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Concept of a Universal Smart Circuit Breaker with Protection against Spark Discharge

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Abstract: The concept of a universal device that can provide diagnostics and monitoring of individual and collective power supply systems, the construction of life support systems, the state of household appliances, the Internet of Things devices and housing and communal services devices is considered. This paper proposes new design solutions able to improve the existing technologies for assessment of the quality of the energy flow by two orders of magnitude in terms of overall characteristics relative to the existing analogues. The developed Smart microcontroller is designed to operate as an intelligent unit, to analyze the parameters of the AC voltage network and control the electromechanical elements of the Smart Circuit Breaker, as well as to send data through a standard interface. The implementation of protection against spark discharge is proposed. The proposed solution is based on the application of cloud and boundary computing technology. The possibilities for improvement of the efficiency of design technologies and construction of energy-efficient buildings, provision of the industry and households with a new type of information management services (monitoring energy infrastructure, etc.) are presented.

Keywords: smart circuit breaker, monitoring, control, smart networks, power supply systems, Internet of Things.

1. INTRODUCTION

The creation of a technological basis for the development of innovative housing infrastructure that provides diagnostics and monitoring of the energy status of the infrastructures, individual and collective energy supply systems, building life support systems, monitoring of the state of household appliances, Internet of Things (IoT) devices and housing and utilities infrastructure is a very relevant task and corresponds to the goals of the Energy.net roadmap [12, 18]. This process is accompanied by the development of technological solutions in the field of energy status monitoring and predictive maintenance and repair [2, 3, 5, 14, 27-29]. One of the directions for the implementation of the roadmap action plan is the transition of the electrical support systems to the IoT concept [20-22, 25, 26, 28].

At the moment, there are many solutions in the market aimed at protecting the household network against various malfunctions [1, 10, 12, 18, 23]. However, in general, they implement only certain types of protection. There are practically no solutions to implement comprehensive protection, including the following functions: overload and short circuit protection; current leakage protection; spark protection; overvoltage or overload protection; determining the cause of the shutdown after the automatic triggering; sending data to an external device; ability to shut off the circuit breaker at the command of the remote user. Some companies have the solutions, partially performing these functions, in the form of several individual devices. For example, the solution of the company ABB (https://new.abb.com) has the form of 5 separate devices, with a total width of 11 standard

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modules. The solution based on Schneider Electric devices (https://www.se.com) represents 5 separate devices, with a total width of 7 standard modules, and Legrand (https://legrand.ru/) has 4 separate devices in 7 standard modules. The installation of a system of several devices imposes additional requirements on the qualifications of electricians.

It is obvious that modern requirements for the qualitative characteristics of energy consumption require wider use of intelligent controls and predictive services, which can be distinguished by the complexity of their functions and would be implemented in a public-private partnership [6, 8]. To solve this problem, the goal was set to develop a universal smart circuit breaker with protection against spark discharge, the concept of which is presented in this study.

2. POWER PROTECTION REQUIREMENTS

Power quality takes into account all aspects of electromagnetic compatibility, but characterizes only the electrical network. The permissible levels of electromagnetic compatibility established for it are called Power Quality Indicators (PQI). The regulatory values of the PQI and the list of them are set by the standards (in the European Union – EN 50160, IEC 61000-4-30: 2008; in Russia – GOST R 54149, GOST 13109-97, etc.), which are the guidance for the developers of the electrical equipment connected to the network, in terms of their noise immunity, on the one hand, and the level of interference, on the other. If the noise immunity level of these technical devices is higher than the maximum permissible PQI values for the network, electromagnetic compatibility (EMC) will be ensured [10]. The actual PQI values should be monitored using specialized measuring instruments under operating conditions, and the corresponding characteristics of EMC – by the necessary tests during their development and production.

Indicators of power quality can be divided into three groups. The first group includes frequency deviations and voltage deviations, which are associated with the peculiarities of the process of production and transmission of electricity. The quality of frequency and voltage deviations regulation determines their level in the electric power system. The second group can be attributed to the PQIs, characterizing the non-sinusoidal shape of the voltage curve, the asymmetry and voltage fluctuations. The sources of these distortions (emitters) are mainly electrical receivers. In order to take into account the impact of electromotive forces generated by such electrical receivers, it is necessary to take technical measures both at the stage of development and production and during their operation. The third group includes the PQIs characterizing random electromagnetic phenomena and electrical processes, which are inseparably connected with the technological process of production, transmission, and consumption of electricity. These include voltage dips, overvoltage, and voltage pulses.

