POLITEHNICA UNIVERSITY of BUCHAREST

ELECTRICAL ENGINEERING DOCTORAL SCHOOL

PhD THESYS

CONTRIBUTIONS REGARDING MONITORING AND OPTIMISATION OF ENERGY CONSUMPTION BY SMALL INDUSTRIAL CONSUMERS

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SUMMARY

BUCHAREST
2023

Thank you address

Designing and accomplishing a PhD thesis can only be achieved by having scientific guidance of the highest quality within a team of dedicated researchers.

I would like to address special thanks to mister Costin Cepisca, PhD. Eng. emeritus university professor, for all the trust that he put in my work, for the guidance and encouragements received, guidance and encouragements that helped me complete this thesis.

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The author

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Abbreviations

API Application Program Interface
CMS Content Management System
CCO Optimistically Concurrent Control
CRUD Create, Read, Update, Delete
CSV Comma Separated Values
DBMS DataBase Management System
DLR – Dynamic Line Rating
FN1 Normal Form 1
GC Garbage Collector
HTML Hyper Text Markup Language
HTTP Hypertext Transfer Protocol
HTTPS HyperText Transfer Protocol/Secure
JSON JavaScript Object Notation
MVCC Multiversion Concurrency Control
NIST – National Institute of Standards and Technology
NoSQL Non SQL(Structured Query Language)
PNR – National Reform Plan
PMU –Phasor Measurement Units
RDBMS Relational DataBase Management System
REST Representational State Transfer
SPoF Single Point of Failure
SQL Structured Query Language
WASA – Wide Area Situational Awareness
XML Extensible Markup Language

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INTRODUCTION

In the last couple of years, we notice a fundamental change of the technical principles that govern the design, main function and day to day use of electrical networks regarding transport, distribution and usage of energy. Today's electrical grid has a new component that is represented by computing power and communications working in unison with the classic electric grid.

Research conducted in this thesis aims to develop a method of optimizing energy consumption at small industrial consumers by developing a system represented by a cost-effective Smart Grid modular equipment that can be a profitable investment for the small industrial user.

Chapter 1 is represented by an analysis of the main concepts and technologies used in energy parameters measuring and acquisition process and the analysis of methods to optimize energy consumption within smart electrical grids.

Chapter 2 analysis of energy quality concepts and impact of renewable energy production on smart electrical grids.

Chapter 3 presents the main process of developing an effective installation destined for small industrial consumers, system that ensures monitoring of electrical energy consumption, power coefficient compensation and minimization of the effect of induced harmonics as well as renewable energy sources integration.

Chapter 4 contains elements used in designing the database used for data logging of all the data acquired within the system.

Chapter 5 covers the software application development, which integrates the hardware acquisition system with the database system.

Chapter 6 presents the experimental results gathered from the tests caried on the hardware components and tests carried on the software components included in the measuring system.

The last part of the thesis contains general conclusions, personal contributions and future ways to further develop the system.

The literature studied is composed of 51 articles and the annex represents electrical schematics and experimental data.

CHAPTER 1

SYSTEMS USED FOR THE MONITORING AND OPTIMISATION OF ELECTRICAL ENERGY CONSUMPTION WITHIN SMART GRIDS

1.1. CHARACTERISTICS OF SMART GRIDS

In the last couple of years we notice a fundamental change in the technical principles that govern the manufacturing, function and use of electrical grids, at the electrical energy transport level as well as at the distribution level. Implementing informational technology and communications leads to a new image of the smart grid. Fig. 1.1 depicts the working principle of a smart grid:

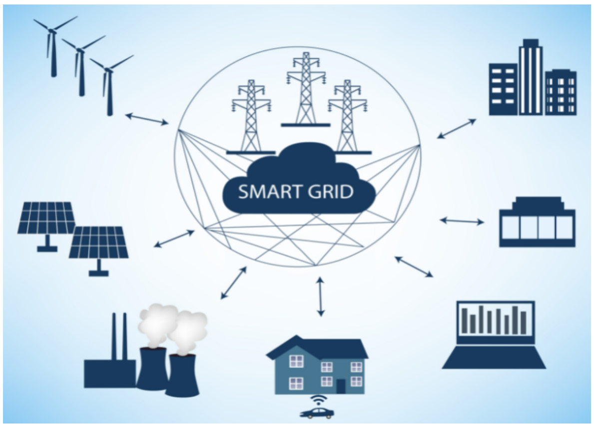


Fig. 1.1. *Smart network - Concept of operation.*

The analysis carried out within this doctoral thesis led to the highlighting of the main characteristics of smart grids.

1.2 CURRENT SOLUTIONS FOR ENERGY MONITORING AND OPTIMIZATION SYSTEMS

Currently, most of the equipment destined for the smart grid area is directed towards th electricity production and transport and less in the field of consumption optimization for the industrial installations and beneficiaries. Regarding the internal networks of industrial consumers, be they small, medium or large, the equipment used is not entirely categorized as a smart systems specific to Smart Grids, most of the equipment contains primary elements of data acquisition and possible commands given through the operator.

Recent implementations point to the globalization of the problem and the increasingly important resources allocated: Enel SpA Italy over 27 million smart meters in Italy, 8 million smart meters in Northern Europe in 2012 alone, CPFL Energia Brazil invests $ 124 million in 2012-2013 in smart grids, etc.[6].

1.3. INTELLIGENT SOLUTIONS FOR ENERGY MONITORING AND CONTROL SYSTEMS

Fig.1.3 shows some centralized monitoring and control systems based on SCADA.

The architecture based on intelligent systems – Fig.1.4, appeared relatively recently due to WEB technologies and can be positioned as an entry point in monitoring systems. This takes advantage of standard communication services and protocols and unlicensed software packages.

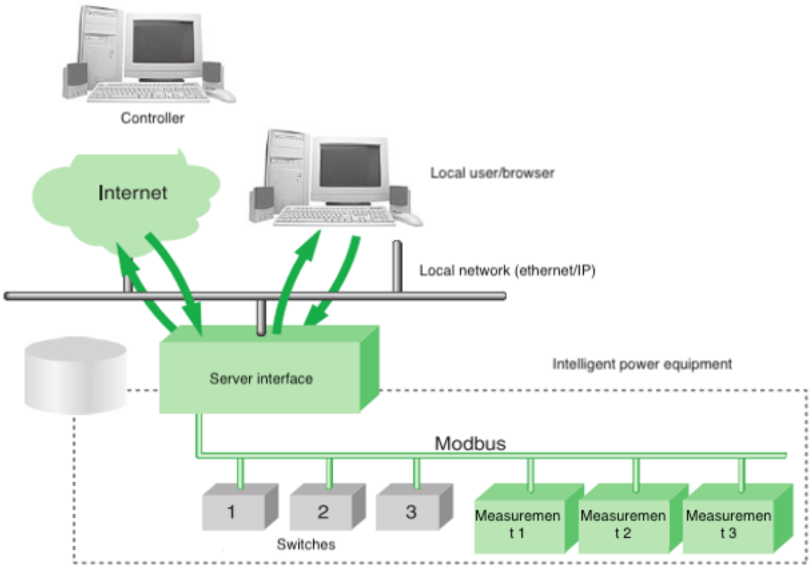


Fig. 1.4. *Intelligent systems architecture* [10]

Automation systems in the field of electricity distribution shall contain specific elements, such as:.

- control post where the operator can view the database and ensure management;
- distribution automation, which includes the devices involved in remote controls at stations and feeders level;
- components that can be interconnected with flexible protections;
- Measuring Infrastructure (AMI). [11].

