Reducing Power Consumption of Measurement and Control Modules Fed with Autonomous Power Supply

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Abstract. In this paper, a detailed analysis is made of the possibility of reducing the energy consumption of the measuring and control modules when they are powered by an autonomous source, a battery, without the possibility of restoring its charge. These modules are designed, in particular, to work in the system for emergency and post-emergency monitoring of equipment and the territory of complex technical systems (for example, nuclear power plants), which must ensure a long (according to regulatory documents - at least 72 hours) data and commands exchanging. The issue of saving energy consumption is considered: (i) at all levels of building measurement and control modules - from wireless data interchange and commands at the level of the structure of the system as a whole to the structure of the most measurement-control modules and circuits of their nodes (ii) in the context of providing informativity, survivability and reliability of data exchange and commands in the system of emergency and post-emergency monitoring of equipment and the territory as a whole. It is shown that the use of modern technical elements (in particular, drones operating as data and instructions retransmitters) and structural solutions (in particular, calibration of analog-digital and digital-analog converters) enables to ensure a high reliability of data and commands exchange despite simplifying the structure of nodes for saving energy consumption.

Keywords: monitoring, measuring and control modules, power consumption, autonomous power supply, wireless communication.

1 Introduction

Reducing power consumption of devices that obtain power supply from battery without the possibility of recharging in the case of technical facility accident is an important problem to be solved. For example, the power supply and communication networks are the most vulnerable subsystems among the emergency and post-emergency monitoring systems (EPEMSs) on the territory of complex technical facilities because of their long length.

It should be noted that the methods for ensuring complex technical facility security have not been developed yet, so large man-made disasters are inevitable. The speed of their elimination and the amount of losses depend on the quality of the decisions taken during the elimination. The best decisions can be taken only on the basis of the relevant information about the current state of the facility. Therefore, the development of EPEMSs is an urgent task today, which is economically justified. The costs for development of such systems are not equal to losses caused by non-optimal decisions taken during the elimination of the consequences of an accident.

According to the above-mentioned, important parameters of complex technical facilities, for example, nuclear power plants (NPPs), should be monitored by measurement and control modules (MCMs), which can operate in isolation mode [1, 26]. This implies long battery life without the possibility of its recharging (72 hours according to regulatory documents).

The task is complicated due to the necessity of the use of wireless communication over long distances. For example, in the case of nuclear power plant accident, the center of decision-making should be several kilometers far from the reactor. And, according to [2, 3], transmitters of wireless modules consume up to 70% of the power of the entire module. Therefore, let us consider the general concept of reducing power consumption of EPEMS, as well as the possibilities of its implementation in relation to MCMs, which are the components of such a system.

According to [4 - 6], the reliability of wireless sensor networks is determined, among other things, by their ability to work from autonomous power supplies. Moreover it’s very important to provide a metrological reliability - the property of MCMs to maintain the established values of metrological characteristics for a certain time under normal and operating conditions [19, 24, 25].

Thus, the purpose of this paper is to provide a set of measures aimed at reducing power consumption of MCMs fed with autonomous power supply that are designed to monitor and control over critical decision making parameters.

2 A general concept of creating the emergency and post-emergency monitoring systems

According to [1, 26], the main parameters of EPEMS are determined as the following ones: informativity, durability and reliability of the data:

1. Informativity is determined as the ability to provide a consistent, steady flow of reliable data on all the facility and adjoining territory parameters, which are necessary for making the optimal decisions.

2. Durability is defined as the ability to provide informativity under the conditions of the intense impact of the destructive factors.

3. Reliability is defined as the ability to ensure the unity of the measurements, that is, the state at which the measurement results are given in the specified units and are

accompanied by the current error parameters [7, 8]. If the error parameters do not fit into the permissible limits, then the MCM must apply the built-in error reduction means. If it is impossible to provide the specified error parameters, then these results will be accompanied by the current parameters of the actual error [9].

