of the architectural framework was published in December 2018 [1]. During the two years that passed, the project team has come a long way. The Infrastructure Center «EnergyNet» performed a large amount of theoretical work and consultations with Russian and foreign power and electric engineers (including specialists from IEEE and CIGRE), a demonstration complex (full-scale model) of architecture implementation was created together with the partners at the Moscow Institute of Physics and Technology (MIPT), and a real-time testbed was launched at the Moscow Power Engineering Institute (MPEI) to verify the compliance of technological solutions with the requirements of the IDEA. Besides, in terms of the project and by the efforts of its partners, prototypes of a number of new technological products used in the Internet of energy were created: energy router (by Smart Electric Power Systems LLC) and energy hub (by Energy Development Engineering Center LLC), ØNDER transaction platform (by Eliot LLC), an instrumental A-platform for distributed power (by RTSoft JSC) are being developed. A consortium consisting of the project team, the Institute of Arctic Technologies of MIPT, Eliot LLC (startup ØNDER) and RTSoft JSC signed an agreement with Nanyang Technological University, within of which a pilot project was launched for the implementation of the IDEA elements in Singapore at the REIDS test sitetest site (Semakau island). Besides, in cooperation with the Institute of Arctic Technologies of MIPT, the AHEAD project was launched for creation of the «Snowflake» International Arctic station, which implements many of the provisions of the IDEA.

All this work made possible the detailed development of the preliminary version of architectural description, reconsidering and clarification of many of its provisions, addition of new ideas. As compared to the preliminary version, the architectural framework has been supplemented with the vision of digital agents (software agents) of power cells, with the versions for forming a system for power flows control and maintaining reliability called Neural Grid system, comprehension of relationships between the components of the Internet of Energy was clarified, and the architectural description itself now contains a detailed representation of the modular implementation of the IDEA on the example of the demonstration complex.

The next step in the development of the IDEA should be made by its full implementation in pilot projects of new energy communities, microgrids, energy services, for example, related to the demand side management and demand response, power centers and power systems management.

We invite all interested organizations of the energy sector to joint implementation of the IDEA at your facilities and in the context of your projects.

Besides, efforts in advanced research and development of new technologies are needed in order to implement the IDEA architecture and its key components in practice. We invite scientific organizations and technology companies to partnership in the development of the IDEA and creation of products based on it.

You can get acquainted with the concepts of the Internet of Distributed Energy Architecture, the project status and partner projects implemented in the EnergyNet NTI ecosystem by visiting the project website idea-go.tech, and also on the EnergyNet NTI website energynet.ru.

The urge of a new architecture for energy systems

New architecture for distributed energy systems

The necessity for developing a new architecture of energy systems is determined by the fact that effective progress of energy sector within the framework of currently dominating paradigm of centralized energy systems is no longer possible. The centralized architecture of energy systems has exhausted its capabilities for satisfying the requirements and requests of consumers and providing the growth of energy system efficiency.

Rapid progress and mass implementation of distributed energy solutions is based on an alternative paradigm offering closeness of generation to the consumer, localization of energy balances, changing the roles of consumers, and the emergence of new types of entities in energy systems that combine the properties of generators and consumers – so called prosumers. From the point of view of satisfaction of the needs of consumers and ensuring the economic efficiency of power supply, the distributed energy system, especially when properly coupling with the traditional energy system, is often more efficient than the centralized electricity supply by bulk generation and grid. Thus, the report «Active energy complexes – the first step towards industrial microgrids in Russia» shows that such solution of a distributed energy as the industrial microgrids reduces the expenses of consumers by 5% to 25% as compared with energy consumption solely from a centralized grid [2].

Figure 1 shows a comparison of the principles of arrangement of centralized and decentralized energy systems (the Internet of energy approach). The centralized energy system assumes that electricity is generated at bulk generation – power plants with single capacity of hundreds and thousands of megawatts – and then is transmitted in one direction over the transmission system and then over distribution network to end consumers, large as well as distributed small ones. Information – in this case, information related to consumption – moves in the opposite direction from the consumers via the network and utilities to the centralized dispatching control system and to bulk generators.

The distributed energy system in its ultimate version is an energy system in which bidirectional flow of electric energy between electric grids and their users is implemented. Generally, these users can be prosumers, that, depending on the circumstances, can either produce energy and export it to the grid, or receive electricity from the grid and consume it. Besides, the decentralized energy system includes distributed generation and consumers, including those that have the capability to control their consumption. Free energy exchange supported by the energy infrastructure is sustained among all these entities, and a multi-way exchange of information necessary for energy exchange and mutual trade carried out on some or other marketplaces.

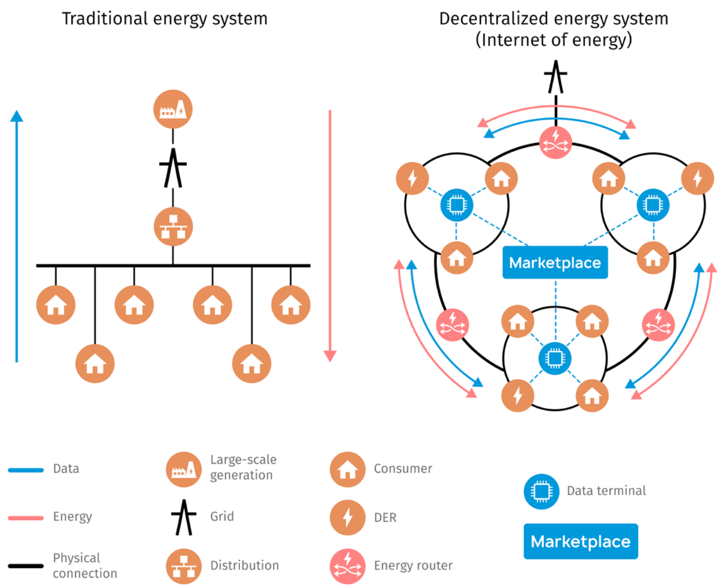

Figure 1. Comparison of the principles of arrangement of centralized and decentralized energy systems

But the implementation of distributed energy system using the centralized architecture of energy systems is inefficient: significant problems and costs arise when integrating distributed energy systems into centralized energy systems, system reliability of the energy system in this case is often deteriorated, and the potential of distributed energy cannot be achieved in full measure. As a result, this leads to various administrative and technological barriers in the interaction of distributed and centralized energy systems. Distributed energy system and the centralized architecture of large energy systems get into conflict with each other.

On the other hand, it is unreasonable to develop the electric power industry according to the principle of complete autonomy and autarky, when each consumer owns his own generation providing only his needs for energy supply. A simple analysis shows that the available capacities in this case are used with lower ICUF, while the cost of electricity supply with the same level of reliability as provided by the grid is increased by a factor of 3 or even more. Autonomous supply makes sense only in the areas located far from the grids of centralized power supply, isolated and hard-to-reach areas, but even there it is reasonable to create local energy systems, rather than to self-supply each consumer individually.

All in all, it is impossible to develop effectively the distributed energy, which has a huge economic potential, without a new architecture suitable for it, which would offer a decentralized approach to the arrangement and control of energy systems.

Drivers for transition to the new architecture

Change in the nature of consumer demand for electricity

The nature of the demand for electric energy and the requests of electricity consumers in the world have changed significantly over the past 10 to 15 years. First, these requests became more differentiated. The growing importance of climate agenda and worldwide struggle against climate change, which led to the adoption of the Paris Agreement and various national and regional programs and plans for its implementation, have made the carbon footprint the most important characteristic of electricity. For numerous consumers in Europe, the United States, Canada, Japan, Australia and many other countries, it is important how «green» is the electricity they receive, and this characteristic becomes more important than the price of energy, which is confirmed by the introduction of appropriate national regulation as well as by the growing popularity of «green» tariffs. For other consumers, on the contrary, the cost of electricity supply is the most significant factor. This is typical for both industrial and agricultural developing economies, especially those where the electrification process is not fully completed yet. Finally, a new type of consumers has appeared, which has got a provisional name of «digital demand», for which the quality of electricity (mainly the voltage level stability) and the reliability of electricity supply (the values of CAIDI and CAIFI) are the decisive factors. As a rule, such consumers are associated with computer equipment (data centers), precise industrial processes and additive manufacturing. The toughening of requirements to quality and reliability of electricity supply from the «digital demand» was forecasted by RAND Corporation as far back as 20 years ago [3], and is now confirmed by researchers from Lancaster University, who forecast the growth rate of electricity consumption by digital devices and ICT infrastructure at the level of 7% per year and show that peak hourly consumption in the UK and the Netherlands coincides with the peaks of use of digital equipment and Internet resources [4].

Hence, the emergence of these groups of demand for electricity with qualitatively different requirements to electricity must lead to customization of the supply on the energy market. But the traditional electric power industry and the centralized power systems that form its basis do not provide for the possibility of such customization, they ensure the supply of standardized electricity identical for all consumers, and practically do not allow consumers to influence such characteristics of electricity as quality or origin.

Secondly, due to the increase in energy efficiency, both in developed and in many developing industrial economies, the growth of electricity consumption has practically stopped, but the average number of consuming electrical devices per consumer is growing. For example, in the UK, during the period from 1972 to 2017, the GDP growth rate increased from 1% to more than 3%, while the increase in electricity consumption throughout this period was at the level of 1% per year, and since 2008 it is steadily decreasing to values less than 0.8% [5]. The emergence of new types of energy-receiving devices, such as electric vehicles and mobile robots, has changed the very nature of demand in the electric power industry: while overall demand for electricity is growing slowly, the demand for capacity is growing sharply, in particular, the capacity required for charging stations. Thus, according to McKinsey & Company estimate, the daily unevenness of household electricity consumption (peak consumption) after mass spread of electric vehicles will increase by 30% as compared to the present-day level [6]. This means that the market value of the capacity (kW) connected to a consumer will grow much faster than the value of electricity (kWh). When using the traditional, centralized architecture of power systems, this leads to increase in the costs of construction and maintenance of the relevant generating and network capacities, while the efficiency of their use, in particular, ICUF and infrastructure load, are decreasing. The growth of these costs inevitably leads to increase in the cost of electricity supply for the end users.

Moreover, the centralized electric power industry has now reached its limit of efficiency. This is true in regard of technological improvement, which is expressed in increase of generation efficiency, reduction of specific fuel consumption, decrease of transmission losses and improvement of other technical parameters, as well as in regard of improvement of the economy of power industry, which is expressed in such indicators as levelized cost of energy (LCOE) of large generators and total expenses of consumers on electricity supply. The economies of scale, when increase in the unit capacity of a power plant resulted in decrease of unit cost of electricity generation, ceased to be a significant factor as far back as in the early 1990s [7]. These unit costs for traditional types of generation are not decreasing for more than a decade. The possibility of reducing technological losses in power grids is also almost exhausted. At the same time, the expenses of end consumers for energy supply in centralized power systems are growing, despite the fact that the cost of fuel can decrease, and sometimes – during sharp falls in oil prices – decrease significantly. For example, according to the analysis by non-commercial partnership «Energy Consumers Association», the average price of electricity for industrial enterprises in Russia in 2019 increased by 2.7% in dollar terms, while the ruble-dollar exchange rate decreased during this period, and the price increase in rubles was 6%, twice higher than the average annual inflation [8].

At the same time, the capabilities of consumers themselves in regard of the power system are changing. The advent of digital technologies allows consumers to control their loads effectively and transfer remote control of these loads to other entities. This means the emergence of «active consumers» who influence the balance in power systems by regulating their consumption. Another significant factor in changing the role of consumers in energy systems in recent years is the spread of energy storage systems, which technologies are becoming cheaper, and the storage devices are becoming affordable for consumers. Storage devices provide consumers with flexibility in regard of consumption from the grid, up to the possibility of temporary stopping consumption and even exporting electricity back to the grid. Finally, the reduction in the cost of small distributed generation, both gas-fired and based on renewable energy sources, including microgeneration, makes possible for consumers to be generators as well, reducing the consumption of electricity from the grid and exporting excess electricity to the grid. It is clear that consumers would like to use these new opportunities to their advantage, but the architecture of centralized power system does not allow this to be done, because it does not provide for bidirectional energy flows or such a role as a prosumer.

