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The integration of an automatic reserve switching controller into a railway traffic control system power supply through the use of a Petri net and a graphical programming language

Integracja sterownika załączenia rezerwy zasilania urządzeń sterowania ruchem kolejowym z wykorzystaniem sieci Petriego i graficznego języka programowania

Abstract

The requirement for high reliability and safety in the operation of measuring and control systems is particularly relevant in critical applications in which system failure can lead to large material losses and can constitute threat to health and even to life. Railway traffic control systems are one such application. There is a requirement for the use of powerful tools and methods of modelling the function and operation of this system. The purpose of this publication is to present the use of a Petri net in modelling automatic reserve switching device controllers of railway traffic control system power. The publication also shows the practical implementation of such a controller. It was implemented using the hardware platform of the NI CompactRIO family of controllers and an application made in the National LabView graphical programming environment.

Keywords: power supply of railway traffic control systems, Petri nets, graphical programming of industrial controllers

Streszczenie

Wysoka niezawodność i rzetelne działanie systemów pomiarowo-sterujacych w zastosowaniach krytycznych w obecnej dobie jest coraz bardziej wymagany. Niewłaściwa praca takich systemów może doprowadzić do dużych strat materialnych, a nawet utraty zdrowia i zycia ludzi. Dlatego tez uwarunkowania te wymuszają stosowania narzędzi i metod do formalnego modelowania funkcji oraz symulowania pracy powyższych systemuów. W artykule zaproponowano wykorzystanie Sieci Petriego w procesie modelowania funkcji sterownika układu automatycznego załączania rezerwy urządzeń zasilania systemów steriwania ruchem kolejowym. W artykule przedstawiono także praktyczną realizację sterownika wspomnianego wcześniej układu. Zrealizowano go na platformiie sprzętowej rodziny sterowników NI CompactRIO oraz aplikacji wykonanej w graficznym środowisku programowania LabView firmy National Instruments.

Słowa kluczowe: zasilanie systemów sterowania ruchem kolejowym, Sieci Petriego, programowanie kontrolerów przemysłowych.

1. Introduction

Nowadays, measurement and control digital systems (MCD systems) are commonly used in industrial processes [12]. These systems are constructed using hardware platforms such as PLC's, industrial computers and embedded systems. The functionality of MCD systems depends on implementing software applications. Thus, the quality of the action of this system is influenced not only by a hardware platform, but also by its software. The need to ensure high software reliability and reliability of the entire MCD system is required especially in so-called critical applications. In these applications, malfunction or damage of MCD systems during their operation can lead to abnormal functioning of the monitored process which can result in loss of life and material waste. Ensuring the required quality of the MCD system in its design and prototyping stages requires the use of appropriate tools and methods to formalise its functions and actions. Suitable instruments for this purpose may be Petri nets. These are graphic and formal tools for modelling, formal analysis and the design of discrete event systems. A model represented by such a net allows the analysis of the characteristics of the system's behaviour and allows its evaluation within each phase of the system's life cycle.

The aim of this publication is to present the possibilities of using Petri nets in modelling MCD systems in a critical application [2, 4, 5, 6, 7], specifically, the integrated controller of the automatic reserve switching device of a railway traffic control system power supply. This publication also shows the practical implementation of such a controller [7, 8, 17].

2. Power supply of railway traffic control systems

2.1. Railway traffic control systems

Railway traffic control systems (RTCS) provide the safe, reliable and efficient movement of rolling stock on the railway network [2]. Therefore, RTCSs are classified as critical equipment and systems [5, 6, 7, 8]. The history of RTCSs dates back to the end of the nineteenth century, when the industrial revolution introduced rolling stock for the transport of first goods and then people. Initially, railway traffic safety devices were simple and the main role in the decision making and execution process was fulfilled by a person. Currently, mounted station-based RTCSs are comprised of either a relay and computer systems, or only computer systems without a relay [2, 4]. In relays and computers systems, security is ensured in the relay layer, and the setting functions are performed by a computer control panel [2]. The development of information and computer technology has led to the construction of secure computer systems. For systems of this type, PLCs or computers with '2 of 2' or '2 of 3' voting systems are used to provide the required level of security [2, 4, 8].

