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Installation for Carrying out Thermal Tests on the Current Paths of Electrical Power Equipment

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***Abstract* - Today's electrical networks, as part of the national power system, must meet a number of requirements imposed on power transmission and distribution equipment. The main requirements are: continuity of electricity supply to consumers, operational safety, quality of electricity supplied, development of networks, economic viability of investments, environmental impact requirements. In this context, the testing of the technical performance of the various elements that make up the electrical networks, both at the design stage and, in particular, at the certification stage, is of great importance and is regulated by internationally recognised technical standards and norms. The performance of tests under laboratory conditions requires the existence of specialised installations and equipment capable of generating the electrical parameters to which the various elements of electrical networks are subjected, for the purpose of performance testing and certification. The paper presents an installation for carrying out thermal tests on the current paths of electrical power equipment with a fully digital control system based on virtual instrumentation, which replaces the physical control panel made up of electronic modules and analogue devices. This enables the transition from primarily manual local control by the operator to remote control and eventually full automation of the thermal test process for medium and low voltage switchgear. By taking advantage of virtual instrumentation, the solution can be easily implemented and enhanced by integrating process control and computerisation applications.**

Cuvinte cheie: *curenți intenși, echipamente electrice de putere, instrumentație virtuală, sistem de comandă şi control, teste de creștere a temperaturii.*

Keywords: *high currents, electrical power equipment, virtual instrumentation, command and control system, temperature rise tests.*

I. INTRODUCTION

The temperature rise tests [1], [2] performed on low/medium voltage switchgear assemblies require a stable and highly efficient current source. The source should be capable of delivering a wide range of currents with greater accuracy than that required by the test standards [3]. There are several types of power supply suitable for the application, depending on the installed power, maximum current output and load voltage. Conventional sources use synchronous generators as voltage regulators, one for each phase of the source. These generators are simultaneously driven by a DC motor which sets the frequency of the voltages produced [4]. The effective value of the voltage, i.e. the currents generated by the source, is controlled by the excitation currents of the three generators. This system has several drawbacks, including complex control and regulation of frequency and current amplitude, difficult maintenance, lower reliability, and operation with noise and mechanical vibration. Fig. 1 shows the schematic diagram of the installation for the thermal testing of the current paths of the electrical power equipment, in which the group of electrical machines is replaced by a set of three regulating autotransformers. The proposed installation is based on a three-phase stabilised AC power source capable of delivering high intensity 50 Hz sinusoidal currents, adjustable over a wide range, and is designed to perform temperature rise tests on low/medium voltage switchgear assemblies complying with SR EN 60439-1 and SR EN 62271-1.

The proposed installation includes, in addition to a stabilized AC power source, a computerized system for command, control, and regulation, as well as a system for measuring, acquiring, processing, and storing data that describes the thermal behavior of the tested equipment.

II. THREE-PHASE HIGH CURRENT SOURCE

A standard three-phase adjustable AC power source with automatic control consists of a source power scheme, a computerised control and automation system and a measurement, acquisition, processing and data storage system.

The main technical characteristics of the power source used in the electrical equipment testing laboratories are:

- rated supply voltage: 3 x 400Vac, 50Hz;
- rated installed power:
  - 225 kVA, three-phase balanced;
  - 75 kVA, single phase;
- maximum current per load: 10 kAef, for a balanced load with a maximum impedance of $6.5 \times 10^{-4}\ \Omega$.

A. Source power diagram

The power circuit of the adjustable three-phase AC power supply with automatic control is shown in Fig. 1 and includes:

1) Power supply cabinet (PSC)

The power supply cabinet is designed to supply the three-phase power circuit of the source as well as the control, measurement and protection circuits. It is equipped with a dedicated relay to monitor the power supply voltages from the low voltage network [5], [6].

2) Voltage regulating autotransformer group, type ATMU-75, consisting of three single-phase units

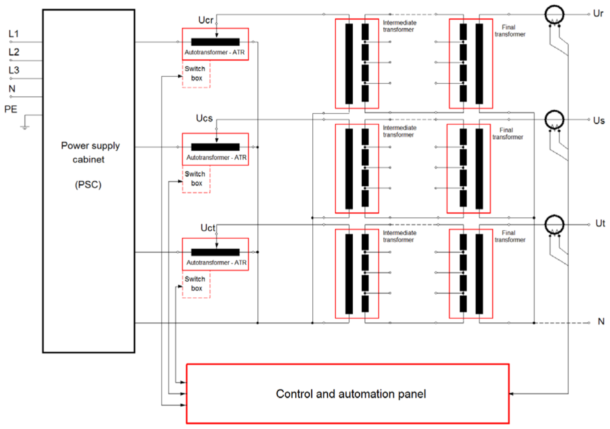

Fig. 1. Block diagram of the functions of the proposed system.