According to these definitions, the main parameters of EPEMS are mutually dependent. Informativity of EPEMS relies on its durability. And reliability is an important condition for informativity. It cannot be asserted that optimal decisions based on data, the reliability of which has not been proved (in the conditions of emergency and post-emergency doubts have justified about the reliability of the measurement results and created control effects of each MCM that is in the area of the accident), can be taken.

Long-distance wireless communication during 72 hours requires a significant battery power that feeds the MCM. Therefore, in [1, 26] the concept of EPEMS creation is proposed. This concept provides the following technical decisions making for ensuring the high informativity, durability and reliability of data:

1. providing the MCMs, which monitor critical parameters, with autonomous power supply;
2. providing the MCMs with wireless communication modules, which are economical in terms of consumed power;
3. retransmission of wireless communication module signal by means of drone-repeater fleet;
4. providing the possibility of adapting (decreasing) the transmitter power of MCMs due to the commands of drone-repeaters in accordance with the conditions of data exchange;
5. deploying the drone-repeater fleet immediately after an accident. Therefore, such a fleet will not be damaged in the case of an accident, and the damaged drone can be easily replaced after the accident;
6. recharging the battery, the drones must be returned to the base, and their functions must be performed by the drones sent from the base;
7. reducing the power consumption, drone-repeaters can land in the selected location;
8. providing the drones equipped with a video camera are used to select the location of drone-repeaters landing;
9. foresee, when the MCM monitoring the critical parameters is damaged, drones can deliver the backup module to the specified location;
10. selecting the location for landing the drone-deliverer of the backup module, then the observation results of the drone equipped with the video camera are used;
11. using the methods for power consumption monitoring of MCM in order to reduce a power consumption;
12. using the methods for reducing the power consumption for all units of MCM.

Thus, as it can be seen from the above-mentioned, high informativity, durability and reliability of the data transmitted from the MCM, even in the case of limited power consumption, can be provided. Implementation of these possibilities allows to simultaneously increase the same parameters referring to the subsystems monitoring the MCM. Therefore, we will consider the possibilities of implementing the ways of reducing the MCM power consumption intended for use in EPEMSs.

3 Reducing the power consumption of wireless communication subsystem

A significant reduction of the wireless communication subsystem power consumption is mainly provided by the use of drone-repeaters. However, in this case it is possible to additionally reduce power consumption due to the proper drone-repeaters deployment and the adaptation of the power of wireless communication transmitters to the data exchange conditions.

Drone-repeaters interaction promotes solution to the first problem. In this case, the following tasks must be performed:

1. to determine the efficiency of the decision-making center in the case of the MCM accident [1,26] and estimate approximately the data exchange conditions, i.e. the level of the signal, the intensity of the noise, the availability of dead zones;
2. to distribute preliminary, the required for the drone-repeaters MCMs to retransmit data from them taking into account the required efficiency of the MCMs and the bandwidth of the drone-repeaters;
3. to perform a preliminary optimization of drone-repeaters deployment according to the criterion of the minimum power of wireless communication modules, included in MCM [10];
4. to determine the conditions of communication and adapt the power of the wireless communication module transmitters of the MCM to these conditions after drone-repeaters deployment;
5. to specify, if it is necessary, the distribution of the required for the drone-repeaters MCMs and their location.

As it is shown in the above-mentioned, the development of specialized software is necessary in order to solve the problem of optimal interaction between the MCM and drone-repeaters. In this case, there are two possible ways of developing such software – all drone-repeaters "negotiate" with each other or one of the drone-repeaters assumes the role of the leading one and controls all the rest. The first way is much more complicated, but the most important is the fact that the time required for the implementation of points 1 – 3 above is sharply increasing. However, the availability of a leading drone-repeater causes sharp decrease in the durability of EPEMS, that is, its damage or malfunction leads to the EPEMS failure.