1.4. ENERGY CONSUMPTION MONITORING METHODS APPLICABLE TO SMART MINI-GRIDS

1.4.1. Invasive methods of detecting consumers

Invasive methods of consumer detection involve a certain degree of intrusion into spaces where consumers are being monitored. Depending on the nature of the intrusion, invasive methods can also be classified into:

Physically invasive methods

These methods consist in the use of auxiliary devices for measuring energy consumption, mounted in parallel with the supply network, at the electrical apparatus-network interface.

Electrically invasive methods

They consist of injecting a signal, such as a harmonic of the current or a transient signal, into the supply network. By analyzing changes in the reflected waveform, we can obtain information on the devices active in the total load at that time.

1.4.2. Non-invasive methods of consumer detection

It uses a minimal hardware system along with a complex signal analysis algorithm. The three steps specific to the application of the non-invasive method are indicated below:

The variants of use are:

→ Using a single smart meter (SM) - Fig.1.8, which measures the total energy ($E=E_1+ ...+E_N$) in the network, without reference to the different consumers in the area.

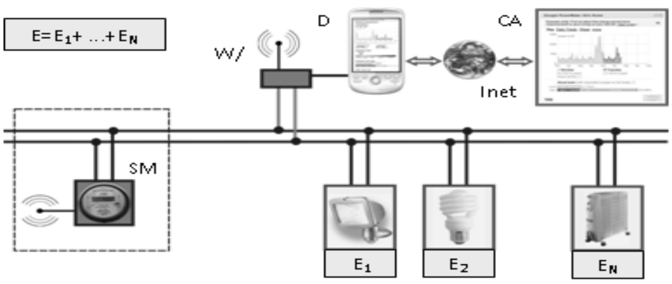


Fig. 1.8. *General consumption counter* [14]

→ The use of several smart meters – Fig.1.9, ensures the measurement of electrical parameters at each consumer installation (SM_1, SM_2...).

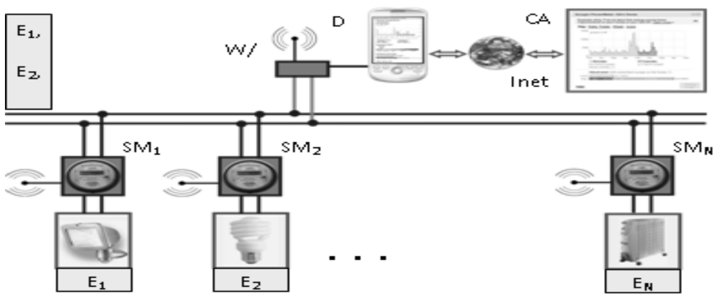


Fig. 1.9. *Multi-meter smart system* [14]

The "micro smart grid" smart installation that I propose in my PhD thesis, intended for a small industrial consumer, is based on the use of several smart meters. They allow the acquisition of detailed information about individual consumptions, data processing and possible optimization orders.

1.5 ELEMENTS FOR OPTIMIZING ELECTRICITY CONSUMPTION AND ITS QUALITY

Optimizing electricity consumption and preserving electricity quality mainly concern two elements:

1.5.1. Power factor compensation

Systems for offsetting the value of the power factor in the network lead to a decrease in the reactive energy absorbed and thus contribute to the reduction of supply costs.

1.5.2. Harmonic reduction systems

The elimination of some harmonics is carried out by using active or passive filters.

CHAPTER 2
ELEMENTS ON THE QUALITY OF ELECTRICITY IN SMART GRIDS

2.1 QUALITY OF ELECTRICITY IN THE ELECTRICITY GRID

Any periodic deviation of the purely sinusoidal waveform of the voltage can be presented with a sum of sine waves and its integer multiples. The expression of a deformed wave is:

$$u(t) = c_{U0} + \sum_{k=0}^{\infty} c_{Uk} \cdot \sin(k \cdot 2 \cdot \pi \cdot f_1 \cdot t + \phi_{Uk}) \tag{2.1}$$

c_{U0} – the direct current component of the voltage waveform;

c_{Uk} – the amplitude of the harmonic *k* of voltage;

ϕ_{Uk} – phase shift of harmonics of order *k* of tension;

f_1 – fundamental frequency.

The assessment of the deformation of the voltage wave is made using the distortion coefficient THDU defined as:

$$THDU = \sqrt{\frac{\sum_{k=2}^{40} U_k^2}{U_1^2}} = \sqrt{\frac{\sum_{k=2}^{40} c_{Uk}^2}{c_{U1}^2}} \tag{2.2}$$

where:

$U_k = \frac{c_{Uk}}{\sqrt{2}}$ – the effective value of the voltage harmony of order *k*;

$u_k = \frac{U_k}{U_1} \cdot 100\%$ – percentage value of voltage harmony of order *k*.

Everything presented for voltage harmonies remains valid for current harmonics and THDI.

2.2. QUALITY OF ELECTRICITY IN A SMART GRID

Fig. 2.2 shows the association of three concepts: the smart grid, renewable source and energy quality conditions.

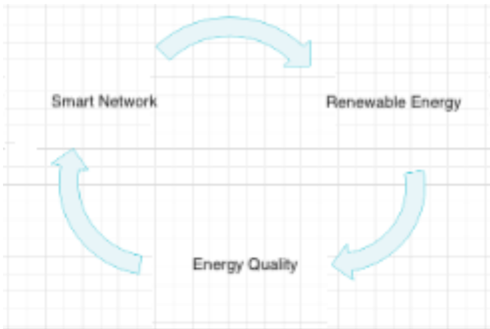


Fig. 2.2. *Pairing energy quality concepts with smart grids*

2.3. ELECTRICITY QUALITY REGULATIONS

Currently, in Romania there is an important concern for the implementation of regulations related to the quality of electricity (norms, national and European standards). [24]

The EN 50160 standard contains the specifications required for the main voltage parameters. All the provisions of the EN 50160 standard related to the supply voltage and harmonics in the system will constitute the input data for the design of the new installation. [26].

CHAPTER 3

DESIGN OF AN INSTALLATION FOR MONITORING AND OPTIMISING ELECTRICITY CONSUMPTION IN SMALL INDUSTRIAL CONSUMERS

The objective of the doctoral thesis is represented by the realization of an installation with built-in intelligence that ensures the optimal supply through real-time monitoring of small industrial consumers in terms of electricity consumption, with low cost solutions but technically efficient.