The use of relays and computer systems requires the provision of adequate reliability and quality of power [16]. Therefore, new, more suitable power supply systems are being introduced that can meet the increased requirements.

2.2. Power supply systems for RTCS

The current requirements for the design and manufacture of power supply systems for RTCS are presented in Chapter 13 of Management Order No. 1/2014 of PKP Polish Railways. [16]. The general requirements (§ 72) of this chapter are to state that the primary sources of power supply for station-based RTCS are power grids that meet the requirements for [6, 16]:

▸ regulations for the construction of power equipment;
▸ strategies for protection against overvoltage;
▸ strategies for shock protection.

In § 73 of the above chapter on power supply, station-based RTCS have the following requirements [6, 16]:

▸ electricity must be supplied from terminals from a non-traction line (LPN); This power supply should be provided by two 3x400/230V power network meshes;
▸ power supplies must have a built-in backup (emergency) power supply in the form of a combustion-power unit (chiller), inverters or UPSs;
▸ bypass systems for switching equipment and a backup power supply should be provided;
▸ voltage fluctuations in the power supply and the backup power supply sources must not exceed ± 10 % of the nominal value;
▸ circuits for powering electronic and computer systems must be protected against overvoltage protection;
▸ dedicated AC circuits of stations-based RTCSs and circuits supplying DC relays requiring an uninterrupted power supply should be supplied with power during the changeover from dedicated power sources such as inverters; Inverter batteries must ensure that they sufficiently operate for 1 hour;
▸ the power supply system of stations-based RTCSs should have:
  ▹ equipment for the control and automatic switching of power lines, equipment for controls and automatic (or manual) switching of the power line to a backup source;
  ▹ components for the distribution of electricity to individual circuits;
  ▹ equipment for signalling the status of power supply equipment and the table of setting fuses (in the control room).

A general block diagram of the power supply system intended for relays and computer, computers station-based RTCS is shown in Fig. 1 [6, 13, 14, 15].

As shown in the above block diagram, the power supply system is powered by two independent 3x400/230 V power networks. A spare power source (the power generator) is also included in the system. Overvoltage protection elements (OVPs) are installed on the power lines in the power supply cabinet (PSC).

The parameters of the mains power supply and the backup power source (power generator) are measured by MS1, MS2 and MS3 measuring modules. The MS4 measurement modul measures the power supply parameters at the output of the automatic reserve switching device (ARS device). These systems in the current solutions are modules for measuring
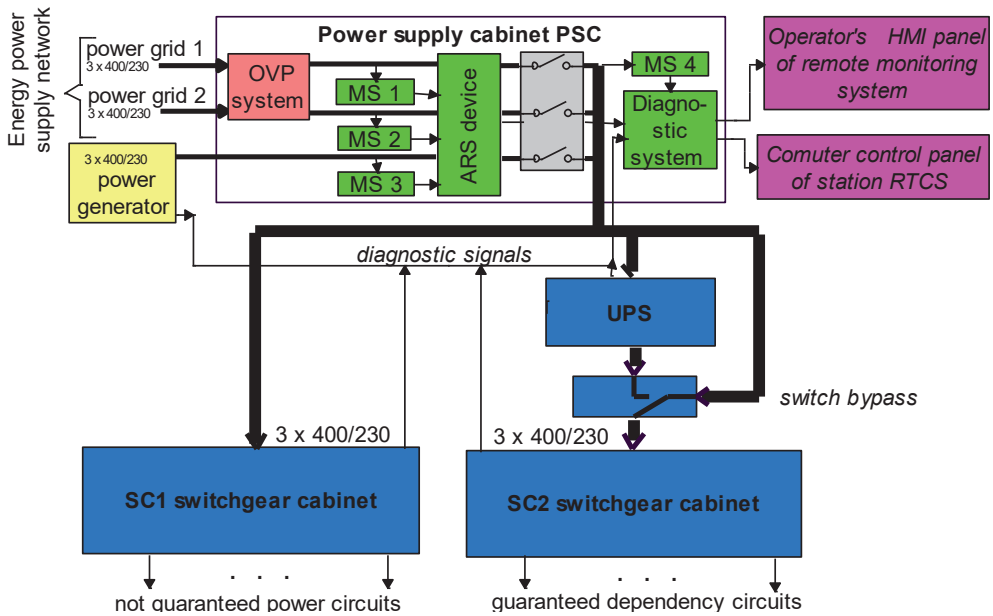
Fig. 1. General structure of the station RTCS's power supply system

power supply parameters. They measure not only the correctness of the power supply voltage but also the frequency, the total harmonic distortion THD and the correct phase sequence. In the case of an incorrect value of any of the measured power parameters, the ARS devices switch the power supply so that the power supply to the station RTCS is uninterrupted. The ARS device, in addition to its control logic, also has a contactor-mechanical coupling that provides power to the device from only one power source, even in the event of an ARS failure.