The three electrically controlled ATMU single-phase autotransformer units represent the elements of the power diagram that allow the control of the current flowing from the source. The autotransformers are oil cooled and have a unique design that is based on the magnetic flux beam splitting principle [7], [8] (Patent RO117053 (B1) / 28.09.2001, owned by ICMET Craiova). The design principle and construction details are presented in the following figures (Fig. 2...Fig. 5).

According to this principle, the voltage regulation step can be as small as desired without increasing the coil height. However, for technological reasons, it is limited to a maximum of 0.2 V, with a maximum voltage per turn of 2.4 V (voltage per turn in the classic design).

The voltage U_{AX1} obtained at the output terminals of the autotransformer is given by the relationship:

$$U_{AX1} = U_{AX} /N \cdot n + U_{AX1} /N \cdot k/K \quad (1)$$

where:

- U_{AX} is the nominal supply voltage of the autotransformer, i.e. 230V, 50Hz;
- N is the total number of turns of the autotransformer;

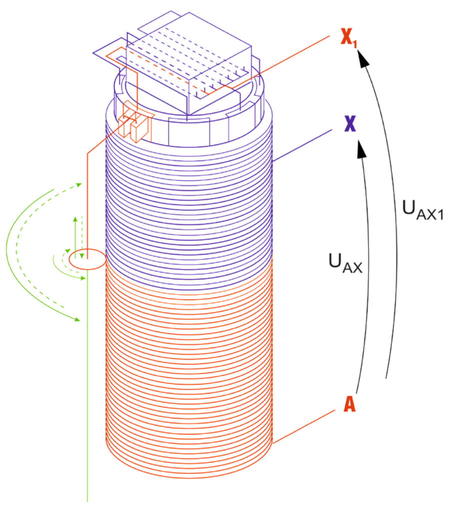

Fig. 2. Principle of beam splitting.

- n is the number of turns between the end A of the winding and the active roller of the current collector sliding shoe;
- K is the number of half-sections of the magnetic flux divider;
- k is the number of flux divider half-sections in the circuit of the last turn, corresponding to the position of the brush on the fixed collector.

$$n \le N \quad (2)$$

$$k \le K \quad (3)$$

The output voltage regulation step is given by the relationship:

$$\Delta U_{AX1} = U_{AX} /N \cdot 1/K \quad (4)$$

Fig. 3. Internal structure of the autotransformer showing the flux divider and slip ring collector.

Autotransformers are equipped with electrical systems to actuate and control the voltage and, implicitly, the slider position. The design principle and cursor position command and control allows the current source to introduce no harmonic distortion into the current waveform.

Fig. 4. Local autotransformer control and protection box.

The autotransformers have a high transformer ratio (230 V/0-250 V) and are equipped with local control and slider actuator protection boxes (Fig. 4), which allow:

a) local MANUAL control of the slider;

b) selection of the LOCAL - REMOTE control mode;

c) autotransformer overload protection by monitoring the oil temperature in the tank;

d) local monitoring and protection of the autotransformer drive system.

Fig. 5. Voltage regulating autotransformer group - three single-phase units.

3) Intermediate power transformer group, type TMAi-75 - three single-phase units

The three TMAi intermediate power transformers (Fig. 6) correspond to the voltage between the ATMU regulating autotransformers and the TMAf final transformers, in order to obtain accurate current regulation, corresponding to accuracy class 0.2, over a wide range of load impedances specific to the current paths inside the low and medium voltage distribution cabinets manufactured and tested by the beneficiary.

The intermediate transformers are air-cooled and the secondary is divided into four equal winding sections. The sections have the same rated current and can be connected in series, parallel or series-parallel by means of a manual selector with strap bands to obtain different transformation ratios.

Fig. 6. Intermediate power transformer group - three single-phase units.

4) Final power transformer group, type TMAf-75 - three single-phase units

The final power transformer block (Fig. 7) consists of three single-phase TMAf units. These transformers are air-cooled and the primary winding is divided into four equal sections, identical to the secondary windings of the TMAi transformers.