3.1. DESIGN OF THE GENERAL STRUCTURE OF THE INSTALLATION

Intended to be modular in nature, the system allows the optimal supply through real-time monitoring of the consumptions, the parameters within the permissible limits for the quality of the electricity in the local network of the consumer and the possibility of introducing electricity from the renewable sources with which the respective consumer is equipped

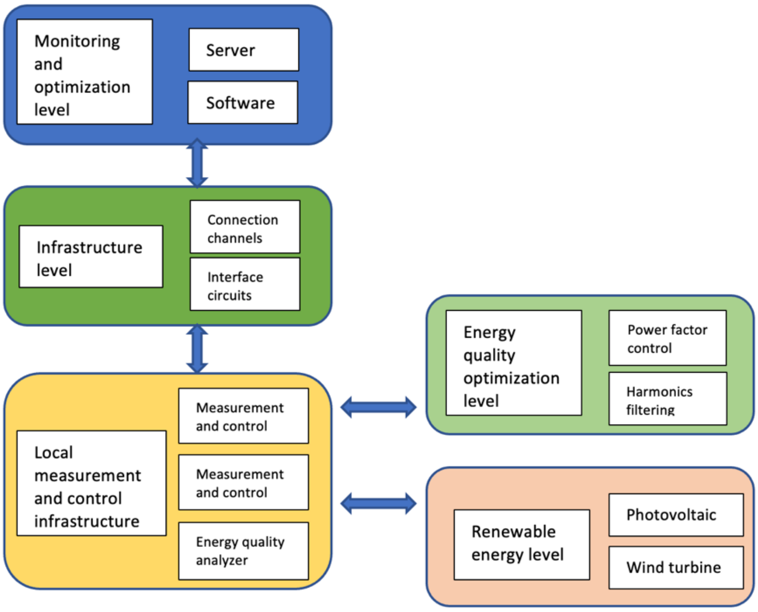


Fig.3.1. Block scheme of the modular installation

The installation is designed to be carried out in three constructive solutions:

1. Solution no.1 - Functions for measuring the parameters of the electricity consumed by a small consumer of industrial type, using a three-phase smart meter. Possible local commands to the equipment in the technological chain, data transmission to the dispatching point that ensures data management and optimization of consumption in real time are ensured;
2. Solution no.2 – includes the equipment specific to solution no.1 to which is attached a module that ensures the fulfillment of the quality parameters of the electricity regarding the power factor and the elimination of the harmonics from the waveforms of the currents and electrical voltages;
3. Solution no.3 – includes the equipment specific to the constructive solution no.2 together with equipment that ensures the introduction on request, following the optimization process, of the energy coming from the renewable sources of the respective consumer.

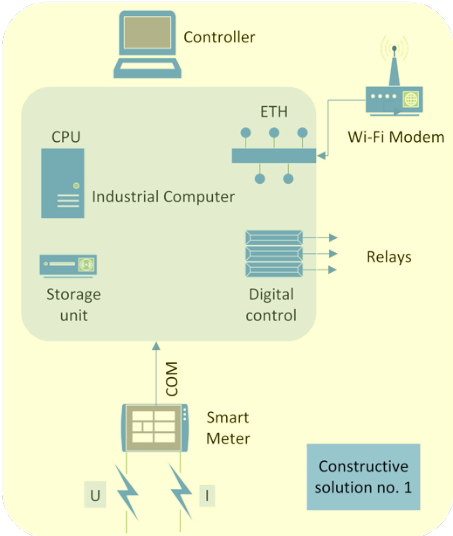


Fig. 3.2. *Constructive solution no.1*

The data obtained from the numerical smart meter is transferred to the industrial computing system that ensures:

1. the processing of data according to the relationships defining the quantities to be determined;
2. calculation of load curves;
3. energy consumption;
4. comparison with the limits imposed for the different energy quantities monitored by that system;
5. local display of some of the sizes;
6. the possibility of locally adjusting the limits;
7. carrying out controls for the control of supervised electrical installations;
8. transmission of data, at certain time intervals defined by the user, to the dispatching point.

The constructive solution no.2 – Fig. 3.3, incorporates the specific subassemblies of the constructive variant 1 and additionally brings functions of keeping the quality of the electricity in the monitored network:

9. Continuous monitoring and regulation of the power factor by introducing a power factor improvement installation
10. Continuous surveillance of the appearance of harmonics and introduction of a filter to remove harmonics from the current curve
11. Continuous surveillance and reporting of deviations from the provisions of the electricity quality norms.

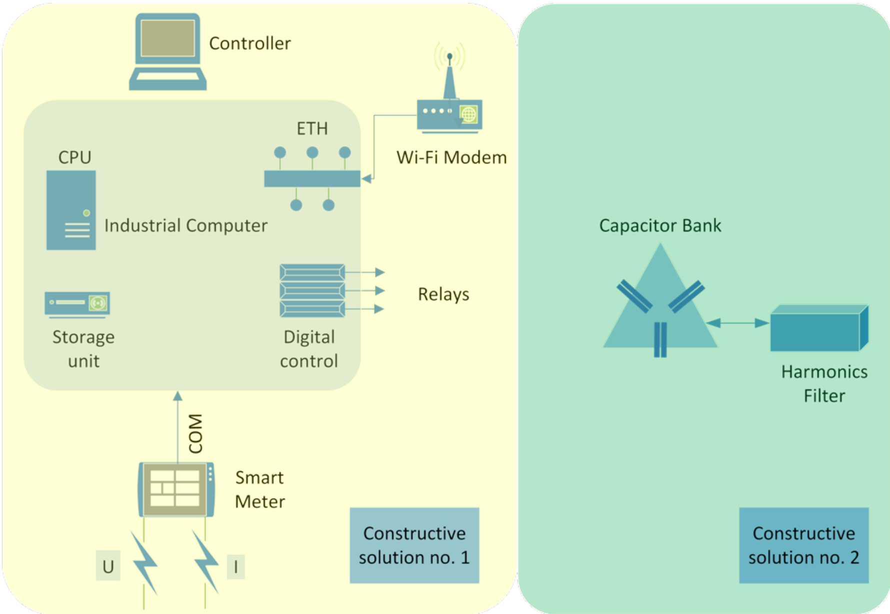


Fig. 3.3 *Constructive solution no.2*

The constructive solution no.3 indicated in Fig.3.4 additionally contains the module for the introduction of energy made from solar / wind type sources. The production of solar-based energy is carried out with photovoltaic panels connected to regulators. These regulators power the battery of batteries. The production of electricity based on wind energy is carried out with a wind generator that provides at the output a continuous voltage that supplies the same batteries of accumulators.

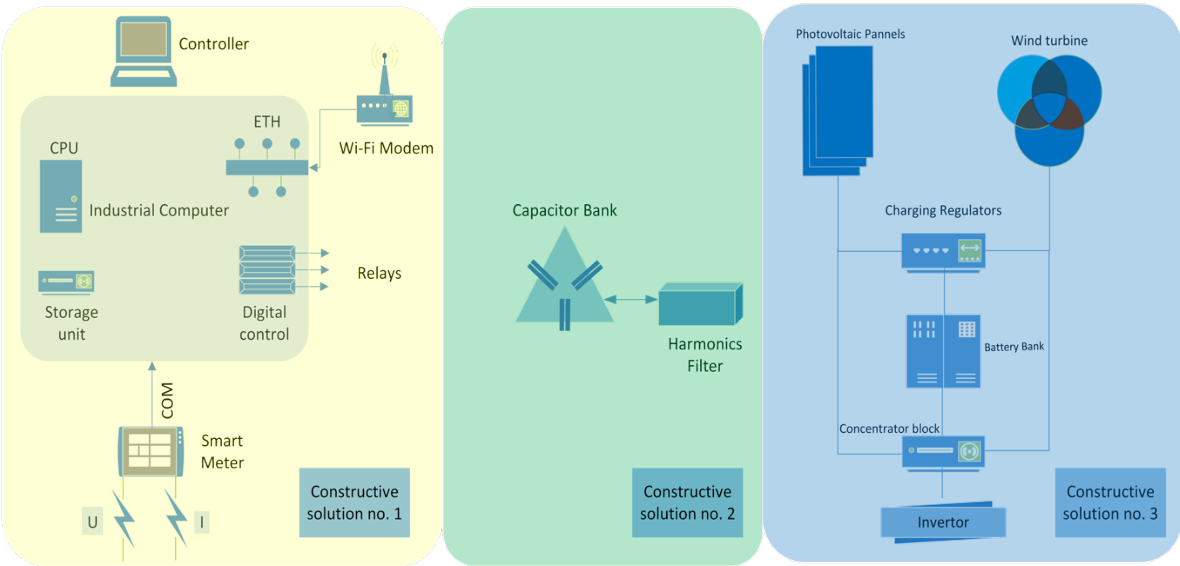


Fig. 3.4 *Constructive solution no.3*

3.2. ELABORATION OF THE CONSTRUCTIVE SOLUTION NO. 1

The intelligent system proposed for this constructive solution of the smart installation ensures the function of real-time acquisition of detailed consumption information from the machines installed in the technological flow and local processing in order to extract useful information for their efficiency. Its functional blocks, made as a result of the design, are shown in Fig.3.5.