Thus, traditional energy industry can no longer supply electricity to consumers with the quality characteristics and at the cost that these consumers need, and give them the opportunities to participate in the operation of energy systems they would like to have.

Energy transition

An important driver for transition to a new architecture of energy industry is the energy transition. The process of energy transaction, as is known, is determined by three components, the so-called «3D»:

1. Decarbonization (transition to carbon-neutral energy);
2. Decentralization (transition to distributed energy);
3. Digitalization (transition to digital technologies in energy industry).

In this regard, decarbonization, which is associated with the use of RES in the first place, leads to decentralization of power system, because many types of RES, such as solar power plants and, in some cases – wind power plants, do not require concentration of their capacities in one place. The economy of scale does not work in these cases: the concentration of capacity does not reduce the unit cost of electricity for these plants, meaning that when they are located near distributed consumers, it becomes possible to reduce the grid costs of transporting electricity to these consumers.

But the integration of RES, both concentrated and distributed, into power systems causes significant problems. These problems arise in connection with the complex dispatching control of power systems with a large share of RES, because due to stochastic nature of electricity generation based on RES, the requirements to power-frequency control and the requirements to relevant capacities increase. Besides, integration of distributed RES complicates the implementation of relay protection and automation in distribution networks. Increase in the share of so-called «electronic» generation, that is, generation connected to electric grids via inverters, also leads to undesirable consequences for the controllability of power systems and stability of power transmission modes in them.

Without a new architecture for building power systems, further significant increase in the share of RES in them is practically impossible. Moreover, increase of RES share causes decrease of system reliability in centralized power systems. For example, one of the causes of a well-known blackout in the UK that occurred on August 9, 2019, was the underestimation of distributed generation connected to low-voltage networks, and the impact of its disconnection from the system on the power balance in the system when the corresponding feeders were switched off [9]. According to the report of Professor Phil Taylor, director of the National Centre for Energy Systems Integration at Newcastle University, made at the Singapore Energy Week in November 2019, the emergency disconnection of a number of low and medium voltage lines instead of unloading the system led to the loss of capacity provided by municipal RES and further development of emergency situation.

Digitalization of energy industry, on the contrary, opens technological opportunities for implementation of distributed energy in the framework of new architectural approach, because it provides the necessary information flows and determines the necessary density of digital controlled devices, including those on the consumer side, in particular, digital electricity metering and remote access to consumer electrical devices.

The problem of integrating distributed energy into energy systems

As can be seen from the above analysis, the implementation of distributed energy in the paradigm of centralized energy systems and its integration into these energy systems leads to obvious problems and unavoidable collisions and conflicts between the new energy practices and the old, traditional energy system architecture. These problems can be summarized in the form of three types of costs which increase with attempts to integrate distributed energy into the present-day energy systems:

1. **Transaction costs** that increase as the number of active participants in the operation of the energy system grows, in particular, the number of participants in the energy exchange;
2. **Information integration costs** related to the necessity to include a large number of participants in the work of distributed energy system into the control circuits and information channels for the exchange of data and commands;
3. **Costs of integration of power equipment into the grids** associated with the complexity of ensuring the reliability of grid operation, as well as the static and dynamic stability of power transmission modes with a large number of energy exchange participants, including those connected to the networks via inverters.

The purpose of Internet of Distributed Energy Architecture (IDEA) is to eliminate these costs and solve the problem of integrating the objects of distributed energy system into energy systems and building fully distributed energy systems.

Conceptual model

The **Internet of energy** is a cyber-physical infrastructure for information systems of decentralized smart (robotized) control of energy systems, energy nodes, power supply systems and integration of distributed active consumers of electric energy, distributed energy sources and energy flexibility into them.

Decentralized smart control over the energy system in the Internet of energy is implemented through **energy transactions** performed in the **framework** of services of Internet of energy. Figure 2 shows the conceptual model of Internet of energy demonstrating the process of performing an energy transaction.

An energy transaction is a set of operations of interaction of users of the Internet of energy and their electrical units with each other as well as with service operators, in which there is a controlled payable change in the parameters of production or consumption of active and/or reactive power by electrical units of the parties to the energy transaction, due to which one party to the energy transaction receives a useful quality, economic value associated with the operation of the energy system, energy node, power supply system, and the other party to the energy transaction receives payment.

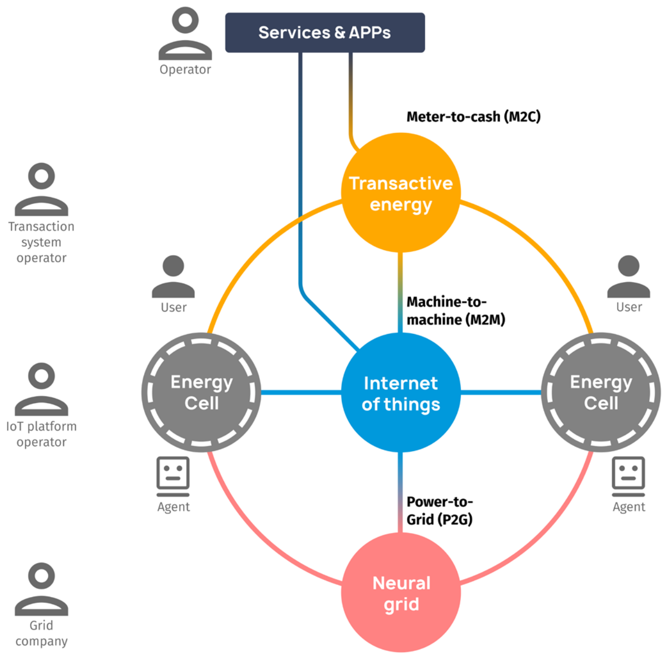

Figure 2. Conceptual model of the Internet of energy

The participant (party) of energy transactions and the structural unit of the energy system controlled by the Internet of energy is the **power cell**. A power cell is a set of energy equipment (generators, storage devices, electric receivers) that is connected to distribution electric grids, has a single **interface** for connecting to the Internet of energy and performs as a single actor in energy transactions with other power cells and services of the Internet of energy.

Each power cell is provided with a **software agent** through which many functions are performed: representation of the power cell on the Internet of energy, coordinated control of interaction of the power cell with all systems of the Internet of energy, its participation in the services of the Internet of energy, dispatching of this participation in order to eliminate the conflict of services for the resources of the power cell, interaction of the power cell with other power cells through their software agents, data exchange with the local automatics of the power cell equipment or its local control system, issuance of control signals and commands to this local automatics of the power cell equipment or to its local control system. One software agent corresponds to each power cell.

Users of the Internet of energy are owners of power cells and providers (operators) of services of the Internet of energy. Owners of power cells are any individuals and legal entities that own electric power equipment (electric receivers, generators or electricity storage devices) and therefore act as subjects of the electric power industry. They include owners of distributed generation, electricity storage systems, and electricity consumers connected to distribution networks. A single user of the Internet of energy can own many power cells, and, accordingly, many software agents can work in his interests. The users interact with software agents by means of user interfaces of these agents or by means of applications of special services.

Services of the Internet of energy are energy practices of economic and technical interaction of the subjects of the electric power industry implemented on the Internet of energy through energy transactions. Energy transactions are the minimum acts of implementation of services of the Internet of energy, their building blocks, and services of the Internet of energy are sets of scenarios and rules for interaction of software agents during implementation of energy transactions. Services of the Internet of energy provide a reproducible opportunity to generate useful economic benefits from new energy practices. Software packages that technically implement the services on the Internet of energy and interact with software agents and users of the Internet of energy are called **service applications**.

Energy transactions between power cells are carried out through the interaction of software agents of these power cells with applications of the Internet of energy and with other software agents. Software agents implement the scenarios and rules embedded in the service applications, and form and execute agreements with other agents and/or service operators according to these scenarios and rules. A single power cell can participate simultaneously in several different energy services. At the same time, the software agent performs dispatching of participation of the power cell in the services in order to eliminate service conflicts for the resources (equipment capabilities) of the cell, taking into account its environment and location in the network topology, as well as prioritizing the participation of the cell in the services according to the settings of the user – owner of the cell. Software agents do not perform optimization and/or dispatching of the operation of power cell equipment, but only transmit signals and commands to the local automatics and/or control system of this equipment which execution will ensure the fulfillment of obligations in the framework of current energy transactions. The task of optimization and/or dispatching of the operation of the set of power cell equipment is assigned to the corresponding service applications.

The main subjects of energy transactions are the market values (useful properties) on the Internet of energy which can be considered as the primary underlying assets of transactional energy system on the Internet of energy:

1. **Electric energy** – electric energy as a commodity produced by power cells and delivered to consumers in measurable supply volumes and with measurable quality characteristics;
2. **Power** – readiness of power cells to provide a given level of active and/or reactive power of their power equipment under specified conditions;
3. **Flexibility** – dynamic influence of power cells on the balance of electricity and active and/or reactive power in the energy system, as well as on the parameters of power transmission mode, performed either upon request or under specified conditions, provided by maneuverability and regulatory impacts of the power equipment of power cells and supplied as a service or commodity.

Two types of energy transactions are available in the Internet of energy, differing by their actors, and they are the main use cases of the IDEA:

1. **Peer-to-peer (P2P) energy transaction** is conducted between two power cells, it assumes a consistent and synchronized change of the parameters of power generation and consumption by these cells. The application of the relevant service acts in a peer-to-peer transaction

as an electronic platform and a set of rules and algorithms for the interaction of software agents of power cells.

2. **Peer-to-operator (P2O) energy transaction** is conducted between a power cell and an operator of the service of the Internet of energy: the operator in this case acts either as a service provider for this power cell or an aggregator of services rendered by power cells in the interests of entities of the energy system that are beyond the Internet of energy (bulk generation, grid companies, system operator, other entities of the centralized energy system). In the case of a peer-to-operator energy transaction, the service operator acts as an intermediary between the centralized energy system and the Internet of energy. The service application interacts with the software agent of the power cell for the purpose of formation and implementation of an energy transaction.

Power cells and their software agents form a mesh network with high interoperability of nodes in which energy transactions between any power cells are principally allowed, including those with significantly different levels of power, as well as with any service operators. The Internet of energy provides consideration and implementation of the necessary conditions for the execution of these transactions, including formation of the necessary physical power flows that lead to execution of the entire pool of formed transactions.

To ensure interoperability during interaction between power cells, their software agents and service applications, as well as for implementation of energy transactions as the main form of these interoperable interactions, three systems operate as part of the Internet of energy:

1. **Transactive Energy (TE)** is the system for implementing the commercial component of energy transactions which incorporates fully automatic formation and secure storage of smart contracts that record the parameters of energy transactions, verification of their execution, financial settlement of fulfilled obligations, fixing of discrepancies and disputes, usage of data for their resolution and performance of clearing functions. The system implements the meter-to-cash function – fully robotized electricity billing and processing.
2. **Internet of Things (IoT)** is the system for implementing the informational component of energy transactions which incorporates machine-to-machine (M2M) interaction and exchange of all information and control signals necessary for energy transactions between power cells and their software agents, access of software agents to the local automatics of equipment and/or local control systems of power cells, as well as

formation, storage and provision of digital twins and digital footprints of power cells and their equipment, operation of auxiliary software for M2M interaction.