The voltage of the power supply from the ARS device is divided into two power distribution cabinets. The first (DC1 switchgear cabinet) supplies components of the station-based RTCS; however, this supply is not guaranteed. This means that these components, in the absence of power, will not endanger the safety of railway traffic at the station. The second distribution cabinet (DC 2 switchgear cabinet), powered by an uninterruptible power supply (UPS), supplies the station components of RTCS that must have a guaranteed power supply. These include: light circuits that prohibit track signallers, DC relays, power supplies for computers and computer control panels. The above mentioned cabinets contain appropriate bypass systems, which can be used to manually switch power sources. The block diagram in Fig. 1 also shows a diagnostic system that collects measurement data and status data relating to power components and devices. This information is saved in the recorder of this system and the selected text or graphic information (pictogram) is displayed on the operator panel display. From the diagnostic system the required information is transferred to the computer control panel of the station-based RTCS.

2.3. ARS controller

The development of an integrated ARS controller has been proposed on the basis of an analysis of the requirements and the technical solution of the currently produced power supply systems of the station RTCS (p. 2.2). This controller integrates power components such as MS1, MS2, MS3 and MS4 measuring modules and ARS logic and diagnostics system with data transfer interfaces. The location of this controller in the power supply system is shown in Fig. 2 [6].
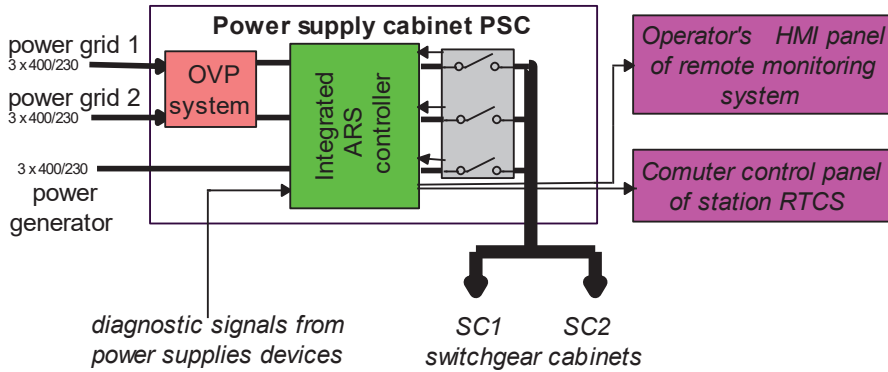

Fig. 2. Structure of the station RTCS power supply system with ARS controller

2.4. Application steps of ARS controller

Controllers for the automation devices are implemented on programmable hardware platforms. They can be classified as being discrete real-time MCD systems. Systems of this type are reactive systems, which implies an immediate (finite) response of the system to events. Designing such systems requires a behavioral approach to modelling functions and system operation. Such modelling enables the effective use of graphing tools such as the Petri nets or state diagrams [1, 3, 6, 8, 10, 18]. An important advantage of these tools is the ability to manipulate state concepts and construct hierarchical structures and concurrent modelling.

Based on the analysis of current solutions [2, 13, 14, 15] and the requirements for power supply systems of station-based RTCSs [16], a functional model of a controller with a Petri net has been developed. Based on the developed net and the use of the National Instruments LabView graphical programming language, software applications have been developed. In parallel with the design and implementation of the software, assumptions are made regarding the hardware platform of the controller. The National Instruments CompactRIO platform as the base platform. The next step of the ARS controller implementation is the integration of the software application developed with the hardware platform. After the integration and positive activation of the controller, functional tests were performed on the basis of a previously developed research program. This enabled the verification of objectives for the ARS controller.