Fig.3.5. Functional blocks constructive solution no.1

The electrical diagram of this constructive solution – Fig.3.6, is physically made within the monitoring and local commands dashboard – Fig.3.7, which includes: consumer connection equipment, protection equipment, command relay block, industrial computer that provides local optimizations, extension boxes, clamp strings.

Electrical wiring diagrams for all constructive solutions are attached in Annex 1.

The data acquisition is carried out with the help of Janitza UMG 104 smart three-phase meters that measure, store and process information on all the sizes of interest in the supervised three-phase network: global instrumentation and phase sizes, billing data, load curves, configuration parameters, status information, energy quality information.

The Smart Grid part is taken over by an Intelligent Energy Terminal (TEI), which is a distinct equipment, physically placed next to the meter. It is represented by the industrial computing system WP 5141.

The data is transmitted to a computer located at the dispatching point, a place where all the data processing activities are carried out, analyzes for optimization, optimal setting of the working regimes, control of the automatic operation of the equipment that ensures the optimization at each feeding place of important equipment.

The design of the software elements includes parts specific to the local point, the dispatcher point and the possibilities of transmitting data within the installation.

The LabVIEW graphical programming environment was used, with drivers developed specifically for the functions of this installation.

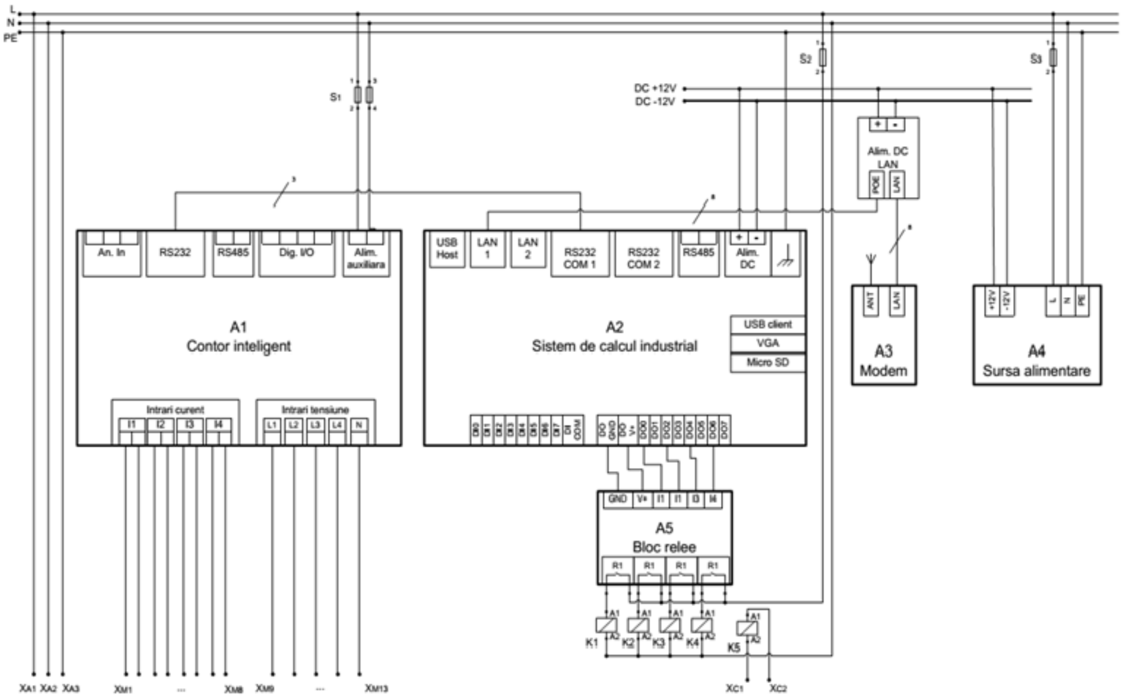


Fig.3.6. Electrical diagram for constructive solution no. 1

Fig.3.7. TLMC-1 panel with current measuring transformers

3.3. ELABORATION OF CONSTRUCTIVE SOLUTION NO.2

This constructive solution additionally adds to the constructive solution no.1 a subassembly designed to preserve the quality of electricity.

For the system realized in solution no. 2 an automatic capacitor battery consisting of three electrolytic capacitors connected in a triangle of 3 x 22 µF is used. For harmonic damping, a passive LC filter consisting of the 3 capacitors and three inductivities is provided.

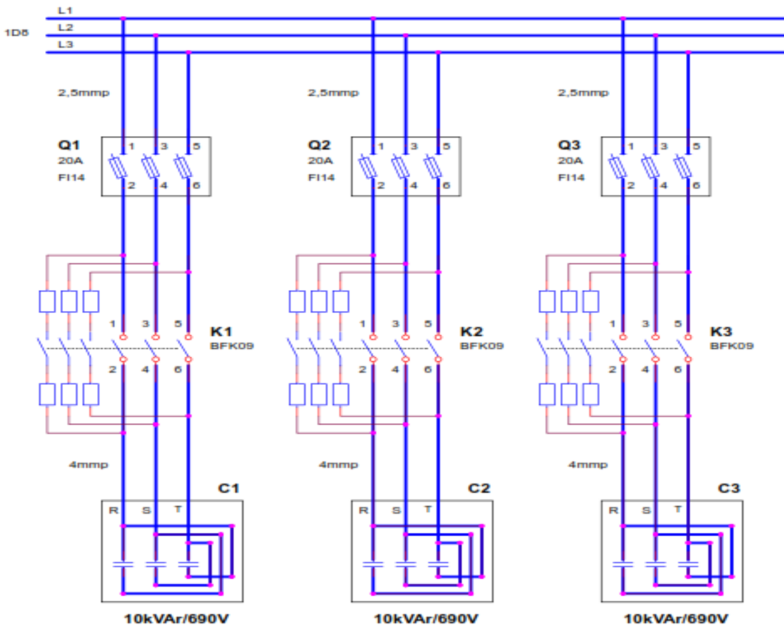


Fig. 3.9. *Connection of the compensation installation*

Fig. 3.10. *Electrical panel constructive solution no.2*

3.4. ELABORATION OF CONSTRUCTIVE SOLUTION NO.3

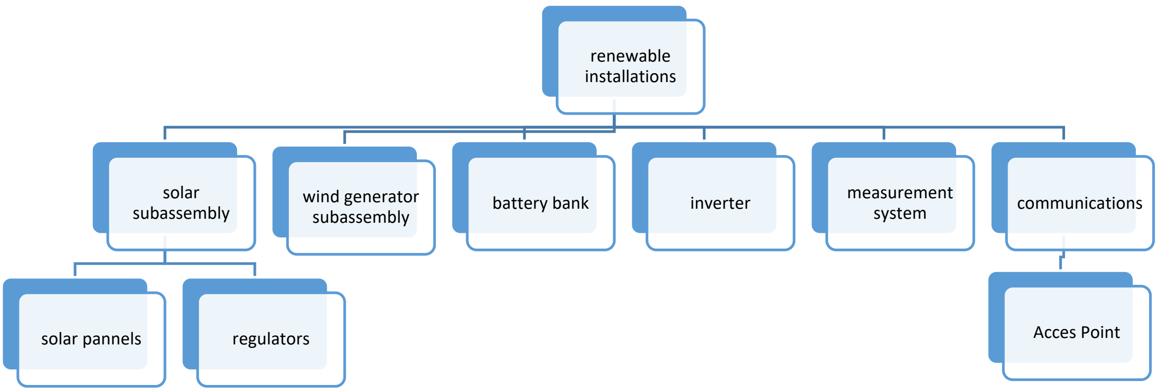


Fig.3.11. Insularized solution for renewable energies

Solar-based energy production is achieved with 4 photovoltaic panels mounted two in series and connected to a regulator each. The two regulators power the battery pack. It consists of 4 independent 12 V batteries, connected two by two in series to obtain the continuous voltage of 24V that powers the inverter.

