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Temperature control system for the electromagnetic system of the Globus-M2 tokamak

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Received May 30, 2022
Revised June 21, 2022
Accepted June 21, 2022

The temperature control system used for monitoring the thermal regime of operation of the electromagnetic system of the Globus-M2 tokamak is described. The system is a hardware-software complex built on the Arduino platform based on microcontrollers of the AVR family. The developed graphical interface continuously reflects the temperature at the controlled points and signals when it goes beyond the specified range. Automatic saving of measurement results by controlled events is provided.

Keywords: tokamak, electromagnetic system, temperature control.

DOI: 10.21883/TPL.2022.08.55057.19264

The spherical tokamak Globus-M2 [1] was launched at the Ioffe Institute in 2018. A distinctive feature of the facility is the plasma current, which is confined in a magnetic field up to 1 T, and increased to 0.5 MA (by 2.5 times compared to the Globus-M tokamak [2]) The confining magnetic field is created using currents flowing through the coils of the electromagnetic system (EMS) of the tokamak. In order to identify emergency situations and prevent overheating of the coils, a large number of sensors have been installed on them for on-line temperature control. To automate the process of monitoring and warning about an accident, a digital temperature control system (TCS) was developed.

TCS is a software-hardware system based on a simple and reliable platform of the Arduino debug board family based on AVR microcontrollers [3]. The board can be connected to a wide range of different devices, including sensors (temperature, humidity, pressure, light sensors), actuators and transceiver devices (Ethernet-, WiFi-, GSM-modules), input-output devices. The modularity of the platform gives the flexibility needed to solve a wide range of automation tasks. The presence of the development environment and the library of programs allows you to quickly create working prototype of a device/system and test it. This library can be used to work with temperature sensors DS18B20 (DALLAS) [4], which are widely used due to low cost, ease of connection, high accuracy, wide temperature range, digital temperature code output. TCS structure is presented in Fig. 1. TCS includes temperature sensors (TS) (up to 60 pieces at maximum data transfer rate 115 200 Bd and bus 1-Wire topology of „tree") type, data bus 1-Wire, isolating board, a control module (CM) Arduino UNO R3 and a personal computer (PC) connected to the local network of the tokamak. TCS is powered from one USB port of the PC. The received data are stored on the facility database server.

TCS performs the following functions:
— operating modes control of TS;
— temperature measurement in step cycle;
— analysis of measurement results and comparison with set threshold values;
— temperature information presentation via a graphical interface with the ability to sort by temperature value or sensor number;
— operating modes control by means of the graphical interface;
— recording measurement data to files (three modes).

To check the operability of the selected circuit solutions based on the 1-Wire interface and debug the software of the microcontroller of the Arduino board, the debug set-up was used [5]. With the help of the set-up, the operability of the system with more than 40 TSs connected by a long cable (30 m), the possibility of using the topology of TSs connecting of „tree"type, the operability of galvanic isolation on the 1-Wire interface bus, and the transmission reliability data at the highest possible speed were tested.

After that, forty TSs were mounted on the tokamak and the TCS was assembled. DS18B20 sensors have a temperature measurement range from -55 to $+125^\circ$C, and the measurement error is 0.0625°C. In TCS the temperature is rounded to an integer value, and the maximum absolute error is $\pm 0.5^\circ$C. The area of measured temperatures was divided into three sub-ranges („normal", „warning", „critical"), determined by the threshold values set by the operator for each TS: warning temperature (WT) and critical temperature (CT). These subranges corresponded respectively to green, yellow and red colors in the graphical interface.