The PQIs of the first two groups are standardized, and two permissible levels are set for them: normal and limit. The PQIs of the third group are not standardized, but the statistical information about them is of great importance for the normal operation of the electric power system. The frequency f is a system-wide parameter of the SOS mode and is determined by the active power balance. In the event of a shortage of generated power in the system, the frequency is reduced to a value at which a new balance of generated and consumed power is established. On the contrary, with an excess of generated power, the frequency increases. The voltage deviation from the nominal value in the mode of the maximum ($\delta U2$ max) and minimum ($\delta U2$ min) load may differ from the allowable values. In the Electrical Installation Rules, it is recommended to maintain the voltage in the CPU at a level not lower than 105% of the nominal under the highest load and not higher than 100% – at the lowest load. This requirement meets the principle of counter voltage regulation. The means of voltage regulation are used for the implementation. If voltage deviations are created under the influence of relatively slow load changes determined by its schedule, then rapid load changes create voltage fluctuations. Voltage fluctuations are determined by the envelope of the effective or amplitude voltage values and are characterized by the span δUt and the frequency of repetition of voltage changes or the intervals between voltage changes. A significant share of the load in the electrical network is represented by the EDs with non-linear current-voltage characteristic. Such EDs consume current, the form of which differs significantly from the sinusoidal one.

3. DEVELOPMENT FEATURES OF THE SMART CIRCUIT BREAKER

3.1. Concept of a Universal Smart Circuit Breaker

Due to the lack of an integrated solution that implements the listed functions, a conceptual solution of a universal smart circuit breaker is proposed (Fig. 1). When designing the circuit breaker, modern requirements for the protection of consumer and industrial electronics are taken into account. The functions of the circuit breaker include:

- thermal overload protection;
- electromagnetic protection against overcurrent and short circuit;
- protection against leakage (triggered when a difference in phase and neutral currents occurs);
- protection against the occurrence of an arc on the line (triggered when an arc of more than 0.15 seconds in duration appears);
- shutdown by external user command (via RS-485 interfaces);
- measurement of current and power consumed by the load;
- measurement of voltage on the line, as well as the fundamental frequency and frequency spectrum of the network;
- saving information about the reasons for shutting down the circuit breaker and sending data to external devices (via the RS-485 interface, since the device is designed to be used in conjunction with automation controllers, which typically have an RS-485 interface; if necessary, it is possible to transfer data from a smart circuit breaker via the Wi-Fi interface through the automation and monitoring controller).

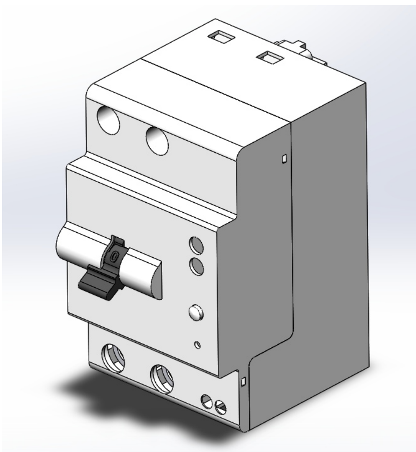

Fig. 1. 3D model of a smart circuit breaker

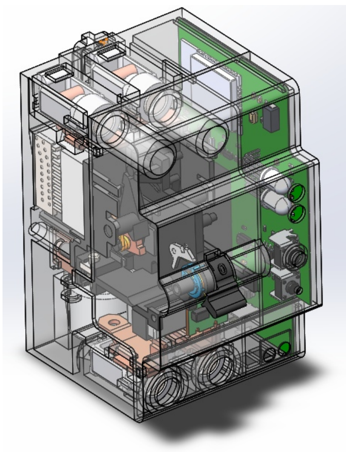

Fig. 2. 3D model of the internal system of the smart circuit breaker

The internal system of the smart circuit breaker, according to the principle of operation, is conditionally divided into two functional units (Fig. 2): a) an electromechanical unit, including electromagnetic and thermal protection mechanisms, as well as transformers acting as current sensors; and b) an electrical unit including an analysis board with an intelligent controller installed on it (intelligent control unit).