3. Petri net based ARS controller

3.1. Petri nets

In 1962, Carl A Petri developed a tool called a Petri net (PN) which is based on graph theory and is used to model discrete systems [1, 3, 9, 10, 11]. As a result of the long-term development of the theory of these nets, a number of classes of PN emerged for which wide applications have been found [1, 3, 5–8]. As the graphical tool for modelling complex systems, during the development phase Petri nets allow for good and clear communication between designers and customers. As a result of this, a comprehensive requirement specification was created, which does not contain vague rules and formal records that are inconvenient for customers. The resulting graphic model of the system can also be applied in computer graphic simulation environments of PN – this resulted in a virtual prototype of the system being designed [1, 3]. This allows designers fast, interactive and comprehensive testing of the functionality and features at every stage of its life cycle. Petri nets are ideal for the system modelling of discrete events and the analysis of their properties [1, 3, 9–11], such as the synchronisation of processes, asynchronous events, competing tasks, conflict shared resources jams, etc. Petri nets are described by linear algebraic equations or other mathematical formula reflecting the behaviour of the designed system [9–11]. The ability to formally verify the model is quite important in the construction of industrial MCD systems. Petri Net that is extended with a time-domain model can be used to model embedded systems [11], real-time systems [1, 10], and in particular, real-time safety critical systems, which include railway traffic control systems [2, 4–8].

One of the essential characteristics of Petri nets is their relatively simple and intuitive graphical representation. These nets, which are derived from the theory of directed bipartite graphs, allow the use of terms specific to these graphs [9, 10, 11]. These graphs contain two types of vertices called places and transitions. The vertices represent states or activity of the modelled system, respectively. They are connected with each other by arcs in such a way that the arcs connect only vertices of different types. The resulting graphic notation is characterised by a net structure. Graphic representation and structural properties are common features for all classes of nets [9, 11].

To be able to fully model the system, taking its dynamics into account, a definition of PN was extended by net marking. This represents the state of the modelled system. The net status is represented by token changes as a result of pass-time simulation of the net. Therefore, a Marked Petri Net (MPN) is an ordered quadruple [6, 9, 11]:

$$N=(P, T, A, M_0) \tag{1}$$

where:
$N=(P, T, A)$ – is the *PN*,
$M_0 : P \to \mathbb{Z}_+$ – is a function defined on the set of places called the *initial marking* of the *N* net.

In this class of net, places have unlimited capacity for tokens, but arcs can carry only one token. Execution of the transition involves the elimination of individual tokens from the input

places and adding the individual tokens to the exit places of this performed transition. In the *generalised Petri net (GPN)* class [6, 9, 11] it is possible to eliminate or add more tokens to one place in the performance of a single transition by assigning appropriate weight arcs. By introducing the function of limiting the capacity of the places for tokens to the GPN, one of the most common net class in literature [9, 11], called *places and transitions Petri net (PTPN)* is obtained [9, 11]. The PNPT can easily replace a GPN which has the same properties. Accordingly, the term PTPN often refers to GPN in the literature [9, 11]. It can be stated that the MPN class is a special case of GPN and PTPN, in which there is unlimited token capacity, and arcs carry only one token (the weight of the arcs is 1).

A Petri net, as a bipartite graph, can have a hierarchical structure [1, 11], greatly facilitating the modelling of complex systems. Constructing the net can be performed in two ways [6, 7, 8, 11]. The first of these, from the specific to the general *(bottom – up)*, involves the extration of separate, small sub-systems of the model system and then building simple nets. These simple nets are then deposited in growing parts until a whole net of the modelled system is given. The second way, from the general to the specific (top – down), is to build a net for the entire system, without a detailed analysis of the fragments and treating the individual parts of the net in a similar. This procedure is called structural modelling (hierarchical modelling). A net built using one of these methods is called a *hierarchical net* and the net elements of the composite structure are called hierarchical net elements [1, 11]. These elements representing parts of the net are called macroplaces and macrotransitions. The choice of modelling depends largely on the type of a system which is being modelled. If the szstem is completely unknown to the designer of the system, using the second method is more efficient. However, when past experience can be used in modelling the system, the first method becomes more convenient.