The electrical diagram of the constructive solution no.3 is presented in Fig. 3.12 and next to it, in Fig. 3.13, the actual realization can be observed.

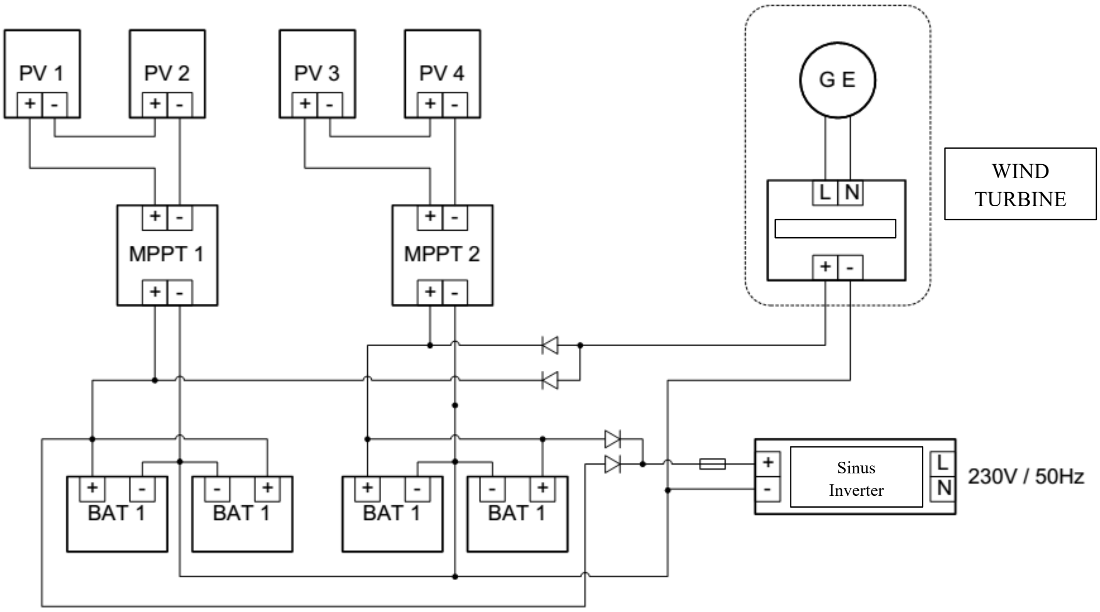


Fig. 3.12. *Electrical diagram mode of constructive solution no.3*

Fig. 3.13.*Practical realization of constructive solution no.3*

3.5. SPECIFICATIONS FOR COMMUNICATION INFRASTRUCTURE AND CENTRAL POINT STRUCTURE MONITORING AND OPTIMISATION

The central dispatcher point contains a dedicated PowerEdge R620 server and a computer system that ensures the retrieval of information from local compute points.

The analysis of consumption shall be based on the monitoring of the following parameters:

-tension;

-current;

- active power;

- active energy;
- reactive power;
- reactive energy;
- power factor;
- energy quality (harmonics, distortions, imbalance).

The consumption analysis is based on the monitoring of the following parameters: voltage, current, active power, active energy, reactive power, reactive energy, power factor; energy quality (harmonics, distortions, imbalance).

Local monitoring and control points, associated with consumers/groups of consumers, are connected via a WiFi communication network at the central dispatching point. Each local point contains:

- UMG-104 measuring equipment;
- programmable controller WP-5441;
- Igap-420 WiFi communication equipment in "CLIENT" configuration

Dedicated configuration and software for the WP-5441 controller in terms of communication network and support for "debug" has been carried out. Also, in order to ensure the communication of the local monitoring points with the dispatching application, it was necessary that the WiFi communication equipment existing at the local measurement and monitoring points be configured in the "CLIENT" mode and at the dispatcher in the "ACCESS POINT" mode.

The central dispatcher type point, to which the local point sends the measured information, is equipped with a computer having configured a database system - SQL Server 2012 Express. It comes with a software application that performs the following functions:

- reading the monitored parameters from the measuring equipment;
- transfer of parameters to the dispatching application;
- storage of the parameters measured during the time when there is no connection with the dispatching application (max. 48 hours);
- control of consumers according to orders given by imposed rules.

The dispatching application has the role of allowing the configuration of the local monitoring points and of centralizing the information received from them in a database that allows their further analysis in order to develop strategies to optimize the electricity consumption. The application was made in accordance with the three constructive variants of the system.

For the constructive variant 1 (monitoring the network parameters, in different nodes) and the constructive variant 2 (variant 1 plus equipment for reactive energy compensation and harmonic elimination), the application offers the user a general and detailed look at the power and energy consumed, as well as other parameters of interest.

For constructive variant 3 (variant 2 plus renewable energy sources), the application offers the possibility of viewing the parameters corresponding to each generator, in a way that can easily be seen the share of the generated energy.

Monitored parameters from the local point are transmitted to a central server containing the database. From here they are taken over by this application, which can run on any PC connected to the server network.

For a good view of the parameters (electrical quantities), they are grouped and displayed as follows:

- instantaneous sizes at local points for all parameters obtained from monitoring;
- selections made by the user for the history of some parameters;
- evaluation, by comparison, of all types of energies and measured powers;
- renewable energy introduced into the grid as a result of the optimization process;

The software application was made in the LabVIEW virtual instrumentation environment and can run as an executable on the user's computer without requiring a license.

To fulfill its functionality, the application runs simultaneously in two main ways of working, data of how to display data. The data stream is illustrated in the diagram below.