The sections have the same rated current and can be connected in series, parallel or series-parallel by means of a manual selector with strap bands to obtain different transformation ratios.

Fig. 7. Final power transformer group - three single-phase units

The high current secondary winding consists of three turns and is placed over the primary winding on the central column of the "shell" type magnetic core to optimise the electromagnetic coupling between the two windings.

The secondary winding consists of four copper bars, each 10x120 mm in cross section, arranged in parallel at a distance of 10 mm to optimise cooling. Additional cooling of the secondary windings is provided by a forced ventilation system, which is automatically controlled by a thermostat when the bar temperature exceeds exceeds 120° C, equivalent to insulation class F.

5) Busbar system

The source busbar system (Fig. 8) provides the transition of the source output terminals from the room where the power circuit elements are located to the adjacent room where the thermal tests on the distribution cabinets/cells are carried out. The 10,000/5A ratio current transformers used in the source control and automation circuit and the metering circuit are located on the system busbars. The bars are made from 10x120mm copper strips, arranged in parallel (across the width of the bar) 10mm apart to optimise cooling.

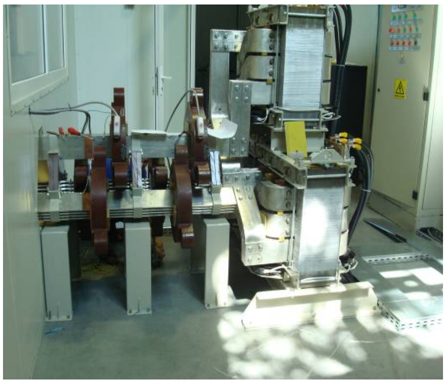

Fig. 8. Source output busbar system

III. Computerised Command, Control and Regulation System

A. Hardware component of the system

Fig. 9 shows the hardware components of the proposed system [12].