In the electromechanical unit during development it is advisable to implement the functions of thermal overload protection, electromagnetic short-circuit protection, current leakage protection function, an electrical circuit disconnection system, and a current sensor for measuring the phase current. The electrical unit must perform the functions of a smart circuit breaker that are impossible or impractical to implement in the form of electromechanical automation.

The intelligent electronics unit must perform data processing functions from the phase current sensor and transformer to measure the differential current, measure the voltage at the input and output of the smart circuit breaker, determine the network parameters (such as power consumption, frequency, sine wave distortion level), switch off the circuit breaker in the case of overvoltage or arc striking on the line, send data to an external device and control the display. A block diagram of a universal smart circuit breaker is shown in Fig. 3.

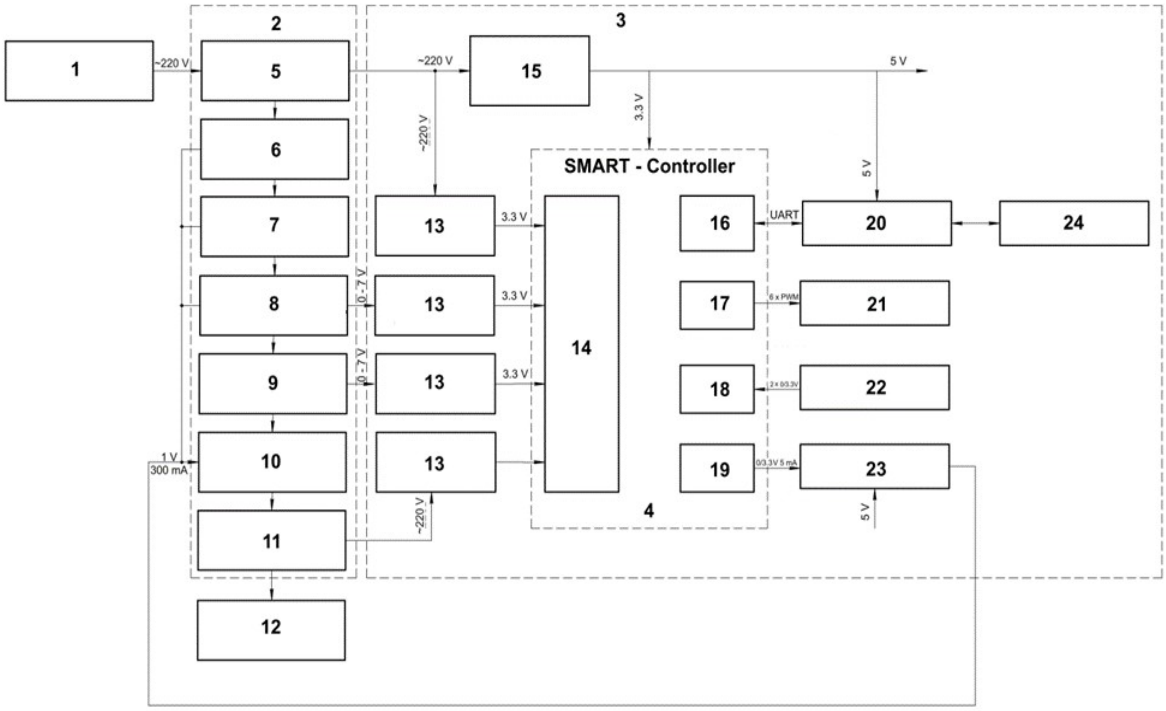

Fig. 3. Block diagram of the smart circuit breaker: 1 – 220 V mains; 2 – electromechanical unit; 3 – analysis module; 4 – electromechanical module; 5 – 200 V input; 6 – thermal protection unit; 7 – short circuit protection unit; 8 – differential current sensor; 9 – current in phase sensor; 10 – relay with arc suppression; 11 – output 220V; 12 – load; 13 – voltage divisor with offset; 14 – ADC; 15 – power supply; 16 – UART; 17 – PWM outputs; 18 – inputs; 19 – control output; 20 – UART-RS485 converter; 21 – RGB-indication; 22 – control buttons; 23 – amplifier; 24 – RS-485 interface.