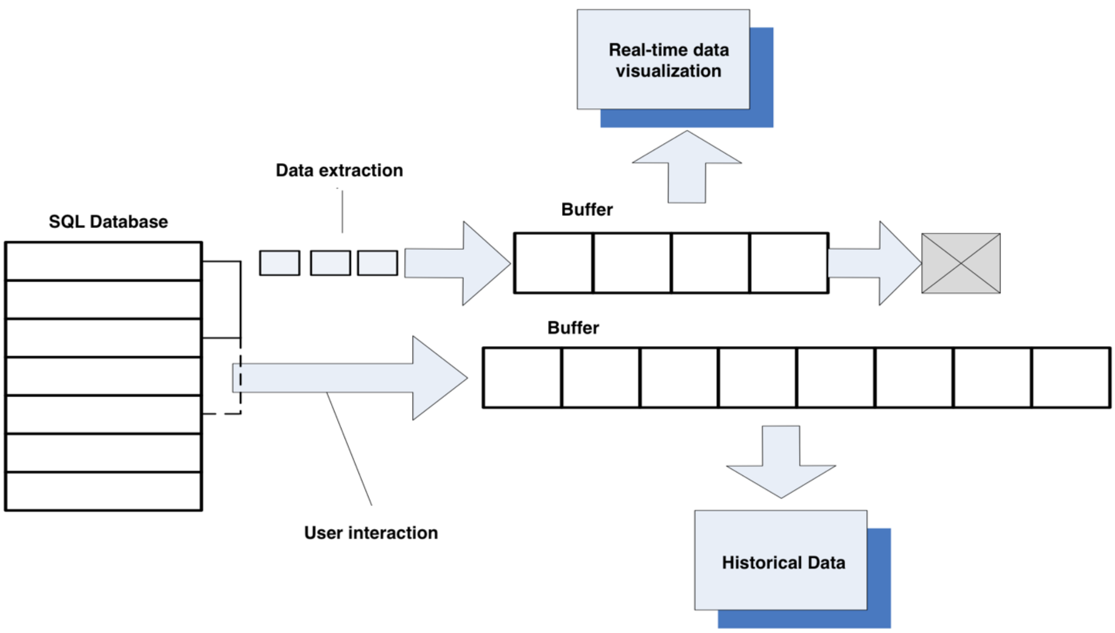


Fig. 3.14. Data flow in continuous display modes: short duration, consumption history

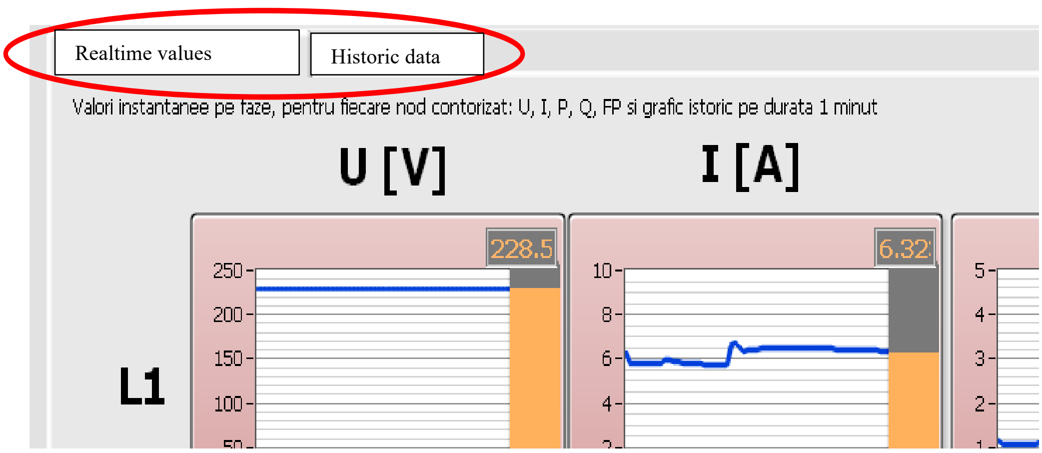


Fig.3.15. Detail of selection of the display mode

In this way, different sizes are displayed italics, listed in the overview, in the form of time variation on the graph and in the form of a bar display and numerical value as detailed in the following figure. The sizes are displayed for a selected local point and represent phase sizes. Their variation over time, over a duration of 1 minute, containing the most recent values extracted from the database, is graphically displayed.

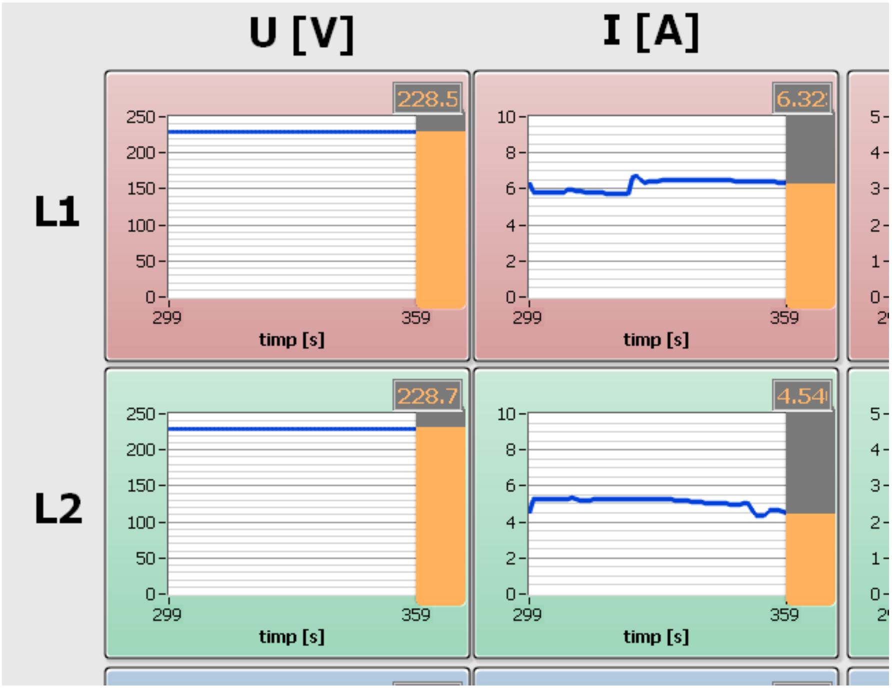


Fig.3.16. Example of instantaneous values displayed continuously

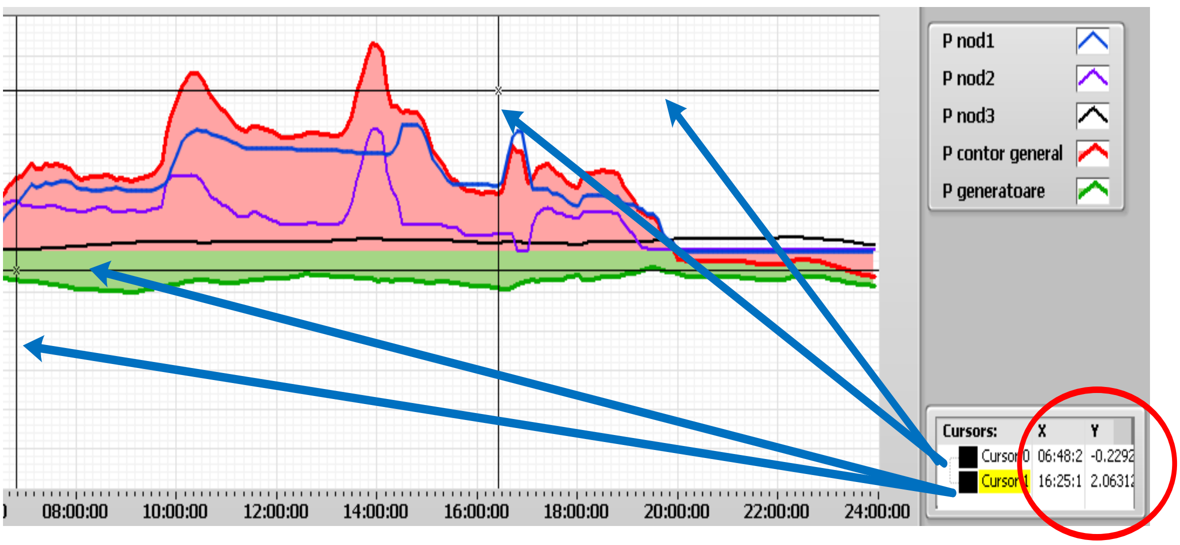
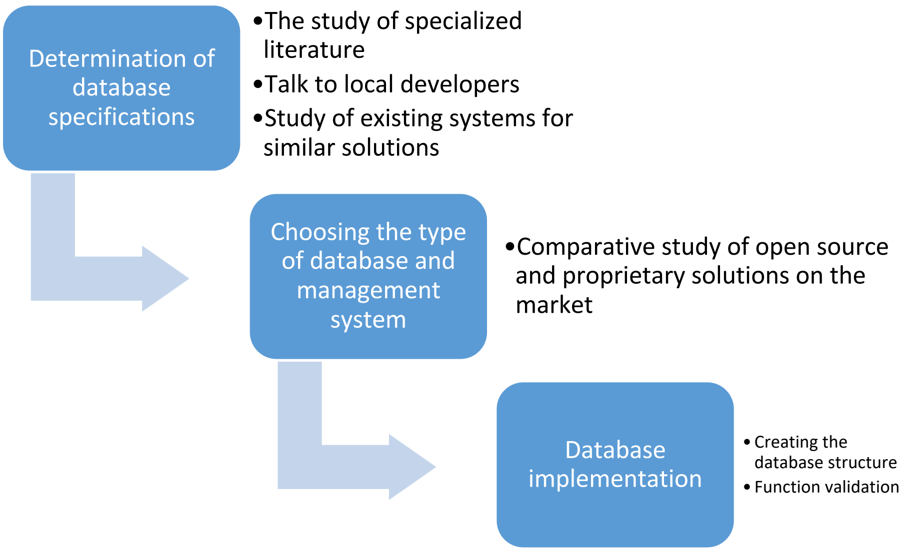