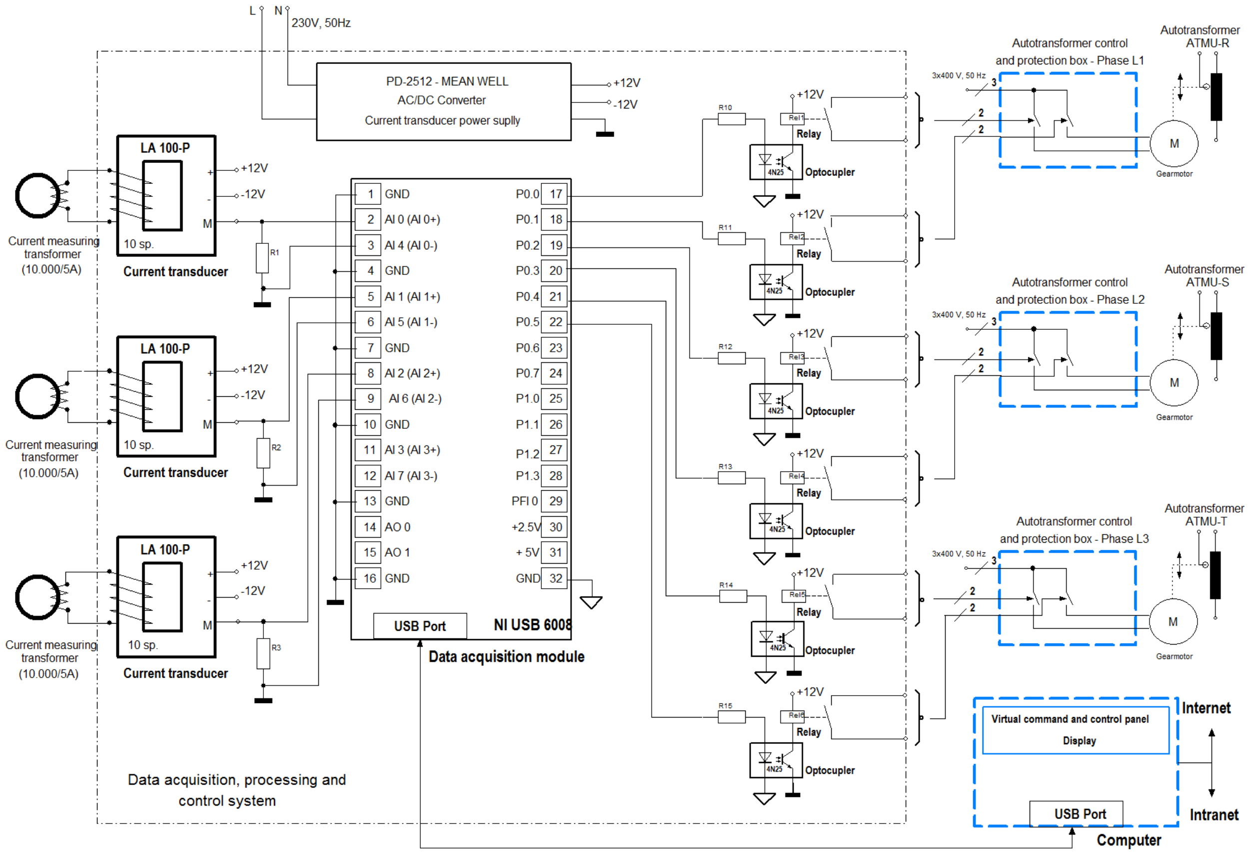

Fig. 9. Hardware component of the system.

The system hardware is built around a multifunctional DAQ device (NI-USB-6008). It provides analogue input/output capabilities, specifically 8 analogue inputs (12 bit, 10 kS/s), 2 analogue outputs (150 Hz) and digital inputs/outputs (12 DIO).

The instantaneous values of the three currents generated by the source are acquired in differential mode (Diff). Three voltages (from LEM-LA100P transducers) proportional to the three currents are applied to the inputs AI0, AI1, and AI2.

The six on/off digital output signals (P0.0...P0.5) are applied to the tap-changer control relays via optocouplers.

The PD 2512 dual source is used to power the LEM current transducers and optocouplers. Since the effective value of the primary current for the LEM current transducers is 100A, a few extra turns (n=10) are added.

B. *Software component of the system*

LabVIEW 2015 is used to create the virtual instrument that allows the user to communicate with the data acquisition module, process data, and control the system.

The front panel of the virtual instrument is divided into two sections [12]:

- the interface for setting the input parameters of the DAQ and the port (lines) where the digital output signals are located;

- the interface for controlling and monitoring the automation of the current source.

Fig. 10 shows the user interface of the program for communicating with the DAQ module. The block diagram of the hardware inputs/outputs of the USB-6008 module is shown. In the center (INPUT) there are the numerical controls (K1, K2, K3) for calibrating the measurement of the RMS values of the currents I1, I2, I3. In addition, the effective values of the currents are displayed both analytically and numerically.

On the right side (OUTPUT) there are controls for setting the digital output port P0 and the lines 0...5. LED indicators are used to signal the commands to increase/decrease the currents on each phase (for example: I1- decrease, I2+ I3+ increase).

The six lines of Port P0 are configured as active drive digital outputs, driving LEDs in optocouplers.

The main communication between the user and the system is done through the interface shown in Fig. 11. The display/signalling and control elements of the interface are horizontally grouped into three identical channels, one for each of the individual currents I1, I2 and I3. Each of these elements acts independently of the others.

The vertical toggle switches select the source operating mode (single phase, two phase or three phase). This is indicated by the LEDs I1, I2 or I3 lighting up. If they are off, the source will not generate power.

Next, the current value I (considered as the Process Variable, PV) is displayed in engineering units (EGU) and as a percentage (%) of the range.