Considering that the data processing and decision-making functions in the electronics unit are implemented by the microchip, the functions of the analysis board are reduced to ensuring the functioning of the chip, converting signals from the electromechanical unit to acceptable levels for the microcontroller, and converting the control signal of the microcircuit to shutting off the electromechanical unit. In addition, on the analysis board, the indication elements of the state of the circuit breaker should be installed, and buttons for manual control of the smart circuit breaker. The necessary functions of the analysis board include:

1. conversion of an alternating analog signal from the CA input (peak voltage is 400V) to a proportional analog signal in the range of 0-UADC (with an offset of 0.5UADC), where UADC is the maximum voltage of the microcontroller ADC;
2. the conversion of the AC analog signal from the CA output (peak voltage is 400V) to the analog signal in the range of 0-UADC (with an offset of 0.5UADC);

3. conversion of an alternating analog signal from a phase current sensor (peak voltage is 7V) to an analog signal in the range of 0-UADC (with an offset of 0.5UADC);
4. conversion of an alternating analog signal from a differential current sensor (peak voltage is 7V) to an analog signal in the range of 0-UADC (with an offset of 0.5UADC);
5. amplification of the control signal of the IC to a power sufficient to trigger the electromagnetic pusher and turn off the smart circuit breaker;
6. the presence of an indication that allows displaying the status of the circuit breaker and the reason for shutdown;
7. the presence of a button for manual control of the mode of operation of the smart circuit breaker, and a button for resetting the electrical unit of the smart circuit breaker;
8. the presence of a converter interface data output of the microcontroller to the RS-485 interface.

Such a set of functions imposes increased requirements on the element base, which makes it expedient to create a specialized "smart controller" as a special IC.

3.2. Approach to the implementation of protection against spark

An important component of the electrical protection of the housing infrastructure is protection against the occurrence of a spark or arc, both longitudinal and transverse. Both types of arc result in heating of the conductor, melting of the insulation, and may cause a fire. At the same time, none of the standard means of automatic protection, such as a circuit breaker, or a differential circuit breaker, can detect such a fault.

There are specialized means of protection against the occurrence of an arc in a line, the so-called AFDDs (Arc Fault Detection Devices). Unlike standard circuit breakers based exclusively on electro-mechanics, almost all AFDD devices are designed as a combination of an electrical board analyzing network parameters and a network disconnecting switch triggered by command of an electrical board [9, 17]. Recently, relatively cheap AFDD devices have begun to appear, but their sensitivity remains controversial.

Based on literature review [15, 16, 17, 26, 27, etc.], one can state that currently, most developers use simplified mechanisms to generate sparks: interrupted circuits based on mechanical contact opening, twisted wires, etc. In some cases, a spark generation unit with the graphite-copper contact is used to demonstrate the operation of the spark detection device. However, the sparking of graphite-copper contact is very different from the sparking of the copper-copper contact under real-life conditions. This paper proposes a new approach based on a special device that provides automatic spark generation at the copper-copper contact; an experimental test bench was built with a spark generating device between conductors (Fig. 4).