This contradiction can be solved due to the fact that each drone-repeater with the necessary software can be the leading one. A drone is specified as a leading one at the place of the accident. To avoid conflicts, a clear criterion must be determined, which is not related to the drone-repeater hardware or software, which is unified. It is proposed to use as a criterion the unique numbers of drone-repeaters, for example, a leading one becomes a drone, whose number is the smallest among those flying to the facility. When a leading drone is damaged, it cannot give control signals. These signals are monitored by other drones. According to the drone-repeaters replies that come to the leading drone, all drone-repeaters have a list of their numbers and determine who will lead. In this case, to reduce the requirements for the processor resources of the drone-repeaters, a leading drone ceases to transmit the data. It shares its tasks among other drone-repeaters. If it is necessary, a leading drone will call reserve drone-repeaters. Also, the task of a leading drone is to distribute and determine the tasks of the reserve drone-repeaters, which it calls when it is necessary to recharge the battery of the drones that need it. Such algorithm ensures a high reliability of the EPEMS operation [11, 12, 27] and the possibility of significant energy savings for all MCMs.

The criterion for adapting (decreasing) the power of the MCM transmitters may be the level of errors in the data exchange in accordance with the conditions of data exchange [1, 26]. It should be noted that in the event of accidents, especially at nuclear power plants, there is a sharp increase in the noise level. Therefore, to ensure the data exchange, error combating codes should be used [13]. However, there is a danger that drone-repeaters and MCMs cannot be able to communicate due to the lack of the data exchange protocol immunity (although the data itself will have sufficient noise immunity). Therefore, it is necessary to solve the following problems:

1. reengineering of one of the standard protocols of data exchange for a sharp increase in its noise immunity and the possibility of error correction [14];
2. ensuring this protocol by function of the current analysis for the number of errors in terms of the possibility of their correction [15];
3. providing the possibility of adapting the power of the MCM transmitter to the level of the noise-proof code accepted for the use [16].

It should be noted that the methods of reducing the power of the MCM transmitter by reducing the voltage of the input signal are ineffective [16]. In this case, the power consumed from the battery decreases in proportion to the decrease in the amplitude of the signal, and the output power decreases in proportion to the reduction square. That is, with decreasing the power of the MCM transmitter, the system efficiency drastically decreases. The supply voltage decreases in the same way due to the serial turned on resistor, stabilizer or digital-to-analog converter. Only a high efficiency pulse stabilizer can increase the efficiency of the power reduction of the MCM transmitter. However, the transmitter consumes power as short pulses. Therefore, when these impulse devices interact, transient processes take place, causing additional errors in the data exchange. In [16, 17] it is proposed to use a capacitor divider of the transmitter supply voltage, which regularly recovers the charge. This method provides a more moderate reduction in the efficiency.

4 Reducing power consumption for other components of measurement and control modules

4.1 The structure of measurement and control modules

In general, the possibility of significant reduction of the MCM power consumption is determined by the use of microcircuits implemented according to CMOS technology. But there are methods of additional power reduction and increased reliability by means of modifying the structure of the MCM and its units. Methods of power reduction will be considered according to the structure of the typical MCM (Fig. 1). The selected multi-point structure of the measurement channel is more promising than multichannel structure in terms of power consumption, durability and reliability.

One of the most effective common method of battery saving is to switch off MCM units that are not needed at the specified period of time. This solution is suitable to the MSP430 microprocessor [15]. In order to implement such a method, it is necessary to include a register into the structure of the MCM, which could control the power on / off switches of certain units. It is advisable to combine the mode of switching off power of the MCM units with the mode of "deep hibernation" of the microcontroller when only the pulse generator and the Watchdog timer are operating.

The first unit of the MCM structure (see a Fig 1) is a switchboard. If it's necessary to suppress a common noise and the inter-channel noise with a small amplitude (up to 30 V), then the switchboard will be performed on MOS switches [16]. Their power consumption is very low. If the voltage noise is high, then the reed switches can be used. It is necessary to reduce their power consumption due to the fact that the voltage of these relays is approximately three times less than the voltage of their operation. Therefore, it is advisable to use a relay, the voltage of which corresponds to the voltage of the battery. For their actuation it is advisable to introduce the additional charged capacitor simultaneously with the battery.