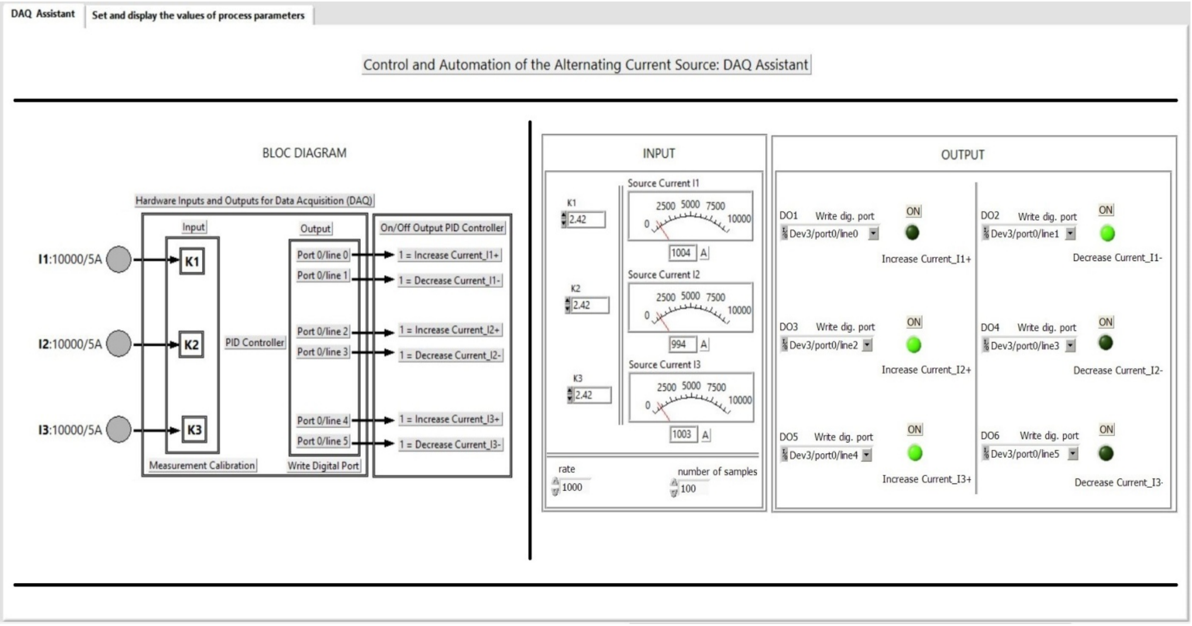

Fig. 10. The interface for configuring inputs/outputs and calibrating the source current measurement.

The current range (2-4-6-8 kA) is selected and displayed. In addition, the LED indicating that the upper limit has been exceeded is also displayed.

The specified current value is set using a horizontal pointer slide potentiometer and is displayed both in EGU units and as a percentage of the range.

The parameters of the PID controller are set: the proportional gain, the integral time and the derivative time. The result of the PID algorithm applied to the current control process is numerically displayed as a percentage (MV %).

The current control error is set between the limits of (-100, +100)% of the set point (SP) of the prescribed current by means of a vertical pointer slide. The current error value is displayed numerically, and any exceeding of the set limits is also displayed.

A hysteresis is applied to the upper and lower limits of the current error to avoid continuous on/off switching of the output.

The on/off outputs that control the current increase/decrease are indicated by two LEDs located on the right hand side of the front panel as shown in Fig. 11.