3. **Neural Grid (NG)** is the system for implementing the physical (related to electric power) component of energy transactions, which, when necessary, provides decentralized frequency controlpower-frequency controlpower-frequency control, control of power flows in the energy system for the purpose of arranging the power transmission mode necessary for the implementation of energy transactions and for maintaining its static and dynamic stability in the conditions of simultaneous implementation of many energy transactions. The system provides the functions of adaptive relay protection and automation – technological protection of power cells and the electric grid in the conditions of bidirectional power flows caused by energy transactions, as well as integration of certain types of power cells with electric grids (connection to electric grids). At the utmost limit of implementation of the IDEA, the infrastructure of the distribution electric grids should become part of this system.

The presence of these three systems provides the possibility of **seamless** connection of new users of the Internet of energy and new power cells on **plug & play** principle and their interoperability during interaction with each other and with service applications. This means that after connection of each new power cell to the Internet of energy, access to all applications of the Internet of energy services and the possibility to perform energy transactions is opened automatically for this power cell.

Software agents of power cells use service applications to form the parameters of energy transactions, the **Transactive Energy** system to form the corresponding smart contracts, verify their execution using data from accounting and measuring devices that transmit data via the Internet of Things system, and perform financial calculations on them to complete transactions. Access of software agents to local automatics and/or control systems of the power cell equipment is implemented via the **Internet of Things** system. Active control of power flows according to the pool of simultaneously performed energy transactions, formation of the power transmission mode necessary for their implementation, maintaining the static and dynamic stability of this mode and providing the functions of technological protection during implementation of energy transactions is performed by the Neural Grid system. For this purpose, the equipment of the **Neural Grid** system which controls power flows in the energy system is provided with the upper-layer control systems that interact via the Internet of Things system with software agents of power cells and with service applications. This equipment receives data related to the planned parameters of power generation and power consumption by power cells according to the pool of current energy transactions, generates cumulative values of the necessary power flows for the execution of energy transactions, and provides actual execution of energy transactions by controlling the power flows.

The listed systems can function independently of each other, and the systems can be implemented separately. In this case, however, they will perform only a part of the functions of the Internet of energy, and only a limited set and functionality of the Internet of energy services and related energy transactions will be available for implementation. The Internet of energy, therefore, is a system of systems.

Use cases

The main use case of the Internet of energy consists of implementation of energy transactions. Information systems that use the Internet of energy implement decentralized smart (robotized) control through the implementation of energy transactions.

An energy transaction is a set of operations of interaction of the users of the Internet of energy and their power cells with each other, as well as with service operators, in which controlled payable change in the parameters of production or consumption of active and/or reactive power by electrical units belonging to the parties to the energy transaction takes place, due to which one party of the energy transaction receives a useful quality, economic value associated with operation of the energy system, energy node, power supply system, and the other party of the energy transaction receives payment.

Main use cases

The Internet of energy must provide the implementation of two main use cases:

1. peer-to-peer (P2P) energy transaction;
2. mixed, or peer-to-operator (P2O) energy transaction.

Peer-to-peer energy transaction

A peer-to-peer (P2P) energy transaction is performed between two power cells under the following conditions:

1. both power cells involved in the energy transaction are connected to the Internet of energy;
2. the application of the service within the framework of which the energy transaction is performed is hosted on the Internet of energy;
3. both power cells participating in the energy transaction are subscribed to the service within the framework of which the energy transaction is performed.

A P2P energy transaction is performed according to the following scenario:

1. one of the software agents of the power cell initiates interaction with the other software agent of the power cell and with the service application by sending messages with a request for an energy transaction according to the procedure and form stipulated by the service;

2. another software agent of the power cell that has received a request for an energy transaction responds to it according to the procedure and form stipulated by the service;
3. software agents of power cells perform interaction, which is expressed in the exchange of messages according to the procedure and form stipulated by the service, and basing on the results of such exchange of messages, the parameters of contractual relations (smart contracts) are formed;
4. software agents of power cells perform recording of the contractual parameters of the energy transaction;
5. software agents of power cells form and transmit to the control system of the power cell or to the control system of the electrical installation of the power cell the commands for changing the parameters of production or consumption of active and/or reactive power that trigger the execution of the energy transaction;
6. the energy transaction is actually implemented due to changes in the parameters of production or consumption of active and/or reactive power;
7. in course of implementation of the energy transaction, static and dynamic stability of the electric power transmission mode, preservation of quality parameters of electric energy in the grid must be maintained;
8. software agents of power cells record the actual value of the flow of active and/or reactive power using measuring equipment;
9. software agents of power cells, basing on the actual value of the flow of active and/or reactive power, monitor execution of the energy transaction, form and transmit commands to the control system of the power cell or to the control system of the electrical unit of the power cell for changing the parameters of production or consumption of active and/or reactive power, completing the execution of the energy transaction;
10. software agents of power cells, according to the parameters of the energy transaction, arrange payment for the execution of the energy transaction on the basis of data on the actual value of the active and/or reactive power flow.

Peer-to-operator energy transaction

A peer-to-operator (P2O) energy transaction is performed between a power cell and a service operator under the following conditions:

1. a power cell involved in the energy transaction is connected to the Internet of energy;
2. the application of the service within the framework of which the energy transaction is performed is hosted on the Internet of energy;
3. the power cell participating in the energy transaction is subscribed to the service within the framework of which the energy transaction is performed.

A P2O energy transaction is performed according to the following scenario:

1. a software agent of the power cell or a service application initiates interaction by sending messages with a request for an energy transaction according to the procedure and form stipulated by the service;
2. a software agent of the power cell or a service application that has received a request for an energy transaction responds to it according to the procedure and form stipulated by the service;
3. the software agent of the power cell performs interaction with the service application which is expressed in the exchange of messages according to the procedure and form stipulated by the service, and basing on the results of such exchange of messages, the parameters of contractual relations (smart contracts) are formed;
4. the software agent of the power cell and the service application perform recording of the contractual parameters of the energy transaction;
5. the software agent of the power cell forms and transmits to the control system of the power cell or to the control system of the electrical unit of the power cell the commands for changing the parameters of production or consumption of active and/or reactive power that trigger the execution of the energy transaction;
6. the energy transaction is actually implemented due to changes in the parameters of production or consumption of active and/or reactive power;
7. in course of implementation of the energy transaction, static and dynamic stability of the electric power transmission mode, preservation of quality parameters of electric energy in the grid must be maintained;
8. the software agent of the power cell and the service application record the actual value of the flow of active and/or reactive power using measuring equipment;

9. the software agent of the power cell, basing on the actual value of the flow of active and/or reactive power, monitors execution of the energy transaction, forms and transmits commands to the control system of the power cell or to the control system of the electrical installation of the power cell for changing the parameters of production or consumption of active and/or reactive power, completing the execution of the energy transaction;
10. the software agent of the power cell and the service application, according to the parameters of the energy transaction, arrange payment for the execution of the energy transaction on the basis of data on the actual value of the active and/or reactive power flow.

Auxiliary use cases

The Internet of energy must provide the implementation of the following auxiliary use cases:

1. connecting the power cell;
2. placing the service application;
3. configuring the software agent of the power cell;
4. performing subscription to the service;
5. changing the composition of electrical installations of the power cell;
6. changing the user of the power cell;
7. updating the service application;
8. terminating the subscription to the service;
9. disconnecting the power cell.

Basing on the specified main and auxiliary scenarios for the use of the Internet of energy, a wide variety of options for the interaction of power cells with each other and with service operators can be formed, that is, a wide variety of different services and corresponding applications with their own scenarios can be implemented, for which scenarios for the use of the IDEA (use cases) will act as building blocks.

Necessary properties of the Internet of energy

In order to effectively implement these use cases, the Internet of energy must have the following properties:

1. interoperability;
2. scalability;
3. openness;
4. reliability.

Interoperability in the Internet of energy must be provided in two senses:

— interoperability of service applications with software agents of power cells and systems of the Internet of energy;
— interoperability of control systems of power cells, control systems of electrical units of power cells with software agents of power cells.

Scalability of the Internet of energy must be provided by means of automated connection of power cells and electrical units of power cells to the Internet of energy with implementation of the principle of automatic occurrence of full access to the functions of the system after connection (plug & play).

Openness of the Internet of energy must be provided in two senses:

— openness of the Internet of energy for third-party developers of service applications and software, providing simplicity of development and placement of services applications on the Internet of energy;
— openness of the Internet of energy for users of power cells, providing simplicity of connecting and working with the Internet of energy.

The property of reliability of power supply in the Internet of energy must be provided by maintaining the static and dynamic stability of the power transmission mode in the conditions of simultaneous implementation of a large number of energy transactions.

Architectural framework

The basic architectural scheme of the Internet of energy is shown in Figure 3. It demonstrates the component composition of the Internet of energy and the interrelations of the components and systems of the Internet of energy with each other and with the external environment which composition is described in the section «Conceptual Model».

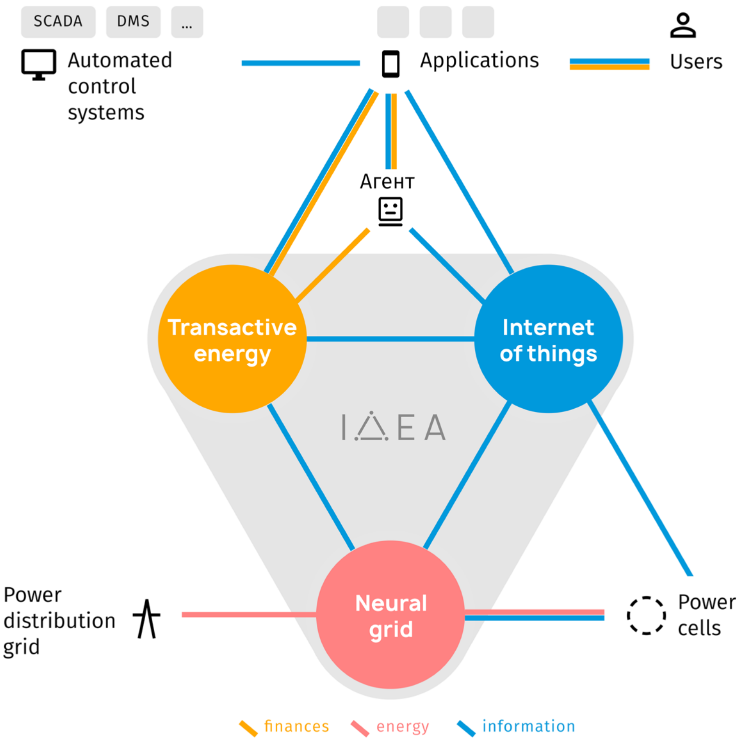

Figure 3. Schematic representation of the Internet of distributed energy architecture (IDEA)

The composition of the Internet of energy must include a multi-agent system of software agents of power cells and the following three systems of the Internet of energy:

1. system of transactions: Transactive Energy (TE);
2. system of machine-to-machine interaction: Internet of Things (IoT);

3. system of distributed power-frequency control: Neural Grid (NG).

Software agents of power cells must have information links with the TE and IoT systems. Software agents of power cells must have the information link for exchange of financial and contractual data («financial» link) with the TE system. Software agents of power cells must have the information link and the link for exchange of financial and contractual data with service applications. Service applications must have information link and «financial» link with software agents of power cells and with the TE system. Users of power cells and service operators must have information link and «financial» link with service applications and software agents of power cells through service applications in the form of user interfaces. Automated control systems and information systems of centralized energy systems must have an information link with the Internet of energy through service applications.

Software agents of power cells must use the TE system for the purpose of formation of digital contracts, verification of their execution using data from electric energy meters and power meters, and performance of financial calculations using them. Access of software agents of power cells to the control systems of the power cell and/or to the control systems of electrical units must be performed using the IoT system. Control over power flows according to the set of simultaneously performed energy transactions, formation of the power transmission mode required for their implementation, maintaining static and dynamic stability of this mode, provision of the functions of technological protection during performance of energy transactions must be performed by the NG system. For this purpose, the components of the NG system that control power flows in the energy system must be linked via the IoT system with software agents of power cells and service applications and receive data from them on the contractual parameters of power production and consumption by the power cells in the framework of current energy transactions. NG components must form cumulative values of the required power flows for the execution of these energy transactions.