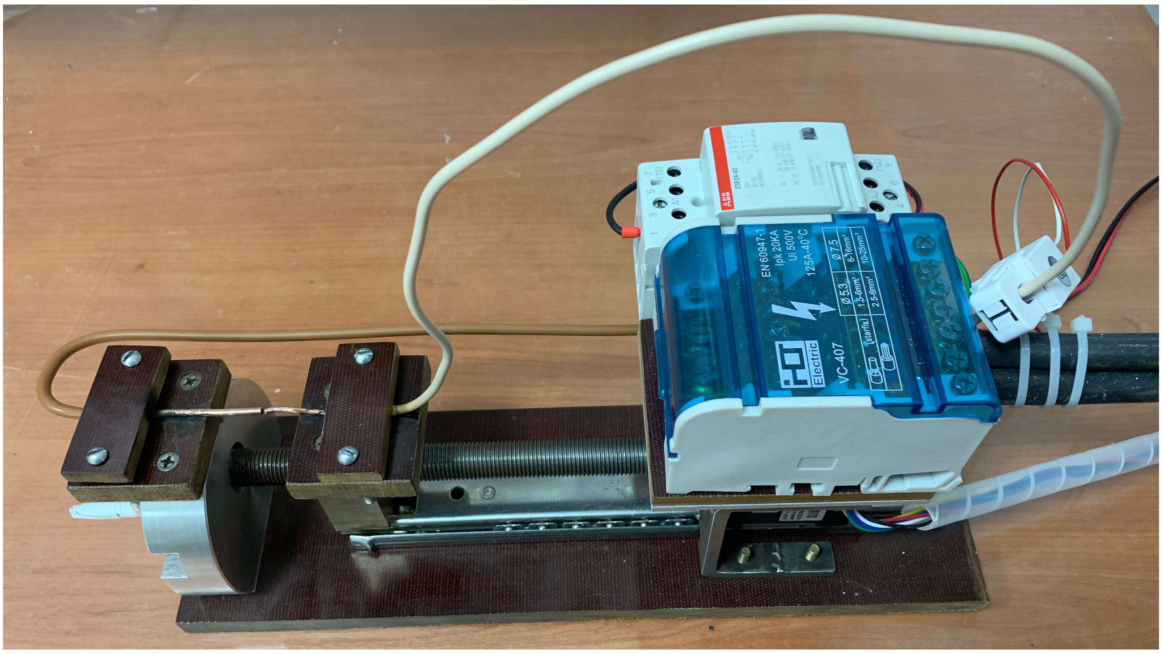

Fig. 4. Device generating a spark in the composition of the experimental stand

The proposed solution provides for fixing two wires and ensuring their contact using a rotary mechanism. Then, voltage is applied and the adaptive spark control algorithm is initiated, which controls the interruption and restoration of the contact based on the current sensor readings in order to ensure maximum possible sparking.

The experiments with a spark under various types of load have shown that when the arc occurs, a sinusoid of alternating current is distorted and the noise-like signals are generated. Spark detection is based on analyzing the network spectrum of a signal by current and voltage. The occurrence of a spark generates a noise-like distortion of the network, often of small amplitude, especially when a longitudinal spark occurs. Due to the high electrical capacitance and inductance of household wiring, the amplitude of the signal generated by the spark weakens with increasing distance from the point where the spark originated. Also, the signal weakens when the active or impulse load in the network is connected between the location of the spark and the location of the AFDD device [4, 15, 16].

The determination of the presence of the arc on the line is carried out through the analysis of the spectrum of the network, as well as the analysis of the shape of the sinusoid AC current. When the arc occurs, the breakdown occurs at a certain phase of the sinusoid of the mains voltage, then the load increases sharply and the sinusoid is distorted. This causes the occurrence of high-frequency harmonics, which can be detected by continuously analyzing the spectrum of the network. In this case, another problem arises due to the absence of a difference between signal distortions caused by the appearance of an arc on the line before and after the circuit breaker. The solution to this problem is the introduction of a filtering element into the circuit of an automaton that changes the amplitude of high harmonics. By the difference of the signal before and after such an element, it will be possible to determine which side of the circuit is the source of high harmonics. If the arc originated from the voltage source, the level of high harmonics from the load side will be lower. In the case of an arc on the load side, the level of harmonics will be lower on the side of the voltage source.

In the simplest case, such an element could be an inductor. The measurement of the amplitude of high harmonics before and after the inductance, taking into account the unpredictability of their composition, is made by measuring the amplitude of the signal passed through the HF filter and the half-wave rectifier.

The calculation of the inductance of the input coil, necessary for the possibility of determining the difference of the amplitudes of the HF signal before and after the filter element, is carried out as follows. Since the voltage difference at the outputs of the rectifiers is actually measured, it is first necessary to determine the minimum step of the ADC of the microcontroller. The resolution of the microcontroller ADC is 12 bits, the range of the measured voltage is 0-1V. Calculate the minimum step by the formula (1):

$$U_{STP} = \frac{\mathrm{U}_{ADC}}{2^{\mathrm{N}}} = \frac{1\ V}{2^{12}} = 0.244\ mV \tag{1}$$

where U_{STP} is the minimum measurement step for the ADC, U_{ADC} is the upper limit of the ADC measurement range, N is the precision of the ADC.

The noise level at the output of the rectifier, determined empirically, does not exceed 0.1 mV, the error level of the ADC is 0.5 minimum step. I.e. the useful step of the ADC is approximately 0.5 mV, or 0.05% of the range measured by the microcontroller voltage.

The arc can occur both in the presence of a load and in its absence. In this case, the arc itself will be the load, the value of which will depend on the distance between the conductors on which the arc originated. The drop in the amplitude of the RF signal at the coil will depend on the value of the coil impedance and the load, i.e. on the load level and inductance value. The greater the impedance of the load, the smaller the drop in RF on the coil, and hence the difference in the signal level. Therefore, one can calculate the required inductance value at the lowest possible load.