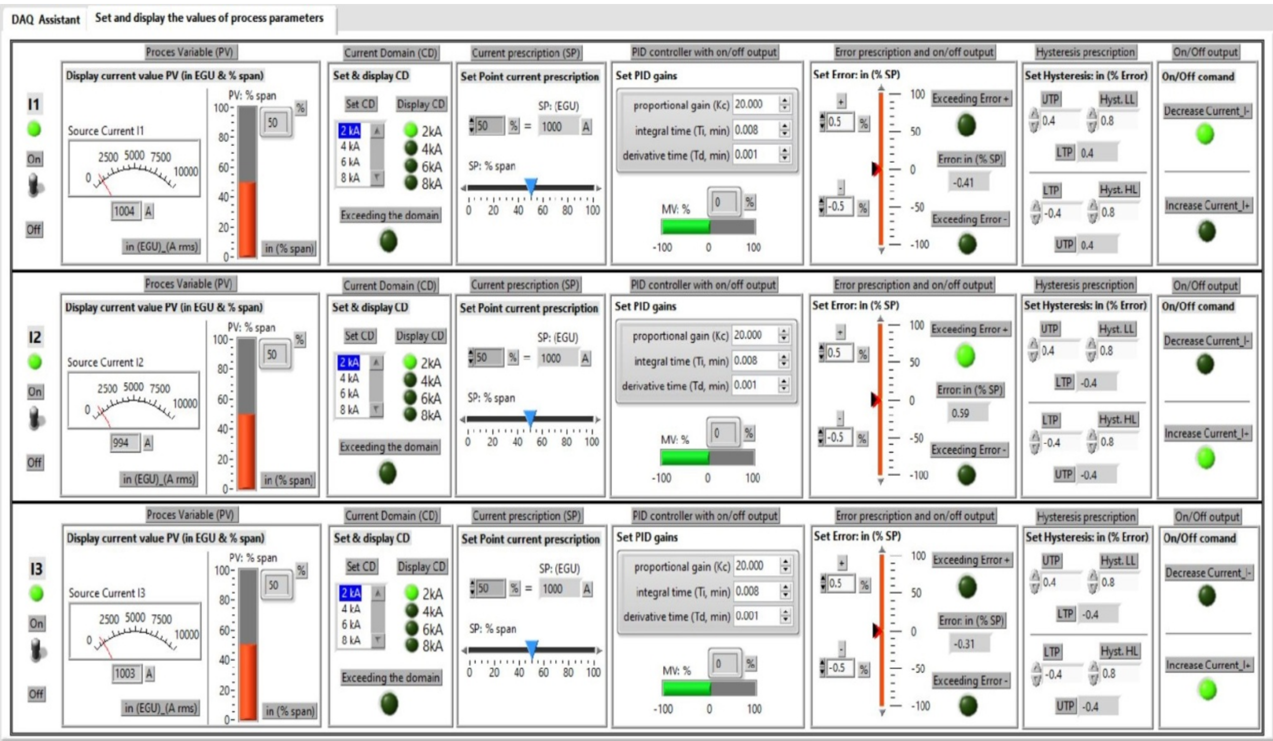

Fig. 11. The interface for setting and controlling the source parameters.

Fig. 12 shows a section of the block diagram where the acquisition parameters are set. This is done using the DAQ Assistant virtual instrument. The effective values are calculated from the instantaneous currents I1, I2, and I3. The constants K1, K2 and K3 are used to calibrate the measurement. Currents I1, I2, and I3 are process variables (PV) and inputs to the PID controller.

Fig. 13 shows a section of the block diagram where the output channels (digital output) are created to control the increase/decrease of the current on phase 1 (Increase Current I1+, Decrease Current I1-). A digital output channel consists of a single line.

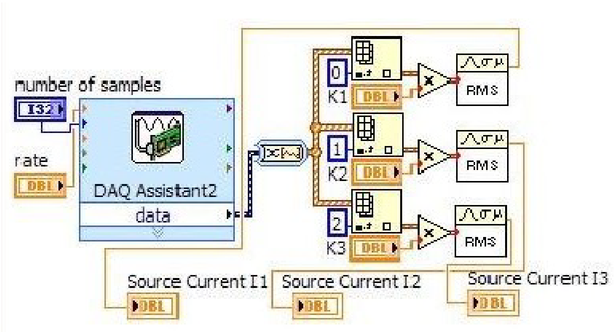

Fig. 12. Detail of the DAQ implementation for analogue inputs.

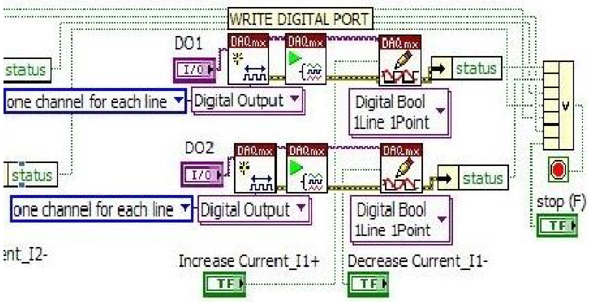

Fig. 13. Detail of the DAQ implementation for digital outputs.

To implement the current regulator function, a virtual instrument is used that implements a PID controller using a PID algorithm [13], [14], [15]. [16].

To reduce the number of graphical connections in the block diagram, we have combined three virtual instruments into a single sub-VI: PID.vi, PID EGU to Percentage.vi, and PID Percentage to EGU.vi. The last two convert units of measurement based on the minimum and maximum range settings in EGU (see Fig. 14).

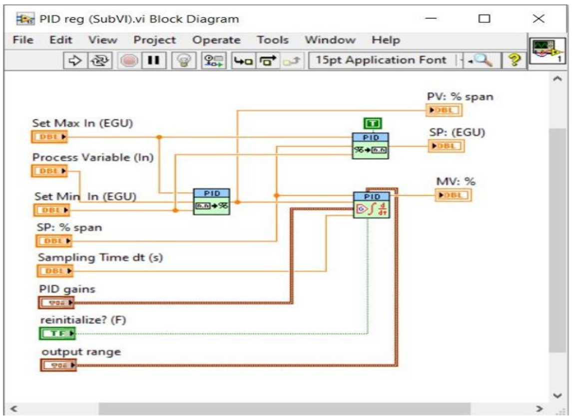

Fig. 14. The sub-VI for implementing the PID controller.