Architecture applicability limits

The sphere of applicability of the reference Internet of distributed energy architecture is only the distributed energy system and the consumers connected to electric distribution grids. Hence, the applicability limit of the reference IDEA is on the boundary of distribution grids and transmission (backbone) grids in energy systems at voltage level of 110 kV.

Power cell

A **power cell** is the minimum structural unit of the energy system which is controlled on the basis of the Internet of energy.

From the point of view of the Internet of energy, a power cell has no internal complexity. This means that for a software agent of a power cell, for software agents of other power cells, and services of the Internet of energy, this power cell is a «black box» participating in energy transactions that has the capability to supply and/or consume electrical power, to receive, send, and process information signals, and due to these capabilities the power cell exchanges electricity and/or data, including electronic means of payment, with other power cells and service applications. The internal complexity of a power cell in regard of other power cells and service applications is removed by the systems of the Internet of energy.

Power cells, depending on their capabilities to supply and/or consume electrical power and their capability to regulate these processes, may belong to one of the six types listed in Table 1. Typological category of a power cell is determined by the roles that the power cell can play in the Internet of energy.

Table 1. Typology of power cells

Capabilities for the supply and/or consumption of electric power	Capability of flexible regulation of the amount of flow (supply and/or consumption) of electric power	
	Available	Unavailable
Supply of electric power only	**Load following generator** Examples: Mini-CHP, diesel-generator set.	**Stochastic, or variable generator** Examples: solar power plant, wind power generator.
Supply as well as consumption of electric power	**Prosumer** Examples: Office building with roof solar panels and electricity storage devices, electricity storage system.	**Consumer with own variable generation** Examples: Townhouse, industrial enterprise workshop building with roof solar panels.

Only consumption of electric power	**Active consumer** Examples: Office building with remotely controlled air conditioners, «smart» thermostat-water heater.	**Passive, or traditional consumer** Examples: Household, metallurgical plant induction furnace.

The need of power cells for energy transactions with each other is determined to a great extent by the fact that these power cells belong to different types, and therefore by the different nature of needs, capabilities, and the different nature of the impact on the energy system and thereby — on each other. Table 2 contains the assessment of possible roles of power cells in energy transactions, and therefore, in the Internet of energy.

Table 2. Roles of power cells in energy transactions

Type of power cell	Subject of energy transaction					
	Electric energy		Power		Flexibility	
	Seller	Buyer	Seller	Buyer	Seller	Buyer
Load following generator	+	–	+	–	+	–
Stochastic generator	+	–	+	+	–	+
Prosumer	+	+	+	+	+	–
Consumer with own variable generation	+	+	–	+	–	+
Active consumer	–	+	+	+	+	–
Passive consumer	–	+	–	+	–	+

The variety of roles that different types of power cells can play in energy transactions and their dynamically changing needs and capabilities produce a large number of possible combinations of power cells that enter into energy transactions for mutually beneficial interaction. This, in its turn, creates the basis for deployment of a large number of services focused on providing efficient operation of microgrids, peer-to-peer trade and provision of services, and other new energy practices for distributed energy system.

Power cells are connected to electrical grids which topology, together with the layout of connection points of power cells, provides the mutual topological position of power cells. Due to this mutual position, cases of «nesting» of power cells in each other relative to the power center of the distribution electrical grid are possible. That is, one power cell is connected to a feeder inside another power cell. Participation of the «inner» power cell in energy transactions in such a situation will affect participation of the «outer» power cell in energy transactions, and vice versa. There is a possibility of a collision with simultaneous non-execution of the parameters of energy transactions of two power cells that affect each other. From the point of view of the Internet of energy, both power cells are still represented as «black boxes» without internal structure. IDEA defines the following ways for preventing such collisions:

1. the service application in the framework of which the energy transaction is formed sends a request to the arbitrator application placed on the IoT system for obtaining either a permission to perform the energy transaction or data to adjust its parameters in order to avoid collisions;
2. software agents of power cells send requests to the arbitrator application placed on the IoT system for obtaining either a permission to perform the energy transaction or data to adjust its parameters in order to avoid collisions;
3. software agents of power cells send requests to the distributed model of the network section placed on the IoT system before initiating the formation of an energy transaction for the purpose of clarifying the resources and limitations of a power cell;
4. software agents of power cells formulate their own model of a network section based on querying of each other before initiating formation of an energy transaction for the purpose of clarifying the resources and limitations of a power cell.

The IDEA does not establish preferences for selecting one of these options and leaves the choice to the developers of IDEA implementations.

Nevertheless, presence of effects of mutual influence of power cells and energy transactions in the Internet of energy makes it important to implement the technologies that allow formation and updating the model of the electric grid, the limitations of topology and mode.

Software agent of a power cell

The functions of the software agent of a power cell are:

1. representation of the user and his power cell on the Internet of energy;
2. support of participation of the power cell in the services;

3. interaction with other software agents of power cells and with service applications;
4. dispatching of participation of the power cell in the services in order to avoid collisions in the conditions of limited resources of the power cell;
5. transmission of energy transaction parameters to the TE system;
6. transmission of commands to the control systems of power cells and control systems of electrical installations of power cells via the IoT system;
7. transmission of data related to parameters of energy transactions to the NG system via the IoT system.

The software agent of a power cell must include the following components:

1. software core of the agent;
2. user interface;
3. software interface with the TE system;
4. software interface with the IoT system.

When implementing a multi-agent system of software agents of power cells, the FIPA-ACL or KQML protocols should be used. When developing the architecture of software agents of power cells, provision should be made for an application programming interface (API) to make possible quick addition of new types of behavior to software agents of power cells through additional software modules.

Transactive Energy (TE) system

Transactive Energy (TE) is the system for implementing the commercial component of energy transactions, which performs fully automatic formation and protected storage of smart contracts that fix the parameters of energy transactions, verification of their execution, financial settlement of fulfilled obligations, fixing discrepancies and disputes, usage of data for their settlement and performing clearing functions.

Functions of the TE system are:

1. formation, recording, stable and protected storage of records related to energy transaction parameters;
2. support of operation of digital wallets of the users, stable and protected storage of user personal data and financial information;
3. verification of fulfillment of energy transaction obligations based on data received from the IoT system;

4. support of energy transaction billing and processing, including provision of instant transfer of money upon fulfillment of the conditions of the energy transaction.

Figure 4 shows a component diagram of the TE system. The TE system includes the following components:

1. transaction platform;
2. avatars of software agents of power cells and users;
3. digital wallets of software agents of power cells and users;
4. user interface;
5. software converters of values and data;
6. software interface with the software agent of a power cell;
7. software interface with the IoT system;
8. software interface with service applications;
9. information security module.

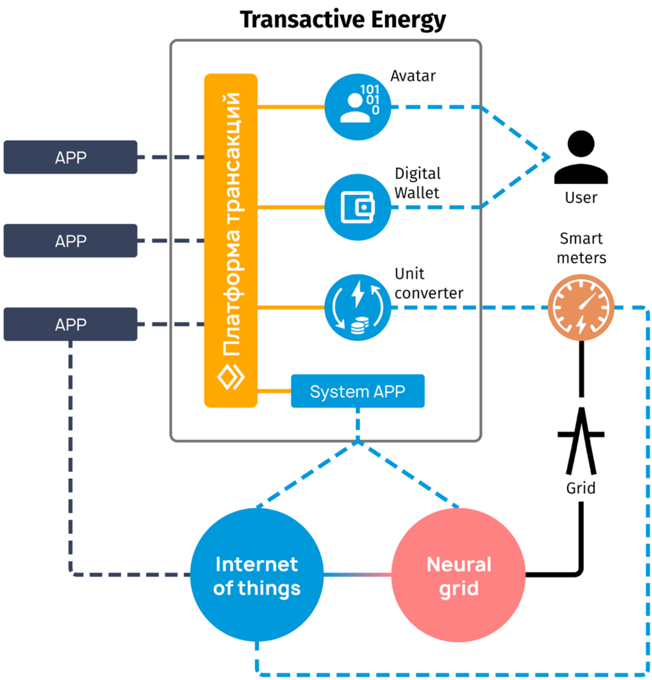

Figure 4. Component architecture of the Transactive Energy system

The transaction platform must provide simultaneous and quick implementation of energy transactions between the users. The transaction platform must be fully automatically scalable in regard of the number of users as well as the number of transactions per unit of time. The use of distributed ledger technology is recommended. The possibility of completion of a pool of transactions between power cells with a period of no more than 15 minutes must be provided.

Internet of Things (IoT) system

Internet of Things (IoT) is the system for implementing the informational component of energy transactions which incorporates machine-to-machine (M2M) interaction and exchange of all information and control signals necessary for energy transactions between power cells and their software agents, access of software agents to the local automatics of equipment and/or local control systems of power cells, as well as formation, storage and provision of digital twins and digital footprints of power cells and their equipment, operation of auxiliary software for M2Minteraction.

Figure 5 shows the component diagram of the IoT system. The functions of the IoT system are:

1. providing access of software agents to control systems of power cells and control systems of electrical units of power cells;
2. ensuring interoperability of software agents with electrical units of power cells connected to the Internet of energy;
3. ensuring interoperability of electrical units of power cells connected to the Internet of energy;
4. ensuring stability and security of data storage related to power cells and their electrical units.

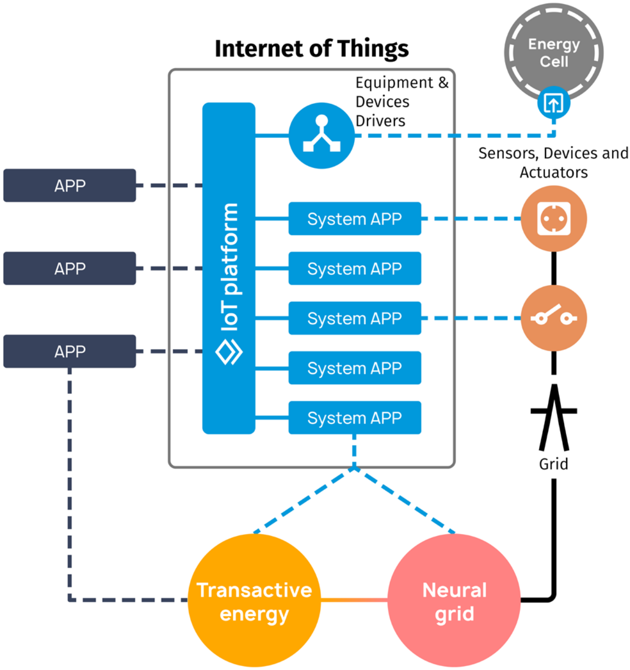

Figure 5. Component architecture of the Internet of Things system

The IoT system includes the following components:

1. IoT platform;
2. interconnecting devices of electrical units of power cells;
3. smart electricity meters and power meters;
4. drivers, adapters, interfaces for connection to electrical installations of power cells;
5. Software interface with software agents of power cells;
6. Software interface with the TE system;
7. Software interface with the NG system;
8. Smart meters (optional);
9. Sensors, transducers, actuators (optional);
10. Auxiliary programs and applications for machine-to-machine interaction (optional).

For the purpose of ensuring interoperability of M2M interactions on the IoT platform, the requirements of IEEE1547–2018, IEEE2030.5–2018 standards should be applied when developing technical solutions for implementation of the IDEA.