The occurrence of the arc, according to the source, is possible at a voltage not lower than 10 V and a current of at least 0.1 A. Based on these parameters, one can calculate the required resistance of the filter element (2-4):

$$\frac{X_{induct}}{X_{induct} + X_r} = 0.05\% \,, \tag{2}$$

$$X_{induct} = \frac{0.0005Xr}{0.9995} \,, \tag{3}$$

$$X_{induct} = 0.0005 \times X_r \tag{4}$$

With a minimum current of 0.1 A and a voltage of 250 V, the total resistance of the arc is (formula 5):

$$X_r = \frac{U_{MAX}}{I_{MIN}} = 2500\,Om \tag{5}$$

then

$$X_{induct} = 1.25\,Om$$

The higher the average frequency of the arc spectrum, the greater the inductance resistance and the greater the voltage difference after rectification. Let the minimum average frequency of harmonics f = 1 KHz. The resistance of inductance X_{induct} is determined by the formula 6:

$$X_{induct} = 2\pi fL \tag{6}$$

Then the inductance is calculated by the formula 7:

$$L = \frac{X_i}{2\pi \times f} \approx 200\,\mu H \tag{7}$$

Thus, in order to determine the position of the source of the arc, it is necessary to include in the circuit of the automaton an inductance coil at least L = 200 μH.

4. RESULTS

Modern comprehensive power grid protection should include: cable overheating protection, short circuit protection, sparking protection, protection against significant voltage deviation, and current leakage protection. The monitoring function is designed to control parameters such as voltage, current strength, power, and electricity consumption. In addition, monitoring in smart security systems should make it possible to determine the state of the system and the cause of the shutdown. The concept of implementing an intelligent smart circuit breaker for the intellectualization of the energy sector infrastructure includes two main functional blocks: an integrated power grid protection unit and a unit for monitoring the power grid parameters. Fig. 5 shows the interaction of components of the integrated power system of the Russian Federation [31]. Individual retail companies interact with end-users; they ensure the accounting and management of end consumers' operation modes. The aim of the work is to develop a concept of implementing universal, intelligent smart circuit breakers, interacting with specific consumers, which provide additional functions to monitor the state of the power grid and provide recommendations for predictive repair.