3.2. Marked Petri net ARS controller

The marked Petri net based ARS controller (MPN ARS controller) has been developed based on the features of the ARS integrated controller power supply system of station-based RTCS (p. 2.2 and p. 2.3 of this article). This MPN is a special case of a GPN and PTPN class of PN in which the capacity of the places is unlimited and only one token can pass through the arc. The developed MPN ARS controller (Fig. 3) can be characterised by [6]:

- ▸ a production process which generates tokens,
- ▸ a storage process (token buffer),
- ▸ two consumer processes that absorb tokens.

In the production process, tokens are generated corresponding to places and transitions p7 – t3, p8 – t4, p9 – t5 and p10 – t6, which represent the voltage signal acquisition by the measurement modules MS1, MS2, MS3 and MS4. Places and transitions p11 – t7, p12 – t8, p13 – t9, p14 – t10 are responsible for the analysis of the measured signals, resulting in parameters relating to the quality of the supplied electricity. These parameters are passed to two consumer processes through the storage process (buffer data), place p15 and transition t11. Consumer process 1 is responsible for the control logic of the ARS controller. In this process, in addition to the supplied power supply parameters (place p16), signals from the

binary inputs of the ARS contactors (place p19 and transition t14) are read from the binary inputs. On this basis, the logic of the ARS controller (place p16 and transition t12) generates control signals for the contactor (place p17 and transition t13) via binary outputs. Consumer process 2 is responsible for recording the power quality parameters and the current state of the ARS controller (place p27 and transition t20). The above data is transmitted to the HMI operator terminal (place p22 and transition t17) and to the computer control panel of the station RTCS (place p25 and transition t19).
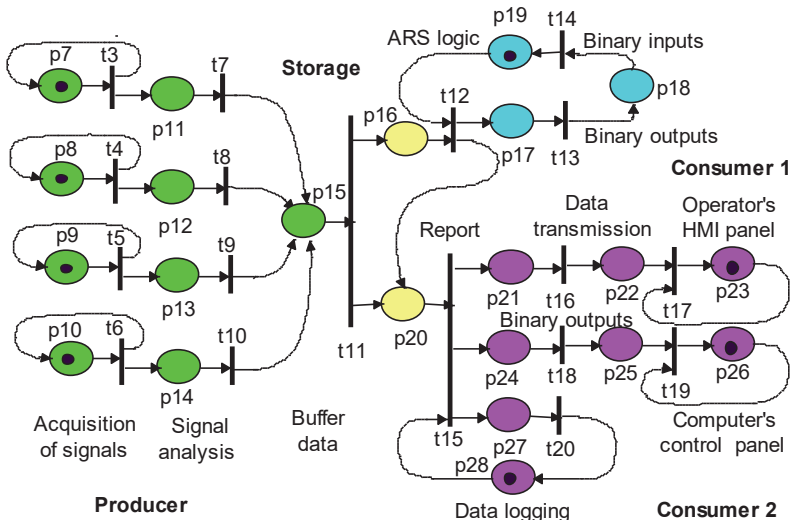
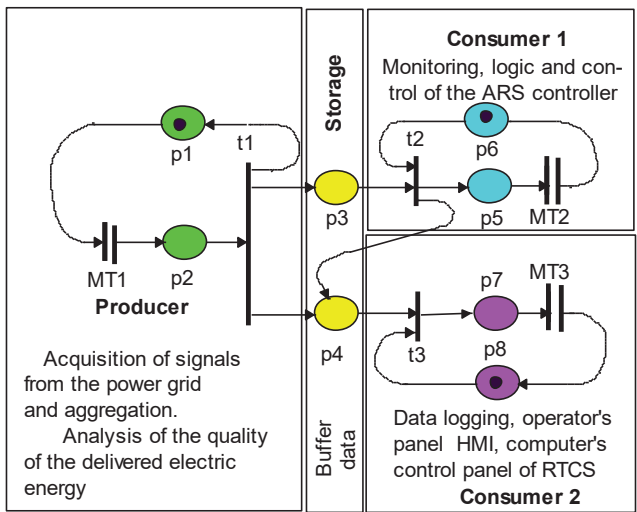Fig. 3. The marked Petri net based ARS controller