Neural Grid (NG) system

Neural Grid (NG) is the system for implementing the physical (related to electric power) component of energy transactions, which, when necessary, provides decentralized frequency controlpower-frequency controlpower-frequency control, control of power flows in the energy system for the purpose of arranging the power transmission mode necessary for the implementation of energy transactions and for maintaining its static and dynamic stability in the conditions of simultaneous implementation of many energy transactions. The system provides the functions of adaptive relay protection and automation — technological protection of power cells and the electric grid in the conditions of bidirectional power flows caused by energy transactions, as well as integration of certain types of power cells with electric grids (connection to electric grids).

Figure 6 shows the component diagram of the NG system. The functions of the NG system are:

1. maintaining static and dynamic stability of the energy system in the conditions of performance of energy transactions;
2. exerting impacts on the power transmission mode necessary for performance of energy transactions;
3. exerting impacts on the balance of active and reactive power in the energy system, energy node necessary for performance of energy transactions;
4. maintaining quality of electrical energy;
5. ensuring technological protection of power cells.

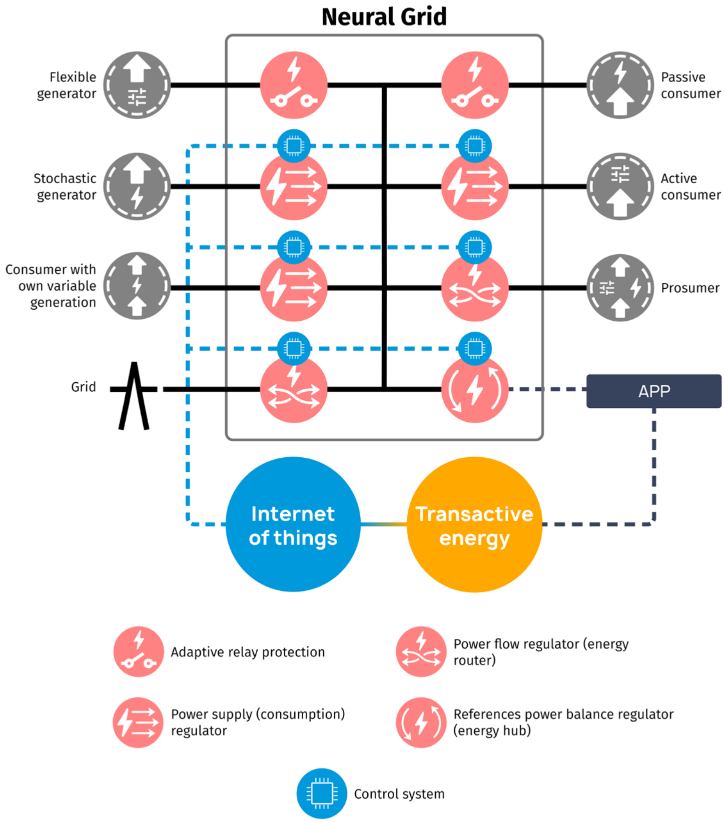

Figure 6. Component architecture of the Neural Grid system

The NG system includes the following components:

1. Power flow regulator (energy router);
2. Reference power balance regulator (energy hub);
3. Power supply (consumption) regulator (energy port);
4. Adaptive relay protection and automatics;
5. Software interface with the IoT system;
6. Software interface with the TE system.

Two-way power flow regulator (energy router)

The two-way power flow regulator is used for control of the power flow for performance of energy transactions; it is installed on the boundary between two sections of the energy system or on the boundary between the microgrid and the energy system, where it is necessary to regulate the amount and direction of the flow of active and/or reactive power for the purpose of performing functions of the NG system.

The two-way power flow regulator must provide possibility of operation in the following modes:

1. power supply from the side of supply network, consumption at the microgrid side;
2. power supply from the side of supply network and microgrid, consumption at the side of other microgrids;
3. limitation of the flow of electricity in the direction of some of the microgrids;
4. limitation of the flow of electricity in the direction of energy system grid;
5. power supply from the side of some of the microgrids, consumption at the side of other microgrids.

The protocols for data exchange with the higher level control system of the two-way power flow regulator should comply with the requirements of GOST R IEC60870–5–104–2004.

Reference power balance regulator (energy hub)

The reference power balance regulator must provide formation of reference voltage in an isolated energy system in which it is installed, and provide primary frequency controlpower-frequency control, including the case of absence of synchronous generators in the energy system.

The reference power balance regulator must provide frequency control according to the requirements of section 4 of GOST R55890–2013.

When implementing the IDEA in technologically isolated power systems that do not contain synchronous generators, reference power balance regulators (energy hubs) must be installed.

Connection of power cells

A power cell, depending on its type listed in Table 1, is connected to the Internet of energy using the interfaces listed in Table 3. The interfaces between the power cells and the Internet of energy generally include transactional, information-control, and power components according to the three systems of the Internet of energy, and are connected to the software agents of power cells through the TE and IoT systems.

Table 3. Types of interfaces between power cells and the Internet of energy

<table>
<tr><th>Type of power cell</th><th>Functional type of interconnecting device</th></tr>
<tr><td>Load following generator</td><td rowspan="2">Power supply (consumption) regulator (energy port or inverter)</td></tr>
<tr><td>Stochastic generator</td></tr>
<tr><td>Prosumer</td><td rowspan="2">Two-way power flow regulator (energy router)</td></tr>
<tr><td>Consumer with own variable generation</td></tr>
<tr><td>Active consumer</td><td rowspan="2">Smart electricity meter and power meter with adaptive technological protection (relay protection and automatics)</td></tr>
<tr><td>Passive consumer</td></tr>
</table>

The specified interconnecting devices must contain the following components:

1. Transaction components:

— node of distributed transaction platform,

— cryptographic key generator,

— value converter.

2. Information and control components:

— set of software interfaces,

— smart measurement system.

In order to ensure integration of power cells with electrical grids and their interoperability with the Internet of energy, the technical implementation of interconnecting devices of the Internet of energy should comply with the requirements of IEEE1547–2018 standard.

Topology of electrical grids in the Internet of energy

Four typical topological models for building the Internet of energy can be defined as a combination of power cells, as shown in Figure 7:

1. **Microgrid**. An energy system composed of power cells and capable of stable operation in isolated mode without limitation of consumption. It can be built according to three main topologies:

— radial distribution network with multiple feeders from the power supply center, which is any of the power cells that is either a generator or prosumer,

— ring distribution network,

— peer-to-peer mesh network with connections «each one with each one».

2. **Grid of cells**. An energy system composed of power cells connected to the distribution networks of the centralized (external) energy system and exchanging energy between each other and with the centralized (external) energy system. Topologically, it can be constructed as a radial or radial-ring structure, depending on the topology of the distribution network.
3. **Grid of microgrids**. An energy system composed of microgrids exchanging energy between each other and with the centralized (external) energy system, connected to the existing distribution networks of the centralized (external) energy system. Topology of the structure of such a network corresponds to the topology of the existing distribution networks.
4. **Mesh of microgrids**. A specific model for building the Internet of energy, which consists in combining microgrids into a peer-to-peer mesh network, in which only «point-to-point» connections are present, and such connections exist between most of the microgrids on the principle of «each one with each one». An important feature of this model is that the deployment of such a mesh network requires that any component included in it maintains its energy balance independently, because no common mode-balance situation is formed in the mesh network under the specified conditions of point-to-point connections and flows, and no joint mode of electricity transmission is present. Power balances are performed only for interconnected pairs of microgrids for each link, requiring independent balance in each of the combined microgrids.

Another logically possible combination of power cells — in the form of a mesh of cells — is shown to be a particular topological case of microgrid arrangement.

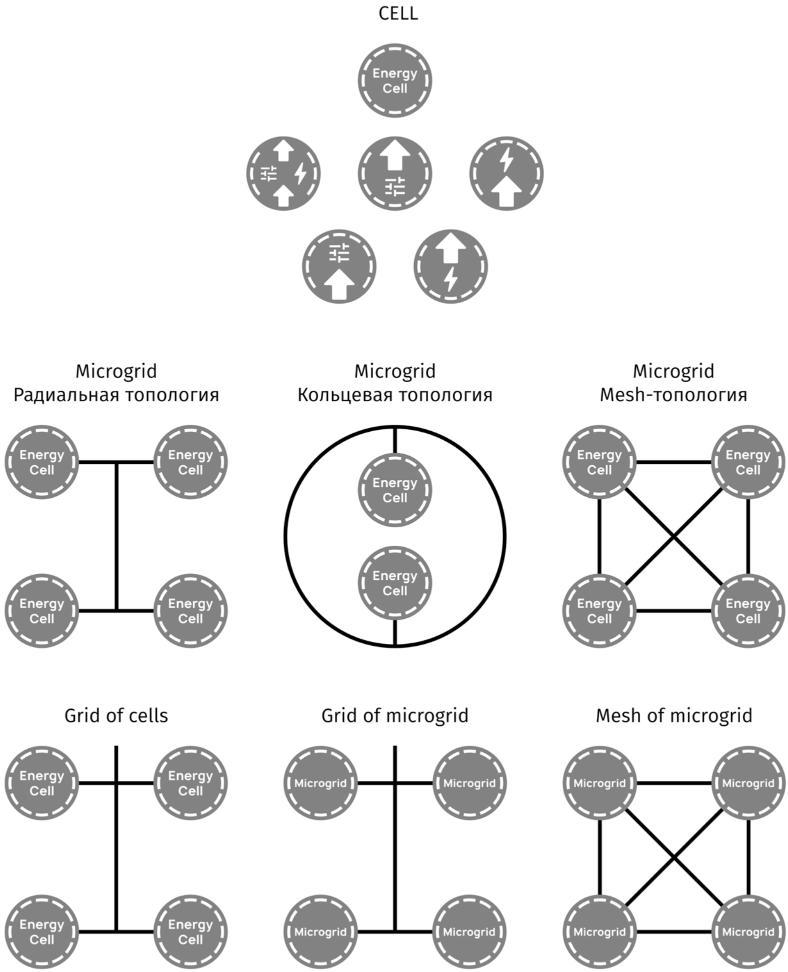

Figure 7. Typical models for building the Internet of energy — options of connecting power cells

Three types of topology of energy systems on the Internet of energy are possible:

1. **Mesh electrical network**. It is characterized by existence of point-to-point connections between the connected electrical installations;

2. **Radial electrical network**. It is characterized by existence of only one route connecting the power supply center and the connected electrical installations;
3. **Complex-looped (ring) electrical network**. It is characterized by existence of ring sections of the electrical network and existence of at least two routes linking the power supply center and the connected electrical installations.

Information security

Information security in the Internet of energy and its systems when implementing the architecture of the Internet of energy must comply with the requirements of GOST R ISO/IEC17799–2005, GOST R ISO/IEC27001–2006, GOST R52448–2005, GOST R52863–2007.

Additionally, the information security of the TE system, its software interfaces and interconnecting devices with the software agent of power cell and other systems must comply with the requirements of GOST R ISO/TO 13569–2007, GOST R57580.1–2017.

Additionally, the information security of the IoT and NG systems, their software interfaces and interconnecting devices with other systems must comply with the requirements of GOST R IEC62443–3–3–2016.

Demonstration complex — modular implementation of the Internet of energy

An example of modular implementation of the IDEA is the demonstration complex of the Internet of energy located at the Moscow Institute of Physics and Technology. Its composition and possible power flows are shown in Figure 8.

In the framework of demonstration complex of the Internet of energy, four prosumers are deployed. Each prosumer includes an energy source (a gasoline-powered generator, two groups of solar panels, an electricity storage device depending on the prosumer), and three loads — electric receivers. Each prosumer, depending on the balance between the generated and consumed power, can act both as a seller and as a buyer of electric energy.