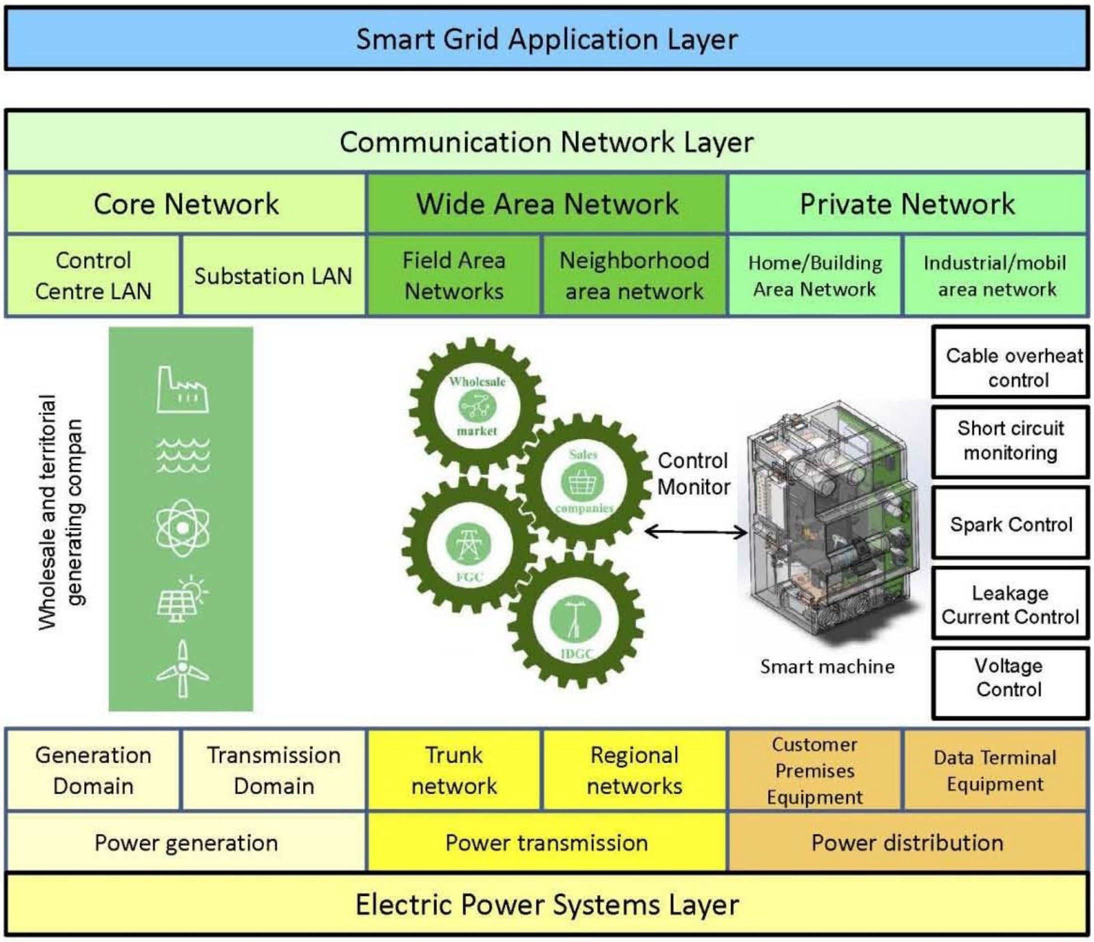

Fig. 5. Functional scheme of integration of smart circuit breakers into intelligent energy infrastructure by the example of the Russian Federation

The proposed smart circuit breaker can be used anywhere, both in private households and in the manufacturing sector. This device provides comprehensive power grid protection and occupies a small part of the electrical control panel. In addition to the basic protection functions, the smart circuit breaker makes it possible to facilitate keeping records of electricity consumption and the quality of power supply, as well as to reduce the number of emergencies due to deeper diagnosis. The advanced functionality of the proposed smart circuit breaker is ensured by using a new specialized microcontroller (SMC).

The use of the proposed SMC ensures the functioning of an intelligent unit for analyzing the parameters of the AC voltage network and controlling the electromechanical elements of the smart automat, as well as sending data through a standard interface. The SMC as part of the smart circuit breaker allows measurement and analysis of the following parameters:

– AC input voltage;
– current in phase;
– difference of phase and zero currents;
– power consumed by the load connected via a smart circuit breaker;
– frequency spectrum of alternating voltage (analysis of occurrence of a spark).

Switching off the smart circuit breaker on a command from the SMC occurs through a signal to its control outputs connected to the electromechanical controls of the smart circuit breaker. The logic of switching off the automaton is given by the algorithm of its operation.

The use of a special microcontroller allows reducing the dimensions of the analysis board. Also, the use of an SMC makes it possible to reduce the prime cost of a smart circuit breaker in the case of mass production.

5. CONCLUSION

The proposed solution is based on the application of cloud and boundary computing technology, and fully allows for remote diagnostics and monitoring of the energy status of the light and digital infrastructures, individual and collective energy systems, life support of buildings, the state of household appliances, IoT devices and housing and communal services. This underlines the ability of the smart circuit breaker to be widely used [7, 11, 13, 19, 24, 27, 30]. As part of the technological solution, this device provides comprehensive protection of the electrical network, while occupying a small part of the electrical panel, and surpasses the existing analogs. In addition to the basic protection functions, the smart circuit breaker will make it easier to record data on electricity consumption and the quality of power supply, and reduce the number of emergency situations by simplifying their diagnosis. It can be stated that innovative smart circuit breakers, the operation of which is based on the principles of the Internet of Things, become an important aspect of social infrastructure. The creation of specialized controllers should ensure at the minimum expense the implementation of monitoring data analysis functions, the transfer of smart circuit breaker data through the service interface to external automation controllers. This paper proposes an implementation concept and recommendations on the configuration of a specialized controller for a smart circuit breaker, designed to analyze the parameters of an AC network. According to the results of the implementation of the technological basis for the development of innovative social infrastructure based on smart circuit breakers using a specialized microcontroller, it can be argued that this approach simplifies development by reducing energy and resource consumption, and the selected controller configuration is the most efficient and fully complies with the requirements imposed on innovative smart circuit breakers. Directions of further research will be focused on improving the computational efficiency of monitoring algorithms and forecasting the state of the power grid with the possibility of implementing the predictive repair functions.

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