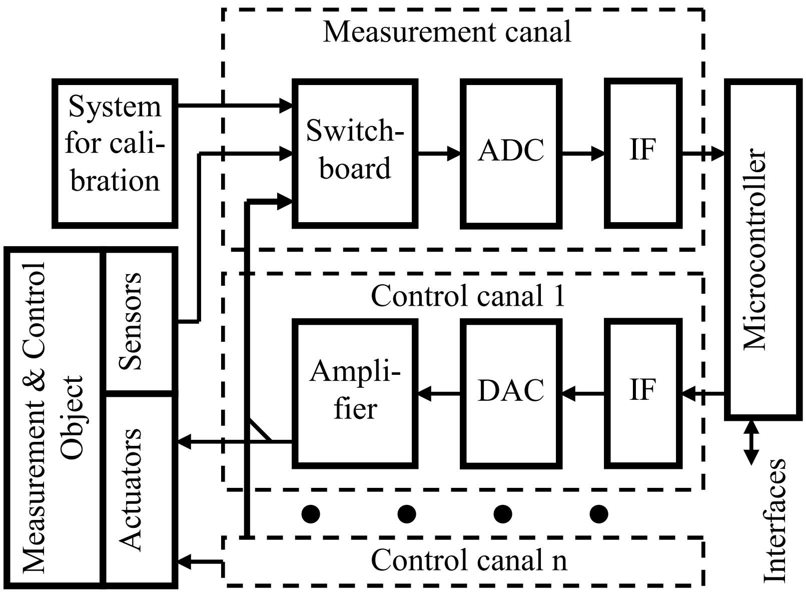

Fig. 1. Block diagram of MCM

Sensor signals are amplified by means of an amplifier in common MCMs. If inertial sensors (temperature, pressure, discharge, etc.) are used, then, it is advisable to apply the 24-bit sigma-delta Analog-to-digital converters (ADC) that have a range of 20 mV conversion [16]. Then, the amplifier is not needed. Other units (see a Fig.1) are: Digital-to-analog converter (DAC) and interface IF.

4.2 Assessment of metrological characteristics.

Proceeding from [19, 24, 25], the values of the metrological reliability for the measurement and control devices are determining experimentally on the basis of their metrological characteristics during the statistical tests of such devices. Given the lack of a ready-made MCM sample, the authors consider it possible, based on the results of testing the experimental samples of the developed ADCs and DACs, to perform the following assessment of metrological characteristics.

It should be noted that sigma-delta ADCs provide the zero setting and calibration to ensure the high accuracy and reliability [19]. However, destructive factors during an accident can drastically increase the nonlinearity of ADCs. Then, successful zero setting and calibration can "hide" the big error of the ADC. In [18] methods of determination and correction of the ADC nonlinearity error on the basis of resistor voltage dividers are proposed. This divider is connected to the ADC calibration voltage source. In this case, the errors of the resistors, in fact, do not affect the error of the determination of the ADC nonlinearity error. If resistors with an acceptable error of 1% are used, the error of determination of the ADC nonlinearity error will not exceed 0.0002% according to [18]. In order to reduce power consumption, it is advisable to switch on calibration and determination of the ADC non-linearity systems as rarely as possible. Therefore, it is expedient to transfer their results to the upper level of EPEMS. This will enable to verify the reliability of data transferred from the ADC and build the ADC degradation model. The model parameters should be transferred to the MCM for current use.

The MCM structure (see a Fig. 1) regarding the DACs is the multi-channel one; each channel must control constantly its actuator. Therefore, the power consumption of the DAC affects significantly the MCM power consumption. The analysis showed that most DACs of the MCMs should not have the high performance. That enables to use the DACs that have only R-2R matrix with powerful resistors and keys for switching it [19]. Such a scheme is characterized by minimum power consumption. At the output of this DAC, a micro powerful operational amplifier with MOS transistors at the input should be set. As the source of the reference voltage, the power supply voltage of the DAC is used.

It should be noted that the errors of such a DAC, due to the instability of reference voltage, will be rather big. However, the ADC precision measurement channel, as a MCM part, provides the high metrological reliability due to periodic zero and calibration [18], as well as the determination and correction of the error of nonlinearity. It can be used as well to correct the DAC error [10]. For this purpose, it’s necessary to increase the number of switchboard channels only.