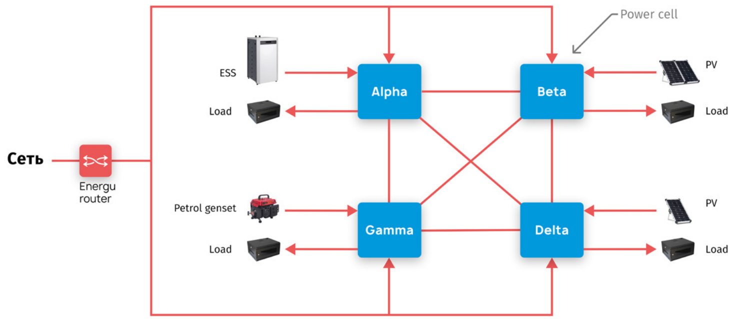

Figure 8. Composition and possible power flows in the demonstration complex of the Internet of energy

The demonstration complex of the Internet of energy allows implementation of the following basic test scenarios:

1. Operation of a group of prosumers in the mode of power supply from the external grid and from their own energy sources, both with and without energy transactions and power flows between prosumers;
2. Operation of a group of prosumers in isolated (autonomous) mode with mutual optimization of power supply using energy transactions and power flows between prosumers;
3. Connection of a new prosumer to a group of prosumers in plug & play mode with automatic connection to the existing services of the

Internet of energy.

Within the framework of the demonstration complex, peer-to-peer energy exchange between prosumers is implemented. Figure 9 shows a modular diagram of the demonstration complex of the Internet of energy.

In order to provide peer-to-peer energy exchange, a multi-agent control system, a transaction system (TE), a machine-to-machine interaction system (IoT) are deployed, and regulators of active and reactive power flow are installed in the network — components of the mode control system (NG), namely:

1. The prosumer common power supply bus 0.4 kV AC is connected to the power supply system (public utility network) of the building via the **regulator of active and reactive power flow — AC energy router**.
2. The prosumer common power supply bus 0.4 kV AC is connected to the prosumers via the two-way **AC\DC regulator of active and reactive power flow**.
3. The lines 48 V DC between prosumers are connected to prosumers via a **DC\DC active power flow regulator**.
4. A buffer system for electricity storage is installed at each prosumer, serving as a **reference and balancing regulator — energy hub**.

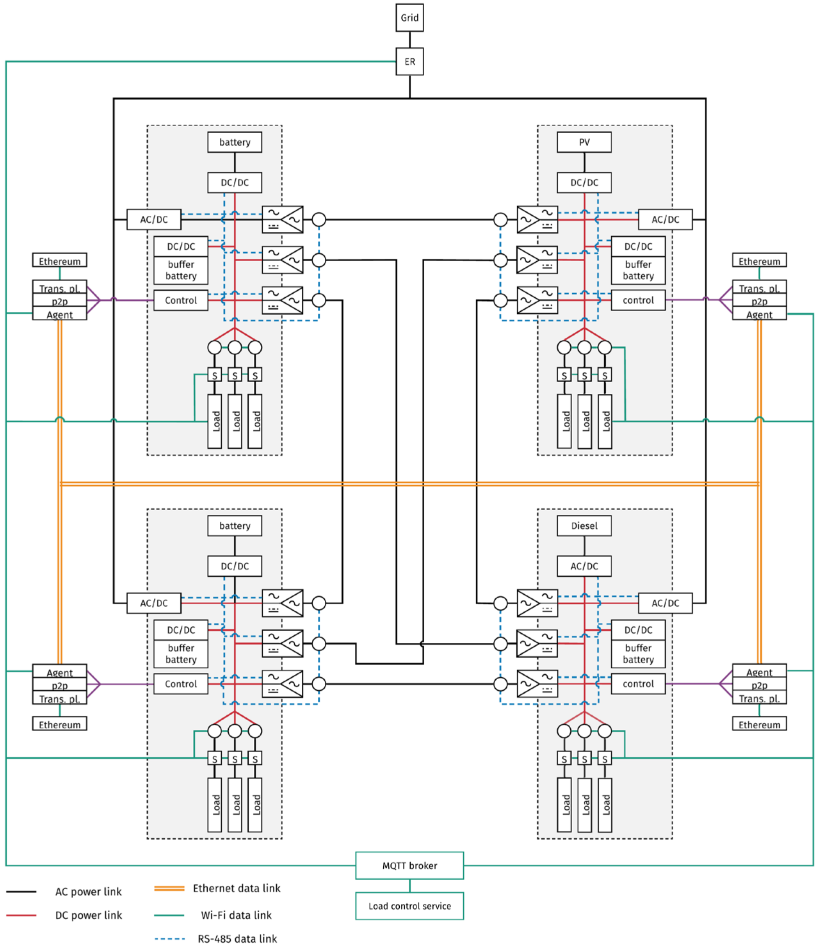

Figure 9. Modular diagram of the demonstration complex of the Internet of energy

Service applications

In the framework of modular implementation of the IDEA, two service applications are deployed in the demonstration complex of the Internet of energy:

1. P2P trading of electricity based on a multi-agent system developed by Smart Electric Power Systems LLC (SEPS LLC);
2. application based on AMIGO software package (developed by RTSoft

JSC) for optimal load shedding upon request from a software agent of a power cell.

Modular implementation of digital agents of power cells

Each prosumer is equipped with a software agent located in the control module — on an industrial computer. Software agents developed by SEPS LLC are digital representatives of prosumers that interact with each other, arrange agreements on energy exchange, send the data related to these agreements to the transaction system; pursuant to these agreements and using the IoT system, send data and commands to the energy equipment of prosumers and to the regulators of active and reactive power flows, so that they form the power balance and energy transmission mode necessary for the implementation of energy exchange according to these commands.

Each software agent includes the following modules:

1. agent code written in JADE programming language;
2. user interface (UI) with the possibilities of registering a power cell, subscription to the service and choosing a profile for participation in the P2P market service;
3. software interface with ØNDER transaction platform;
4. software interface with other agents implemented on the basis of FIPA protocol.

Modules of the TE system

The transaction system is the ØNDER software package (developed by Eliot LLC) which provides the formation of debt payment channels between the avatars of prosumers, fixation of the parameters of energy exchange transactions in the form of smart contracts, verification of their execution based on the data of measuring devices, and automatic transfer of conditional financial units between the electronic wallets of prosumers according to the price parameters of smart contracts and the actual verified volumes of energy exchange.

The ØNDER transaction system includes a distributed transaction platform based on the technology of debt payment channels (a modification of the technology of state channels), as well as modular implementations of the TE system components:

1. cryptographically protected user avatars;

2. cryptographically protected digital wallets;
3. converter of data received from current sensors and electricity meters to tokens;
4. software interface with measurement tools implemented through the IoT system using MQTT protocol;
5. software interface with software agents of power cells implemented using MQTT protocol;
6. software interface with IoT system using MQTT protocol.

The interaction between TE and NG systems in the described modular implementation is not provided. Software agents of power cells, the ØNDER system (distributed system) are hosted on four industrial computers located on the boundaries of power cells and connected to the equipment of the cells via RS-485 interface using Modbus protocol. The AMIGO service application for optimal load shedding is hosted on a stand-alone industrial computer.

Modules of the IoT system

The IoT system includes two subsystems: the MQTT server through which machine-to-machine communication is implemented, and the data transmission system to power flow regulators, built using Ethernet and Modbus and RS-485 protocols. The IoT system provides machine-to-machine interaction, data transfer between other elements of the control system of energy system, and access to power flow regulators and all power equipment.

The IoT platform is implemented in a significantly reduced form due to combining the interfaces and protocols of machine-to-machine interaction specified in Table 4. An MQTT broker is deployed in order to use the MQTT protocol.

Table 4. Modular implementation of the IoT system in the demonstration complex of the Internet of energy

Interface and data transfer technology	Data exchange protocol	Interacting machines
Ethernet	FIPA	Software agents of power cells
RS-485	Modbus	Software agents of power cells Control systems of electrical units of power cells Modules of the NG system DC current sensors of the IoT system

Wi-Fi	MQTT	Software agents of power cells ØNDER transaction system Energy router Load control service application Load control system relays Electricity meters of AC networks

The use of RS-485 data interface and Modbus protocol for communication with the power cells (electrical units) provides access of software agents of power cells to the control systems and drivers of these electrical units. No special device for interconnection with a power cell (electrical unit) is required. Software interface with software agents of power cells is provided by all the specified interfaces and protocols. Software interface with the TE system is implemented by Wi-Fi interface and MQTT protocol. Software interface with the NG system is implemented by RS-485 interface and Modbus protocol.

Current sensors installed on DC lines are connected to the IoT platform via RS-485 interface and Modbus protocol. Digital electricity meters installed on AC lines are connected to the IoT platform via Wi-Fi and MQTT protocol. Controlled relays (actuators) are connected to the IoT platform via Wi-Fi and MQTT protocol. MQTT server and MQTT brokers are hosted on a stand-alone industrial computer.

Modules of the NG system

The NG system for mode control, consisting of the previously listed regulators of active and reactive power flows and reference balancing regulators, receives commands from software agents and, by controlling the active and/or reactive power flows in the sections where the regulators are installed and by exporting or consuming electricity by buffer accumulators, forms the power balance in the energy system and the power transmission mode that correspond to the formed energy exchange transactions between the prosumers and enable execution of these transactions. Table 5 contains the list and number of modules of the NG system that implement the functions of the corresponding components.

Table 5.Modules of the NG system

Component	Modules	Installation location
Power flow regulator	Rectiverter	Connection of the cell to a mesh network
	Energy router	In the public network on the connection to the power supply center
Reference power balance regulator	Accumulator battery connected via DC/DC converter	DC bus of the cell
Power consumption regulator	AC/DC-converter	Connection of the cell to AC bus

Adaptive relay protection in the framework of the above implementation of IDEA was not installed.

The module that performs the function of a component regulating power flow between power cells is the rectiverter. Each power cell is connected to three other power cells by means of four rectiverters located on the boundary of the power cell and connected by one DC side to the bus 48 V DC of the power cell, and by the other DC side — to the lines 48 V DC forming a mesh network connecting the cells. One of these rectiverters receives power via mesh network from three other power cells, the other three rectiverters export power via mesh network to the appropriate power cells.

The second module that performs the function of a component regulating power flow between the public network and the bus 0.4 kV AC that feeds all power cells is the energy router 25 kVA (kVAR) developed by SEPS LLC. It is installed on the boundary between the demonstration complex of the Internet of energy and the public network.

The module that performs the function of a reference power balance regulator is the accumulator battery connected to the bus of the power cell via a controlled DC/DC converter. In total, four modules of reference power balance regulators are installed — one for each power cell — to simplify balance regulation by dividing it into four partial power balances of power cells.

The module that performs the function of a power consumption regulator is the AC/DC converter installed on the boundary of each power cell, connected on the DC side to the bus 48 V DC of the power cell, and on the AC side — to the bus 0.4 kV AC running through the energy router from the public network.

Topology of the electric grid

Each prosumer has a connection to the power supply network 0.4 kV AC and is connected to all other prosumers by the lines 48V DC. The power supply bus 0.4 kV AC common for all prosumers is connected to the power supply system of the building where the demonstration complex is located.

The option of control method of the energy system is implemented in the framework of the demonstration complex for implementing peer-to-peer energy exchange between active consumers connected to electrical networks with mesh topology.

Implementation of energy transactions

An energy transaction in course of peer-to-peer exchange of energy between two prosumers is performed as follows:

1. Software agents, connected via Ethernet and interacting using FIPA protocol according to the settings of the prosumers entered via user interface of the software agents and the rules of peer-to-peer electricity market, perform trading of electricity. The parameters of energy exchange transaction agreed between the two agents are formed basing on the results of this trading.
2. Software agents connected to the transaction system via Wi-Fi and interacting with it using MQTT protocol transmit cryptographically protected identification data, price signals, and other parameters of the energy exchange transaction to the transaction system. The transaction system identifies these agents, binds them to the corresponding avatars and forms a smart contract for energy exchange transaction.
3. Software agents connected via Ethernet to the power equipment and interacting with it using Modbus protocol send commands on increase or decrease of the power for delivery (or consumption, in case of energy storage device) of electricity.
4. Software agents connected via Ethernet to reference balancing regulators and interacting with them using Modbus or RS-485 protocol send commands for the delivery or consumption of electricity for the purpose of providing power balance in the energy system according to energy exchange transactions.