Fig.3.19.Cursors (x,y) for finding values and moments/time intervals

CHAPTER 4

DESIGN AND REALIZATION OF THE DATABASE FOR RECORDING THE MEASURED VALUES

Within the present doctoral research project, the design and realization of the database represents a vital point for the entire functioning of the forecasted system. For this, the following methodology of realization was developed:



4.1. CHOOSING THE TYPE OF DATABASES

In order to choose the optimal database and management system, a comparative study was conducted that treats all products as a set [30] – [51]. Following the analysis, a mySQL relational database was chosen.

For the programming component, the PHP language has been chosen, which provides a visual database management interface, represented by the administration interface called phpMyAdmin.

4.2. DATABASE DESIGN

The installation incorporates data that can be divided into various categories, depending on the set of facilities it has to bear. For this purpose, the following categories of information circulated are noted:

A. Experimental data for the *n* individual consumers.

Each consumer $k = 1... n$ has as data to be stored:

1. Consumer name
2. For the three lines of the electrical system L1, L2, L3 is stored:
3. Electrical voltage
4. Intensities of three-phase currents on each phase
5. Active power
6. Reactive power
7. Power factor
8. Voltage distortion factor$_{du1}$, kdu2, k_{du3}

9. Harmonics (amplitudes)A_1, A_2, A_3,...... A_{100}
10. Distortion factor curentk_{di1}, k_{di2}, k_{di3}

B. Measured data from the network at a time

The design of the multi-table database begins with the mode of interaction between tables – Fig. 4.1.

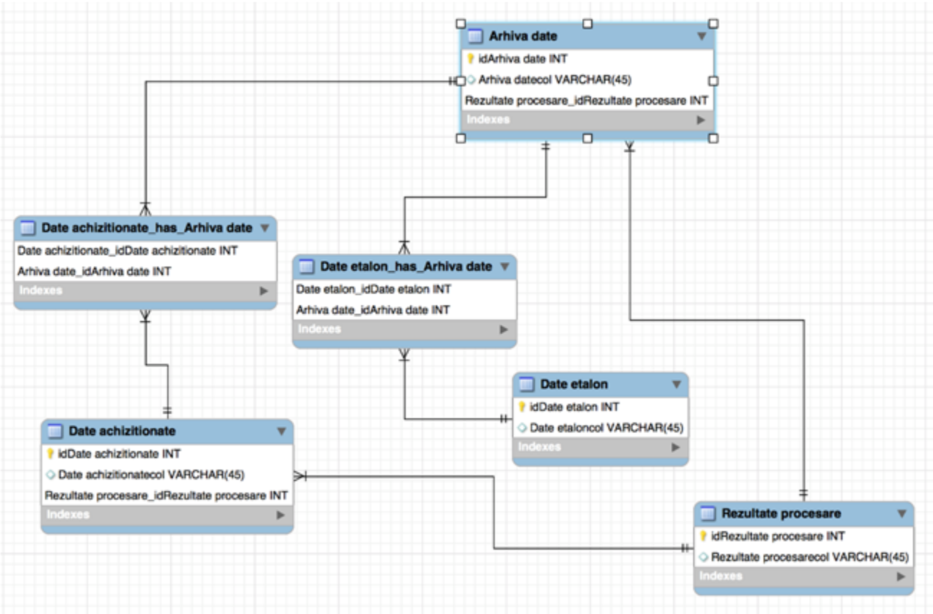


Fig. 4.1. *Multi-tabular structure of the database*

4.3. DATABASE OPTIMIZATION

4.3.1 Database optimizations

The most important factor in making a fast database application is its design:

1. choosing a transactional storage engine – InnoDB
2. compressed tables that use less disk space and therefore require fewer I/O operations to read and write the data. Data compression is available for all types of tasks with InnoDB tables.
3. priority management
4. Cache areas are sized correctly.

4.3.2 Code-level optimizations

The most important implementation aspects were:

Term optimizations WHERE

Extension of the Index (en. Index Extension)

Optimization „IS NULL”

Speed of update statements

4.4. DATABASE TESTING

It was achieved:

Stress test

Performance test

The database for testing is identical in terms of structure to the base used within the developed system, but its popularity will be done with test data that is generated in a control mode to evaluate the performance of the storage system.