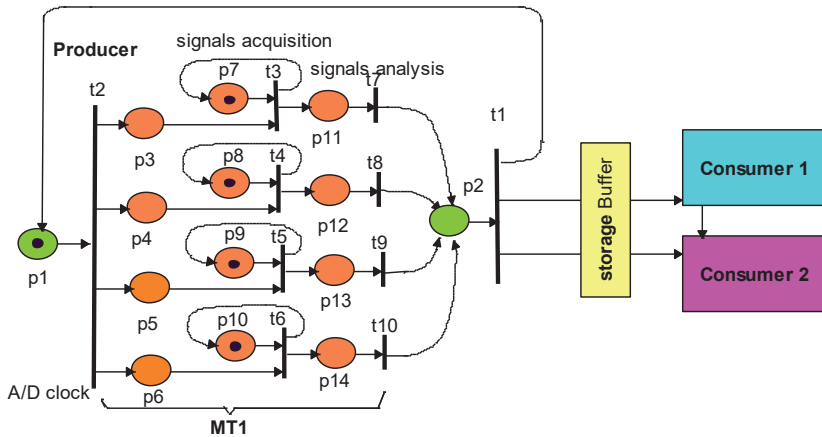Fig. 4. The hierarchical simplified marked Petri net based ARS controller

Fig. 5. The ARS controller block`diagram with macro transition MT1

Fig. 4 shows the hierarchical simplified MPN ARS controller. This net was created as a result of the hierarchy of the ARS controller [6] MPN from Fig. 3, using the bottom – up method [11]. The resulting simplified hierarchical MPN is easier to analyse. This net corresponds to the producer – consumer model system. The class of this type of net is well known in literature [11]. One of the important features of this net is its liveliness; this means that the net does not become jammed, and every producer's token is consumed by consumer processes [11].

Fig. 5 shows the block-diagram of the ARS controller with the macro transition MT1 from the simplified hierarchical marked Petri net [6]. In this macrotransition, the functions of the AC voltage acquisition sub-system were modelled using a measuring card with parallel analogue-digital processing and digital signal processing.

4. Practical implementation of the ARS controller

4.1. Hardware platform of the ARS controller

The ARS controller hardware platform was configured using National Instruments NI CompactRIO components [5, 17]. This is a real-time platform with modular construction. It meets the stringent requirements of environmental standards approved by the Management of the Polish Railway Lines. This platform consists of [6]:

- ▶ NI cDAQ-9135 cassette with a processor module equipped with: an Atom processor 1.33 GHz, 32 GB RAM, 8 slots, Linux RT real-time operating system, an HMI interface;
- ▶ NI PS power supply module: 24 VDC, 5 A, 100-120 / 200-240 VAC input;
- ▶ 4 analogue input modules NI 9244: 400 Vrms L-N, 24-Bit, 50 kS / s / ch, 3-Ch – these modules are designed to measure the supply voltage of the power system;
- ▶ 2 digital inputs/outputs NI 9375: 16-DI, 16-DO, DI / DO – these modules are designed to control and monitor the state of the ARS contactors and to transmit information to the computer control panel of the station RTCS.

4.2. Software application of the ARS controller

The National Instruments LabView graphical software environment [6, 17] was used to implement the ARS controller software application. This environment has many tools for fast software development. The main advantage of this environment is that the execution of the program is based on the data flow between the nodes of the program. These nodes include simple functions, complex functions, the VI Express function and the SubVI functions made by the user. Execution of the node function will only occur if the node inputs have data. This requirement is similar to the mechanism of triggering transitions in the Petri net. This environment also includes programing structure patterns; one of these being the Statechart module [6, 17, 18].

The Statechart module of the LabView graphic programming environment is a tool for creating state machine diagrams. Among other features, the functions of this module enable defining states and transitions, events, hierarchies and sub-states. As a result of the introduction of the appropriate graphical program code to the created diagram structure after translation and compilation, the program code for the designed ARS controller is obtained.