5. Software agents connected via Ethernet to AC/DC- and DC/DC-regulators of active and reactive power flow and interacting with them using Modbus protocol send commands to them for formation of the flows necessary for execution of transactions between the common power supply bus and the prosumers and between two prosumers, respectively.
6. If necessary, software agents can initiate shedding of part of the load of their prosumer in order to form power balance in the conditions of energy shortage. For this purpose, they use Wi-Fi to send the corresponding request using MQTT protocol to AMIGO program hosted on a separate server, which forms optimal load shedding plan and sends, using MQTT protocol, shutdown commands to remotely controlled relays which are communicating over Wi-Fi.
7. Reference balancing regulators, AC/DC- and DC/DC-regulators, according to the commands, form the necessary power balance and energy transmission mode. The transactions are executed.
8. Software agents receive data related to actual power flow from the measuring equipment of AC/DC and DC/DC regulators and send it and the identification data to the transaction system. Using this data, the transaction system performs authorization of software agents, verification of implementation of the energy exchange transaction, and automatic transfer of conventional financial units between the electronic wallets of active consumers. Then the peer-to-peer energy exchange transaction is regarded as completed.

Piloting, verification, standardization

Pilot projects

Pilot project at REIDS test site in Singapore

REIDS (Renewable Energy Integration Demonstrator Singapore) is a large international project which main purpose is to test various integrated solutions for creating «island» autonomous microgrids that include RES based generation in conditions as close as possible to real conditions. Among the project partners who create their own microgrids are major players of global technology market, such as EDF, Engie, Rolls Royce, Schneider Electric, General Electric, and dozens of other companies. The most interesting feature of the test site is that within its framework, all microgrids already operating and being created, as well as shared access equipment (SAS) belonging to Nanyang Technological University (NTU), will be connected by a joint network of 6.6/0.4 kV into a cluster of microgrids that can exchange electricity with each other. This makes the test site very interesting for implementing the IDEA there: it is possible to test energy transactions between all microgrids and shared access equipment, as well as fully decentralized control over such a transaction energy system.

REIDS is a showroom of the world's best solutions for autonomous power supply intended for the entire market of Southeast Asia.

The first autonomous microgrid on the island was the power supply system for a slag reloading shop which was deployed even before the start of REIDS project in the interests of a real-life consumer. This autonomous system, with load of approximately 250 kW during daytime and 180 kW at night, includes 400 kW of roof-mounted solar panels, 200 kWh of electricity storage devices, and two diesel-generator sets 500 kW each.

Besides, shared access equipment (SAS) has been installed already, consisting of two diesel-generator sets 50 kVA each, 400 kW solar panels, controlled simulated load with power of 350 kVA with programmable profile and regulated reactive component. In the near future, an energy storage unit with power of 100 kW and storage capacity of 180 kWh will appear.

Engie in cooperation with Schneider Electric and MuRata has practically completed the construction of a microgrid with a 100 kW wind generator, 200 kW solar panels, three diesel-generator sets with power 200 kW in total, and a 100 kW energy storage unit from MuRata with storage capacity of 200 kWh, as well as a hydrogen cycle energy storage system with an electrolyzer and fuel cells with power of 50 kW each, capable of refueling hydrogen vehicles. EDF is deploying its own microgrid for demonstrating the capabilities of V2G technology in the conditions of autonomous power supply. It is expected that all eight microgrid projects will be deployed gradually.

All the listed capacities are controlled from a single dispatch center — RE-IDS Hub — which also provides access for project partners to the shared access equipment according to schedule. This dispatch center is a microgrid itself, where the equipment is powered by 37 kW solar panels and two energy storage devices: a lithium-ion battery with storage capacity of 31 kWh and a lead-acid battery with storage capacity of 77 kWh.

The plans for implementation of elements of IDEA on the island during the first stage that is currently underway include the deployment by the end of the year of ØNDER transaction platform which will link the accounting data and calculation data flows from all existing units of shared access equipment (SAS) and the power supply system of the slag reloading shop, as well as installation of the optimal control system (EMS) by RTSoft JSC (based on AMIGO solution), which will consistently control the shared access equipment.

Currently, an off-standard balance situation exists at the test site: during the daytime, the generation of roof solar panels at the slag reloading shop is higher than consumption, sometimes by a factor of two. But the capacity of own energy storage systems of this microgrid is not enough to store all the excess solar electricity. At night, on the contrary, this shop is forced to use diesel generation after full discharge of the storage devices, what happens before sunrise. Availability of connections of 0.4/6.6 kV with shared access equipment (SAS), in the first place, with the storage unit and solar panels, would allow, by provision of solar energy storage services (the service of storage «sharing»), to reduce significantly the need of the shop microgrid for diesel generation and increase the efficiency of its power supply. This is one of the scenarios of energy transactions that will be implemented as part of demonstration of the Internet of energy.

The first stage. TE

Implementation of IDEA solution at the first stage is aimed at automating the process of accounting and mutual settlements for the rendered electricity services. The scheme of implementation of the IDEA elements during the first stage of the pilot project is shown in Figure 10.

At the first stage, one of the components of IDEA is implemented — the TE system, namely, the information platform that allows execution of mutual settlements (transactions) between the participants of the energy system based on real data of electricity metering. Already now there are arrangements between ØNDER company and NTU University, and work is underway on implementation of TE platform based on ØNDER platform which will be integrated with the monitoring and control system of REIDS Hub, allowing to collect electricity accounting data for each SAS asset and for MG0 as a whole and make mutual settlements between them.

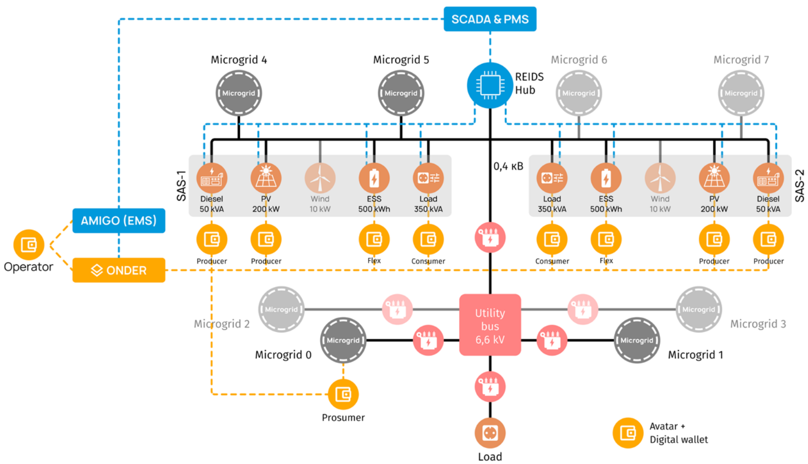

Figure 10. Modular architecture of the pilot project of IDEA implementation at REIDS land fill during the first stage

Besides, in the framework of the first stage, AMIGO EMS developed by RTSOFT JSC is implemented; it is an application of the Internet of energy that performs automated control over distributed energy resources for the purpose of optimizing the operating modes of SAS-1 and SAS-2 via REIDS Hub embedded control system.

During implementation of the first stage, not all distributed energy resources of SAS-1 and SAS-2 will be available; in particular, at the time of implementation of the solutions, the wind turbines and SAS-2 load will not be installed yet.

The main technological solutions in the framework of this stage are:

1. REIDS Hub (SCADA + PMS) software and hardware that allows automatic/

automated control over SAS distributed energy resources (assets) and monitoring of electricity metering data, as well as provides primary regulation in the framework of SAS.

2. ∅NDER platform which allows automatic accounting and mutual settlement for rendered electricity services based on real accounting data (obtained from REIDS Hub).
3. EMS system which provides optimization of electricity consumption based on data of the cost of electricity from the P2P-Energy Market application by regulating the operating modes of energy assets through REIDS Hub control system.
4. P2P-Energy Market application implemented on the basis of ∅NDER platform, which makes possible buying and selling electricity between users (owners of energy resources). During this stage, the application only calculates the cost of electricity and sends the data to ∅NDER platform and to AMIGO EMS.

Target vision. TE + IoT + NG

Implementation of IDEA solution at this stage is aimed at building a decentralized system for control over distributed energy resources through the implementation of the IoT platform. The technical implementation of this solution is achieved by installing an IDEA-Bot device on each SAS asset and on MG0 as a whole. Control over the system is decentralized due to the fact that each of the IDEA-Bot devices has a built-in smart control system (software agent). This system performs control over distributed energy resources based on the information model of itself, its environment and the system as a whole, and can coordinate its actions with the environment. The diagram of IDEA implementation in the context of target vision is shown in Figure 11.

Besides, IDEA implementation is aimed at demonstrating a fully decentralized maintenance of static and dynamic stability of REIDS isolated energy system by installing the following Neural Grid hardware components on REIDS network infrastructure:

1. Energy hub — a device that provides primary regulation, sustaining internal energy balance (in this case, energy balance of the assets of one of SAS), static and dynamic stability of the power transmission mode;
2. Energy router — a software and hardware complex designed for control and distribution of electricity in distribution networks.

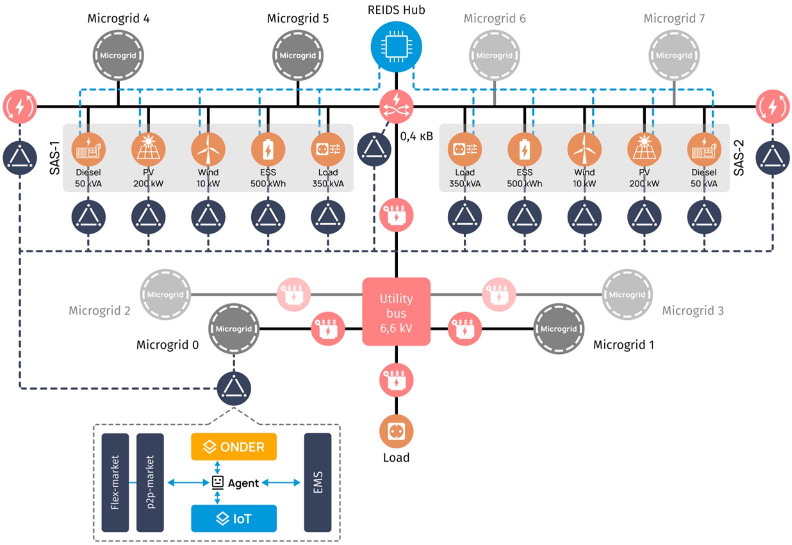

Figure 11. Target modular architecture of the pilot project of IDEA implementation at REIDS test site

The main technological solutions in the framework of TE and IoT systems at this stage are:

1. IDEA-Bot which includes the following software:

— Software agent — software that controls the user's assets basing on user preferences (selected settings) and the calculation of economic expediency. The software agent physically controls the assets via IoT (by sending setpoints), and also provides financial interaction (contracting, mutual settlements) with other agents via TE;

— IoT — software which, basing on commands from the software agent, converts them into final setpoints and sends them to the control system of electrical units;

— TE — software which, basing on preliminary data from software agents, creates and publishes smart contracts and monitors the execution of smart contracts.

2. ØNDER platform which performs automatic accounting and mutual settlement of electricity supply services rendered on the basis of real accounting data.

3. IoT platform which performs automatic/automated control over SAS energy assets and monitoring of electricity metering data.
4. P2P-Energy Market application which provides the possibility of buying and selling electricity (conclusion of smart contracts) between users (owners of energy assets).
5. REIDS Hub — software and hardware that controls the execution of IDEA-Bot commands.