The graphical source code of the virtual instrument can be found in the Block Diagram (BD). Fig. 15 shows a detail of the block diagram with the functions of the proposed system.

All graphical elements are included in a repetitive structure (While Loop) which executes them until the logical conditions of True are met at the Loop Condition terminal.

The maximum current range of the source is selected using a case structure with four options: 2-4-6-8 kA.

To implement hysteresis software for the upper and lower error thresholds, the previous state of these values must be stored. A While loop using a shift register allows the previous output state to be stored for software implementation of hysteresis.

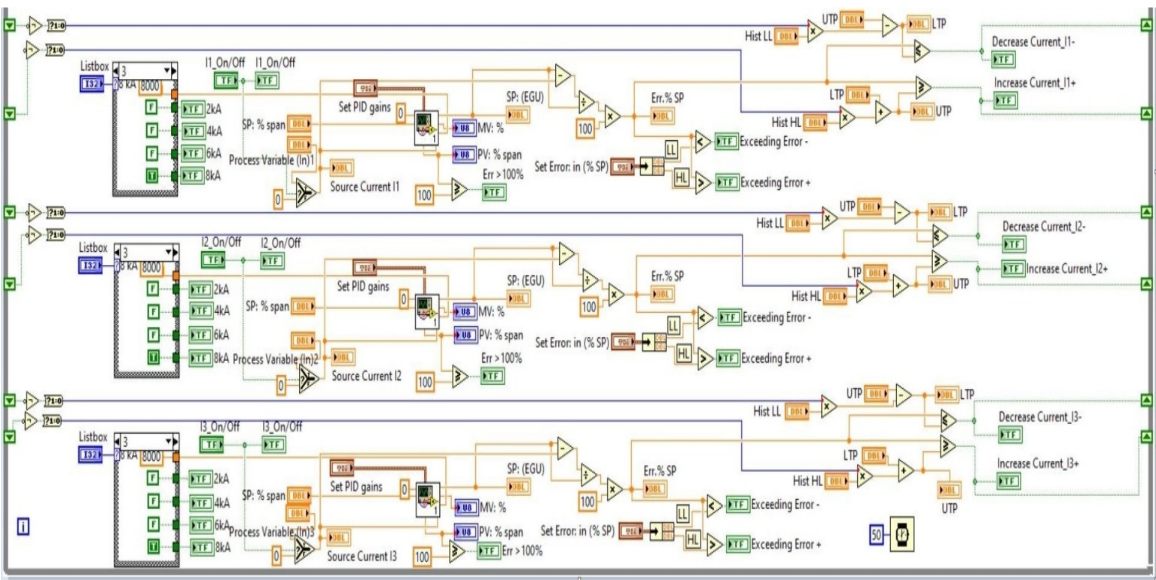

Fig. 15. The block diagram with the functions of the proposed system.

IV. MEASUREMENT, ACQUISITION, PROCESSING AND DATA STORAGE SYSTEMS[10]

The structure of the measurement, acquisition, processing and data storage system (Fig. 16) allows the acquisition of 8 sets of electrical measurements, each set represented by a three-phase current system and a three-phase voltage system, and a maximum of 200 non-electrical signals (temperatures measured on the unit under test).

Currents are measured using current transformers as follows:

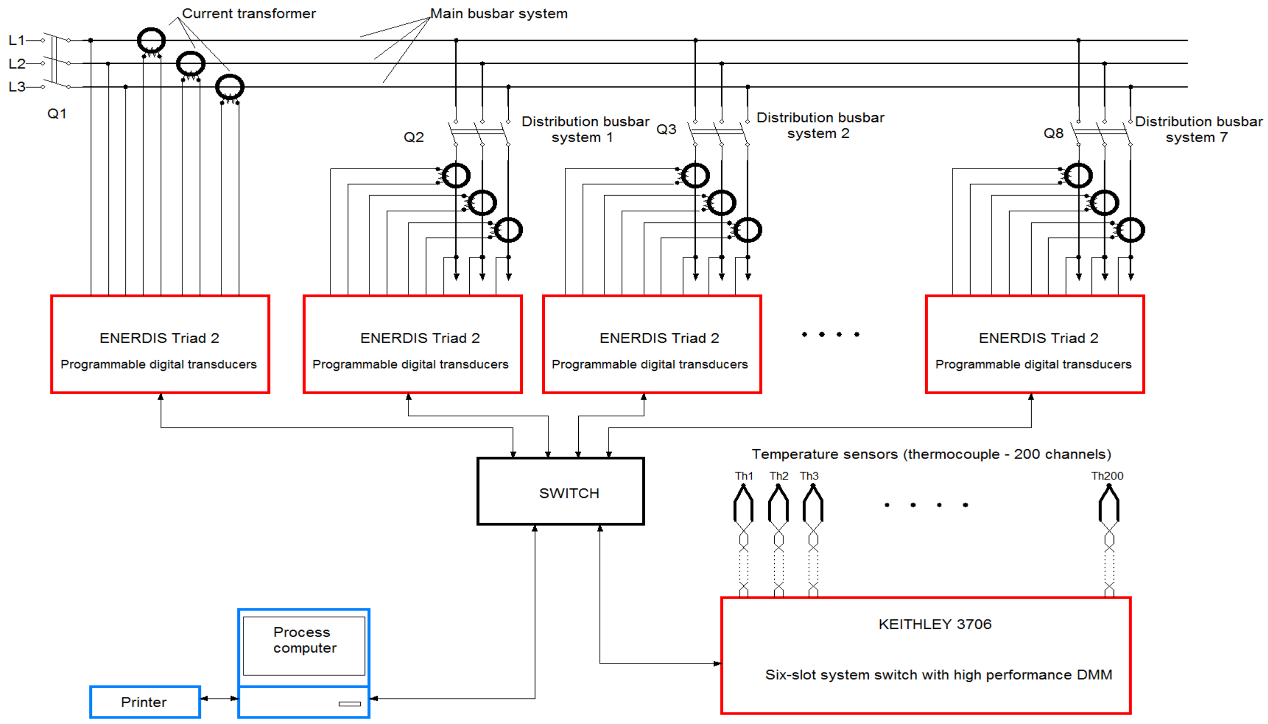

Fig. 16. Diagram of data measurement, acquisition, processing and storage systems.

- a set of three 10,000/5A ratio current transformers for measuring currents through the busbars of the switchboard(s) to be tested;

- seven sets of three measuring transformers with the appropriate transformer ratio selected to measure the currents through the busbars of the switchgear under test.

Electrical measurements are carried out using specialised ENERDIS Triad 2 equipment, which has the functions and facilities of an electrical energy analyser. The KEITHLEY 3706 measurement system is designed to acquire 200 temperature signals from T-type thermocouple sensors.

All signals are processed and transmitted in digital format via an RS 232/RS 485 serial interface to the process computer running a dedicated software application. The application allows real-time visualisation of the value of the various quantities in the process, graphical representation of their evolution over time, data storage and, at the end of the tests, the preparation of specific test bulletins for the certification of the DUTs [11].

V. RESULTS AND CONCLUSIONS

The verification of the performance of the computerised control system presented in this paper was carried out in a specialised laboratory at ICMET Craiova, where temperature rise tests on low and medium voltage switchgear are routinely performed. The high current source in the laboratory is designed according to the schematic diagram in Fig. 1, with autotransformers as control elements with fine (quasi-continuous) regulation of the voltage.

The following table shows the current control performance for the source equipped with the control, command and regulation system based on virtual instrumentation and numerical control algorithms.

TABLE I. EXPERIMENTAL RESULTS

No.	**Current setting [A]**	**Measured current [A]**		**Error [%]**	
		Reference measurement system	***Digital control system***	***Regulating error***	***Measurement error***
1	1000	1020	1015	2	-0.49
2	2000	1975	2005	-1.25	1.5
3	3000	3045	2995	1.5	-1.6
4	4000	4055	4005	1.375	-1.2
5	5000	5050	5035	1	-0.3

It is noted that the accuracy of detection and measurement of the current generated by the installation was within the required accuracy class for all current ranges.

The three-phase stabilised AC power source, designed at ICMET Craiova in several versions since 1999, has been installed and commissioned at various beneficiaries in the country and abroad, as well as in the Institute's specialised laboratory. Modern technical solutions for automation and virtual control have been incorporated into this version to make operation as simple as possible, minimising human intervention. The proposed solution brings a significant reduction in the cost of implementing the high current source control, command and regulation system, a reduction in its dimensions and physical weight, automation of temperature rise tests, increased reliability and safety in the operation of the assembly, remote control of the process through specialised web applications, and offers the possibility of further software development through the integration of process monitoring and computerisation applications.

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First coauthor – 25%
Second coauthor – 25%
Third coauthor -15%

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