D. Harel proposed machine state diagrams [10] as a visual formalism tool to describe complex control systems. These diagrams introduce the concept of state and spread the concept of a finite automaton. The graphical representation of the state machine is a diagram of states and transitions. In the basic, parental state diagram, sub-states that assign states to their state diagrams can be defined. The orthogonality of state diagrams enables the ordering of sequential automata which can model concurrent phenomena. In turn, the broadcasting mechanism is realised by generating events that have a detrimental effect on the functioning of the diagram [17, 18].
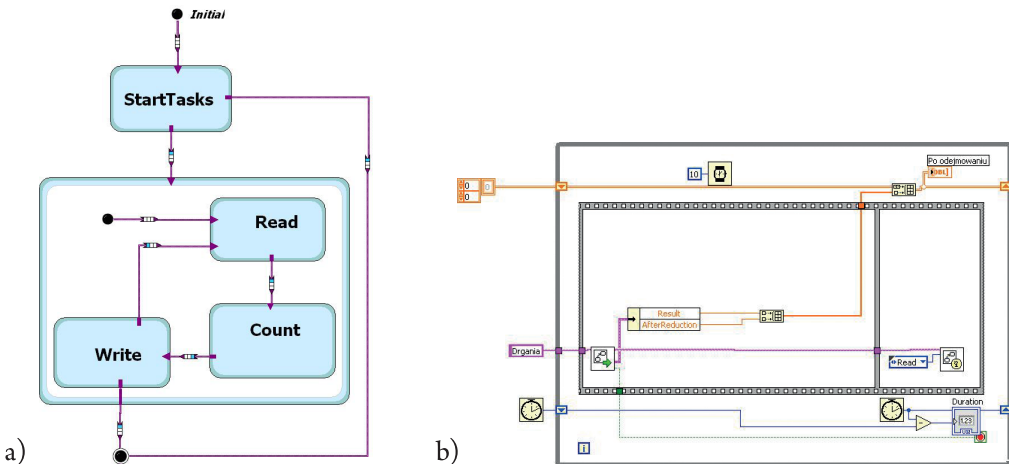

Fig. 6. a. – State diagram of ARS controller, b – main loop

The basic state diagram, corresponding to the hierarchical simplified Marked Petri Net ARS in Fig. 4, performs four basic states:

- ► wait state,
- ► acquisition and analysis of measured voltage state,
- ► ASR logic implementation state,
- ► data transfer to the control system and remote monitoring state.

The main loop of the LabView application of the ARS controller (Fig. 6b) through the state chart Run starts the diagram of the controller's state machine – Fig. 6a. This loop also calculates the execution time of one loop iteration with an accuracy of 1 ms.

Fig. 7. shows the remote monitoring panel of the ARS controller. The visualisation display enables the user to continuously monitor the state of the power supply system.
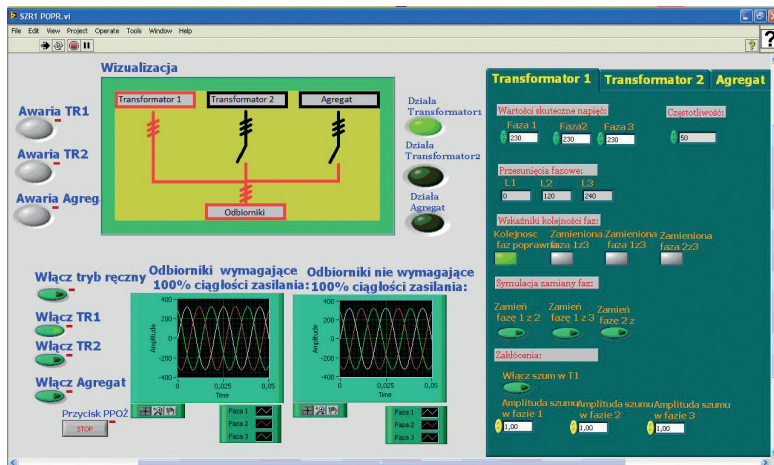

Fig. 7. View of remote control front panel of ARS controller

5. Conclusions

To summarise, functional laboratory tests of the controller were performed after the integration of the hardware platform, the application software and the launch of the ARS controller. These studies were conducted on the basis of a previously prepared research program. After minor modifications to the controller's application software, it can be said that the ARS controller is working properly. This tested controller and documentation was provided by the manufacturer of the power supply system of the station RTCS. The controller is currently undergoing field testing; and once completed, it will be possible to issue an application for use of the integrated ARS controller in station-based RTCSs on Polish railway lines.

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