Thus, the proposed MCM will have the high metrological reliability. All of its components enable conducting the metrological testing during operation. The only component that does not subject to metrological testing is the source of the ADC voltage calibration. To counteract destructive factors, it is expedient to use two or three of such sources. It is advisable to use the data fusion technology [21, 28] to process the calibration results.

The proposed approach of the scheme simplification is mostly based on deleting the components which are a part of the common MCM, for example, voltage regulators and reference voltage sources per each DAC channel. Such simplification can bring the essential decrease of the metrological reliability because the battery voltage may reduce by almost 20% during the discharge process. However, the developed methods for correcting the ADC and DAC errors [18, 20] enable to keep the metrological reliability at the given level.

To ensure the high common noise resection, a galvanic isolation of interfaces IF is of great importance. The optocouplers used for this purpose consume a significant amount of power while the LED is glowing. When using a sigma-delta ADC for galvanic isolation, only 2 optocouplers are required. But each DAC channel requires an individual solution. Reduction of the number of optocouplers as well as the power consumption can be possible due to the fact that the data should only be transferred to the DAC. Reverse data transfer is not needed. Data can be transferred to a DAC using only one optocoupler. Logic 0 and 1 should be transmitted by impulses of different durations. In order to distinguish them, it is sufficient to use a formulator on two CMOS logic elements that consume less power than 1 μA.

To ensure the high common noise resection, the galvanic isolation of supply voltage is not of less importance. In this case, the whole measurement channel power supply decoupling is necessary as well as the decoupling of each channel of the DAC, in particular. Commonly, the high-frequency generator and a transformer are used. The rectifier filters and stabilizers are connected to the separate secondary windings of transformers [22]. This solution is rather complicated and has a low efficiency. To simplify the MCM and reduce its power consumption, it is expedient to use two ways of decoupling.

Firstly, when the voltage noise does not exceed 30 V, the decoupling should be performed on the MOS switches. In each channel of the decoupling, the capacitor is charged from two switches of the power supply circle of the MCM digital units. Then, from other two switchers, this capacitor transfers its charge to another capacitor, which consumes a power from the unit that requires for a galvanic isolation. Power losses in this case are determined only by the voltage drop in the MOS switches resistance during the transient processes of capacitor charging / discharging.

Secondly, when the voltage noise exceeds 30 V, in particular, in the measurement channel, a relay is used to charge the capacitor in the circle of its power supply [23]. Then, the capacitor must have a sufficient capacitance to feed the measurement channel for at least one measurement. The relay should charge this capacitor when the relays of the switchboard are open.

In order to avoid failures in case of the network voltage losses, the network power supply unit and battery should be constantly switched on to consume power from the MCM digital units. To avoid a conflict, each unit must be turned on using a diode. In this case, in order to avoid discharge of the battery in the case of availability of network voltage, the voltage of the power supply unit from the network should be set to 0.2 – 0.3 V higher than the maximum voltage of the battery. To avoid a dissipation of power on diodes, it is shunted by the contacts of the relay. The relay must be fed directly with the power supply of the network. Properly closed contacts of the relay should shunt a diode connected to the battery and properly opened contacts should shunt the diode connected to the network power supply unit.

5 Conclusions

Authors developed a number of methods that can significantly promote reducing the power consumption of measurement and control modules included into emergency and post-emergency monitoring systems. Those methods practically do not increase the weight and dimensions of measurement and control modules as well as its cost. However, they enable to provide the operation of the measurement and control modules within a given time without recharging the battery.

It should be noted that the proposed methods are largely based on the exclusion of components included in traditional measurement and control modules, in particular, voltage regulators and reference voltage sources per each DAC channel. In this case, the reference voltage for the DAC is its power, which is formed directly from the battery voltage. The latter falls by almost 20% in discharge process. Only the developed methods for correcting the ADC and DAC errors enable to provide the high metrological reliability of such measurement and control module.

One of perspective ways for a future research is to explore the possibility of using the analytical tool of reliability theory to assess the metrological reliability of distributed sensor networks, in particular, wireless sensor networks.

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