Verification and standardization

Verification in the international professional community

Verification of IDEA in the international professional community was carried out at the following sites:

1. Workshop on Distributed Architecture at Nanyang Technological University (NTU) with participation of representatives of the university and EDF, Engie, Rolls-Royce companies — Singapore, May 16, 2019
2. Workshop on Distributed Architectures in electric power systems in the framework of the 17th IEEE International Conference on Industrial Informatics INDIN-2019 — Helsinki, July 22, 2019
3. Asian Conference on Energy, Power and Transportation Electrification (ACEPT) in the framework of Asian Clean Energy Summit (ACES) at Singapore International Energy Week (SIEW) — Singapore, October 31, 2019
4. 48th session of International Council on Large Electric Systems (CIGRE) — in online format, July 15, 2020

Standardization

Basing on the described Internet of distributed energy architecture, the following draft preliminary national standards (PNST) were developed:

1. **Draft PNST «Information technologies. Smart energy. Typical Internet of distributed energy architecture (IDEA)»** introduces a conceptual model of the Internet of energy and sets requirements to its useful properties, energy transactions, components, interfaces for connection of electrical installations, information security, as well as recommendations on modular implementation of IDEA.

2. **Draft PNST «Information technologies. Smart energy. Terms and definitions»** sets requirements to the conceptual framework and terminology in the development and description of digital energy practices and introduces the conceptual framework of the Internet of distributed energy architecture.

Texts of the draft PNST are available on the website of the Technical Committee 094 «Cyber-physical systems» at http://tc194.ru/internet_of_energy_public

IDEA implementation options

Industrial microgrid

IDEA represents commercial and industrial microgrids as interconnected power systems in which different entities with their power units perform energy transactions with each other and thereby render various services to each other, from sale of electricity to the regulation of electricity quality. Figure 12 shows a schematic diagram of a commercial or industrial microgrid in the approach using IDEA. Such a microgrid can include generators and industrial consumers with various sources of energy flexibility — controlled loads (regulated electric receivers) and energy storage devices. Some of the consumers may lack sources of flexibility. From the perspective of the Internet of energy, such a microgrid has economic reasons for the formation of a local market of electric energy and flexibility. In this market, the facilities generating electric energy sell this energy to industrial and commercial consumers, and they, in turn, can provide flexibility services to these generating facilities, thereby increasing their efficiency, and to each other, for example, reducing the consumed power at certain hours. The Internet of energy acts as the infrastructure for such a market and for technological control of microgrid energy.

The advantage of implementing a microgrid using the Internet of energy approach is that due to the interoperability and scalability provided by the IDEA, it becomes possible to create easily scalable commercial and industrial microgrids based on electrical units from various vendors. In such microgrids, it becomes possible to connect new power units and new entities according to plug & play principle, providing easy scaling and reconfiguration of microgrids. Besides, IDEA allows to change and expand the set of implemented service applications, and therefore, without significant change of the IT infrastructure, to introduce a technological backbone for the new models of economic relations between microgrid subjects.

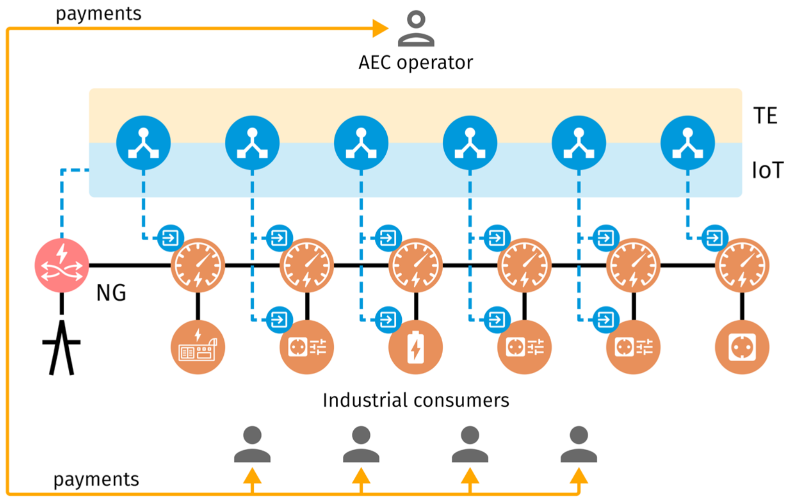

Figure 12. Industrial microgrid in the approach using IDEA

IDEA defines one of the options for implementing a controlled smart connection (CSC) in a microgrid. In order to implement a CSC according to IDEA, a power flow regulator (energy router) must be installed at the boundary of the microgrid and the grid company. An energy router serves as an element of the Neural Grid (NG) system and provides local limitation of power flow between the microgrid and the outer grid. Moreover, in a certain power range, the energy router can regulate the amount of flow between the microgrid and the outer grid without increasing the generation in the microgrid and without reducing the consumption of its subjects.

Each group of energy installations and electric receivers in a microgrid must be equipped with a software agent that performs energy transactions with other software agents. Software agents are robotized representatives of microgrid entities — generators and consumers. Software agents interact with the control systems of power units and electric receivers, as well as with each other, using the Internet of Things (IoT) system. Energy transactions are recorded in the form of smart contracts in the Transactive Energy (TE) system, execution of transactions is verified in the same system (using electricity meters linked with the IoT), and processing and clearing are performed.

In this implementation, the microgrid operator is the operator of the Internet of energy infrastructure which renders services to its subjects for support of operation of the controlled smart connection and, for example, of the local electricity and flexibility market.

The local electricity and flexibility market is one of the options of a service application that can be deployed based on the Internet of energy. An alternative option is also possible — deployment of dispatcher applications of EMS type. Using the appropriate service applications being part of CSC device and deployed on the basis of the Internet of energy, the microgrid interacts with the grid company and with the guaranteeing supplier or sales company.

Advanced Demand Response

The involvement of numerous consumers in demand response practices is associated with significant integration and transaction costs. The smaller the consumers and the larger their number, the higher the proportion and total amount of these costs. These costs include:

- Capital costs for transformation of the consumer load from passive into remotely controlled;
- Capital costs and operational costs for integrating consumers and their loads into the information and control loop of the demand response practice, usually the loop of the demand response aggregator, and maintenance of the relevant information systems;
- Capital costs and operating costs for the integration of consumers into the information systems of commercial accounting, calculation and effecting of payments;
- The costs of intermediary activities necessary for effecting («posting») of accounting, settlement and payment operations (transactions), including verification and check of meter readings, banking activities for clearing, billing, servicing of settlement accounts and personal accounts, and other operations of this type.

These costs are the main constraining factor of scaling up the demand response practices and increasing the «depth» of their penetration into the control of energy system.

IDEA is designed to provide easy and fast scalability of new energy practices. These qualities of implementing the demand response in the IDEA are achieved by installing a sufficiently unified device for connecting to the Internet of energy — the «IDEA agent» — which is a controling add-on device with the relevant software (see Figure 13).

The «IDEA agent», due to the built-in ports and protocols used for formation of the Internet of Things (IoT), gets access to the end equipment of the consumer — load control systems, «smart» sockets and all the equipment that is basically a controlled load.

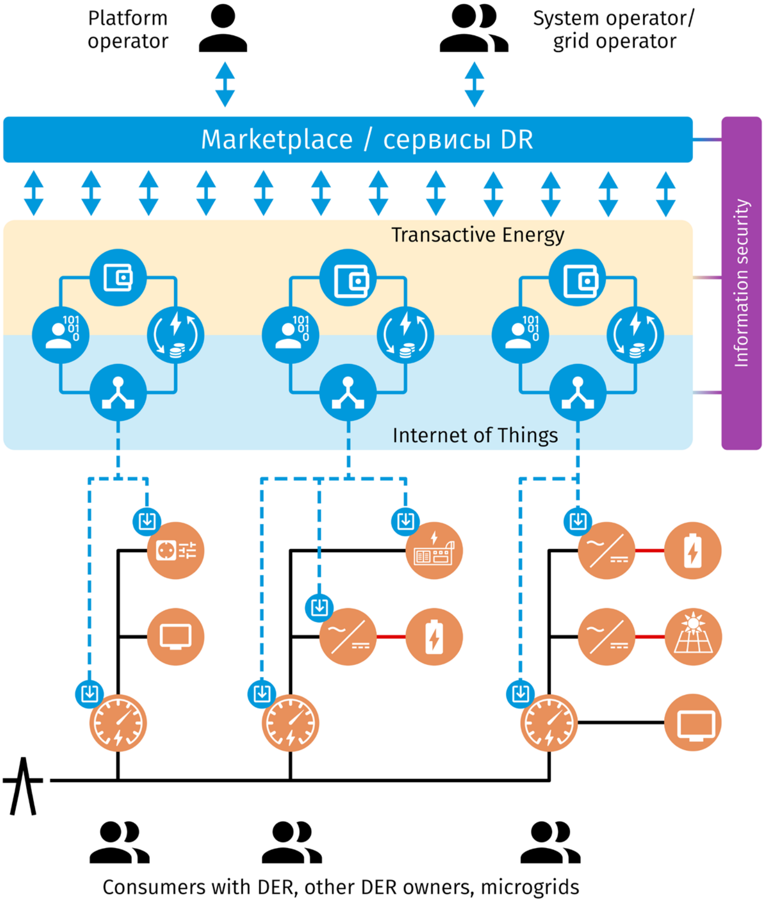

Figure 13. Advanced demand response system in the IDEA approach

Besides, the «IDEA agent» contains a system for connecting to the transaction system and a personal «wallet» of the aggregated consumer, enabling the implementation of all accounting, settlement and payment activities without mediators.

The core of the «IDEA agent» is the software agent itself — the «representative» of the consumer that receives requests from the demand response aggregator. The function of this software agent is: taking decision on participation in the demand response event according to the profiles of participation in the demand response service selected by consumers and transformation of the aggregator requests accepted for execution into commands for the control systems of the loads integrated into the load control. The same software agent initiates accounting of the fact and value of participation in the demand response event, calculations related to this fact and execution of payment for participation in this fact.

Thus, when implementing the practice of demand response based on the IDEA, scaling of this practice is simplified, and from the point of view of the aggregated consumer of electric energy, its involvement in the practice of demand response is reduced to the following set of elementary operations:

1. Purchase of the control add-on device (order via Internet with delivery);
2. Connection of the add-on device (either in do-it-yourself manner or engaging a specialist);
3. Selection on the marketplace and installing the App provided by the aggregator;
4. Registration in the App, selection of the type of service (or participation profile);
5. Monitoring the independent operation of the service through the App;
6. Installing new applications, automatic reception of updates.

Conclusion

The Internet of distributed energy architecture (IDEA) described in this report is at the stage of transition to creation of commercial products based on it, including individual subsystems and architecture elements, and pilot implementation at energy facilities using these products.

However, there are still many questions in the development of the IDEA that have not received the final answers yet.

The most difficult question in implementing the IDEA is to provide the capability of plug & play connection of new power cells (new users) in the distributed power system with AC grid. In this case, significant difficulties arise in regard of consistency of work of the power interfaces (inverters, routers) through which these cells are connected to the grids, and difficulties with the formation of a stable joint power transmission mode. These questions require in-depth theoretical research and practical, technological developments, which are currently underway at the MPEI, MIPT and Skoltech.

Another important and complicated issue of implementing the IDEA is ensuring a really broad interoperability of the Internet of energy (software agents, service applications) with a broad range of different types of electrical units and other equipment mounted in the power cells of different users. Perhaps the standardization of information interconnecting devices and data exchange protocols conducted by IEEE, as well as the development and spread of the IoT standards, will help to solve this issue.

The implementation of pilot projects based on the IDEA and the continuation of research and development in the consortia and partnerships created for promotion and implementing the IDEA will allow to get answers to these questions.

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