TCS software was developed at two levels. The lower level of software is implemented in the Arduino IDE

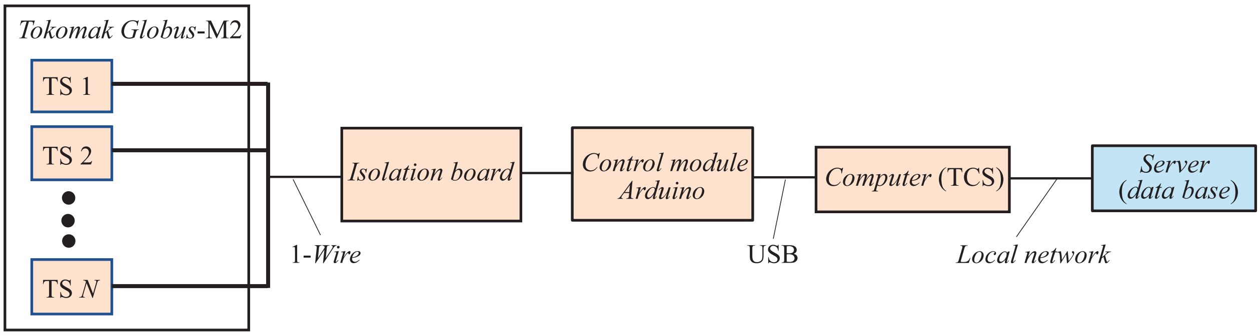

Figure 1. Structure of the temperature control system. TS *n* — temperature sensor with serial number *n*, *Isolation board* — galvanic isolation board, *Control module Arduino* — Arduino control module, *Computer* (TCS) — TCS computer, *Server (data base)* — database file server, 1-*Wire* — bus 1-Wire, USB - – bus USB, *Local network* — Ethernet local network.

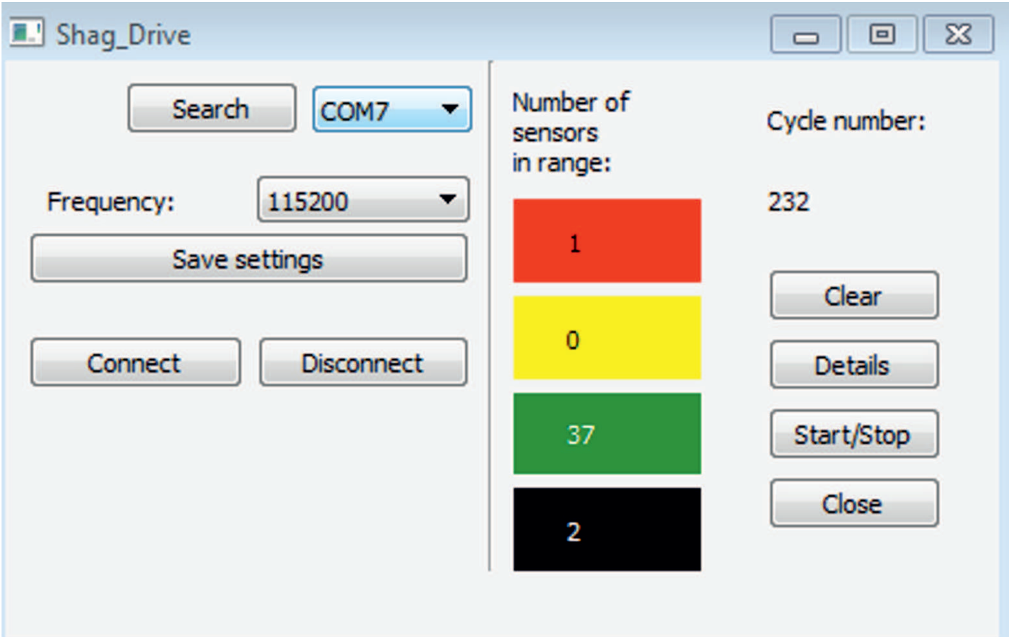

Figure 2. View of the main graphical interface window.

environment. The program is located in the flash memory of the CM and implements the functions of control and reading (collecting) data from the TSs, and transferring data to PC. The top level is implemented in Qt Creator 5.8.0 [6]. The program runs on PC and has the following functions: checking for TS presence, reading data from the CM, management of TCS resources and data visualization using a graphical user interface, events synchronization, received data recording.

At the initial stage of TCS operation, registration of installed TSs is required by creating (editing) a line for each sensor in the register file filein.txt. For example, below is the file line for the sixth TS in the format of a TS unique factory 64-bit identifier; TS serial number; assigned name (3–8 characters); WT; CT:

2874dfa2080000e0; 006; TF6-top; 40; 50

The TCS operation involves the procedure for detecting sensors at the beginning of each start-up and comparing the result obtained with the list of TSs registered in the register. If any of the registered sensors is not detected (TS does not work or not available), then the number 0000000000000000 will appear instead of the identifier. If an unregistered sensor (new TS) is detected, an entry with the identifier of the new sensor (16 characters) will appear in the special file UnknownDevices.txt.

To work with TCS a graphical interface with two types of windows was developed. With the help of the main window (Fig. 2), the control of the connection between the computer and the Arduino board is implemented; control of the work of TSs recorded in the register; activation of the measurement process and temperature mode monitoring in general. The second window (Fig. 3) provides information about each TS separately and provides the ability to write

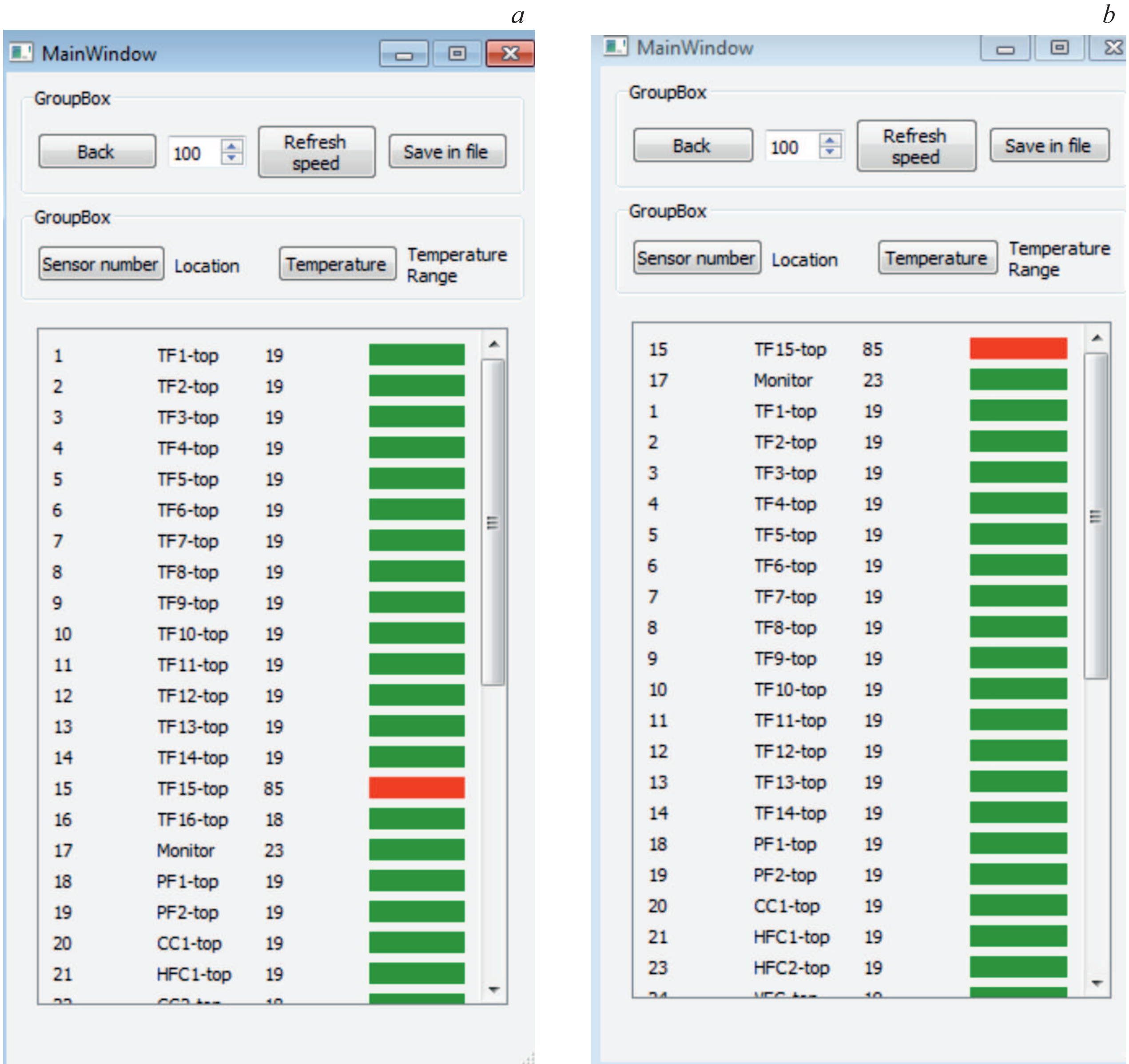

Figure 3. View of additional graphical interface window with information about all TSs: *a* — with sorting by serial number, *b* — with dynamic sorting downwards by temperature value.

data to file. For each sensor its number, the name recorded in the register, and the current temperature value are displayed. The temperature subrange corresponding to the value is displayed in color: „normal“, „warning“, „critical“ (color versions of the figures are presented in the electronic version of the article). You can set sorting by serial number or dynamic sorting by temperature. Faulty TSs are displayed in black.

The TCS provides for a continuous operation mode (24/7) with a cyclic polling of the TSs, regardless of whether any experiments are being conducted on the tokamak or not. For the TCS operation the program must be run on the PC of the tokamak control panel.

The TCS provides the ability to save data to a file in three modes: manual (at the operator's command), automatic monitoring (when a critical event occurs), automatic measuring (during the tokamak discharge). All files have the same format but different sizes and can be viewed with a standard program used to view other files from the experimental database of the facility. The first line of the file contains TS numbers, each next line contains — temperature values for each TS (positive numbers without a sign). In manual mode the operator can write to a file the temperature values in the current cycle of TCS measurements. In monitoring mode TCS fills the file critical.txt when CT is exceeded on at least one of the sensors. The third mode is designed to record EMS temperature changes associated with the tokamak discharge. The duration of the plasma discharge in the Globus-M2 tokamak does not exceed 1 s. At the start of the experiment (start of the facility synchronization system) a unique number of the tokamak discharge is written to a special file on the disk of the control PC of the tokamak, which is available for reading by other devices and systems. The interval between STC measurement cycles is about 2 s, which, on the one hand, significantly less than the characteristic cooling time of the EMS coils, which is tens of seconds, and on the other hand, allows you to poll all TSs. TCS current buffer stores data for the last two measurement cycles. At the end of each cycle the number of the current discharge is read over the local network from a special file of the control PC of the tokamak. If the discharge number changed, a file tcsxxxx.txt is generated in a separate directory, where xxxx is the number of the current discharge, in which the results of two temperature measurement cycles preceding the moment of changing the discharge number, and 28 more subsequent measurement cycles are recorded. In total, data on the dynamics of temperature changes at EMS control points are stored for about 1 min. Thus, the database stores information about the temperature mode of EMS immediately before the discharge and the dynamics of cooling after it.

TCS was tested on the Globus-M2 tokamak in various operating modes of the facility. At the end of the test mode of operation, the system was left as a standard system of temperature mode monitoring of the EMS of the tokamak.

Funding

The study was performed on unique scientific facility „Spherical tokamak Globus-M“, which is part of the Federal Center for Collective Use „Materials Science and Diagnostics in Advanced Technologies“, at Ioffe Institute within the framework of the state assignment for project 0040-2019-0023.

Conflict of interest

The authors declare that they have no conflict of interest.

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