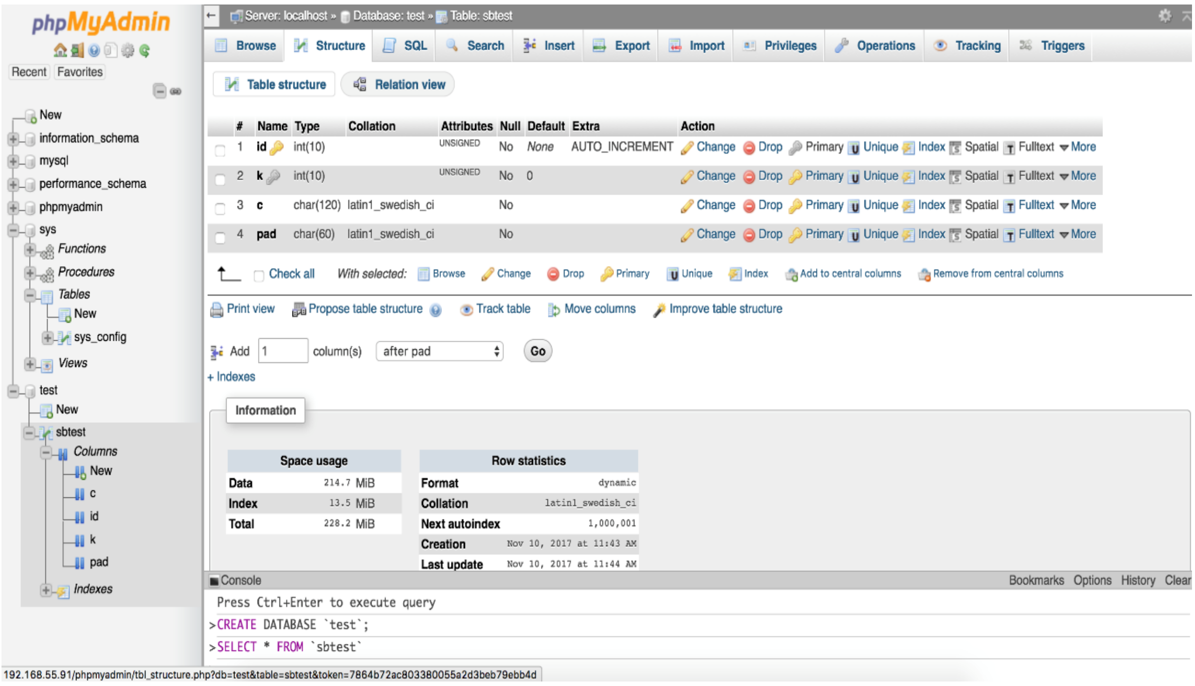
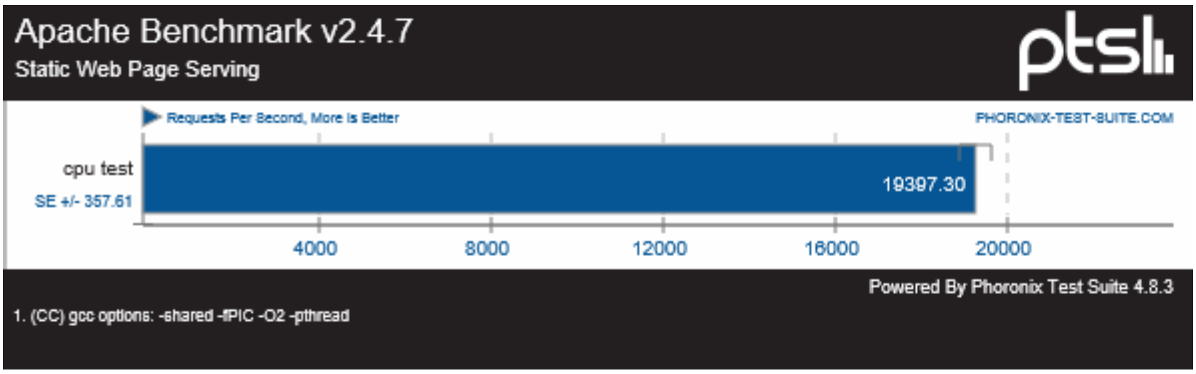
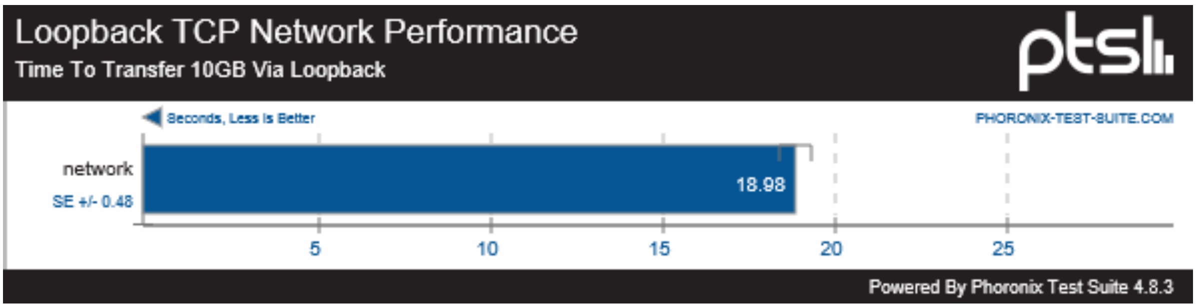


Fig. 4.2. *Test database*

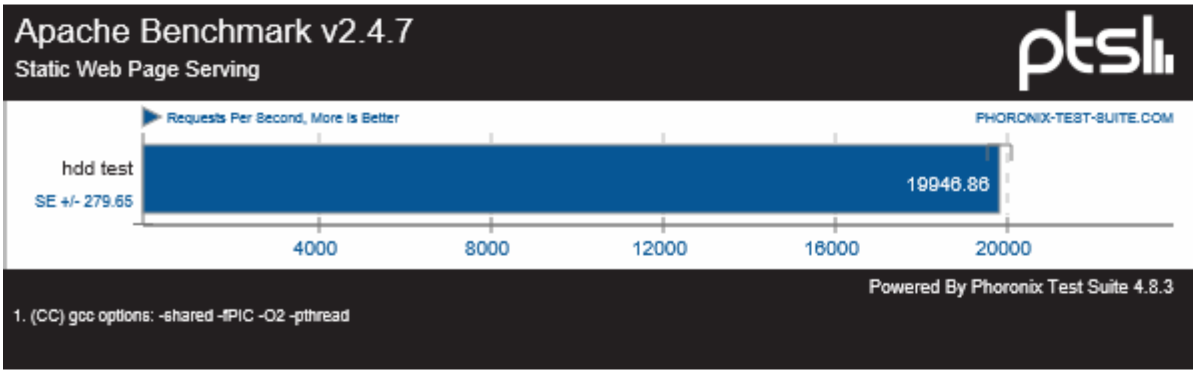
After populating the database, the Apache Benchmark utility was used to establish the hardware performance of the developed storage system.



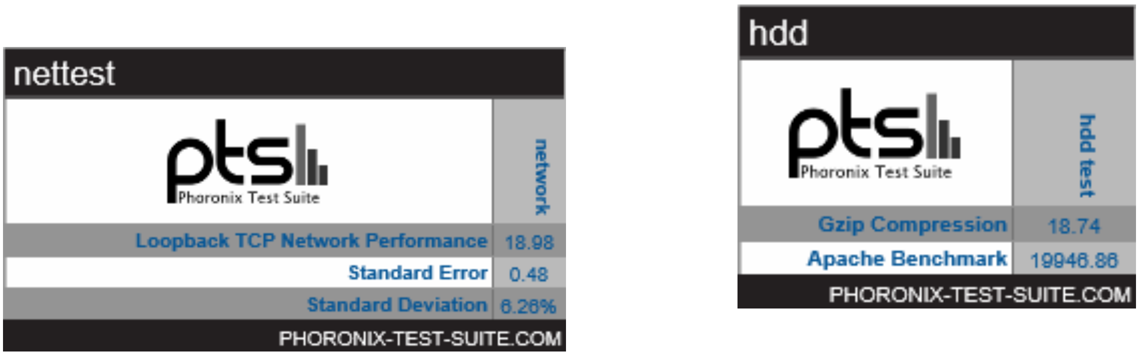
a) CPU Performance Testing



b) Testing of the communication interface



c) HDD Performance Testing



d) Results of the test carried out

Fig. 4.3. Hardware testing of the test database

CHAPTER 5

SOFTWARE COMPONENT OF THE INSTALLATION FOR MONITORING AND OPTIMIZING ENERGY CONSUMPTION IN SMALL INDUSTRIAL CONSUMERS

5.1. DATA FLOW CONFIGURATION

The installation consists of a local point/several local consumption monitoring and control points, associated with consumers or groups of consumers, connected by a WiFi communication network to a central dispatching point.

Each local point contains:

1. umg-104 measuring equipment;
2. programmable controller WP-5441 running data acquisition application with Win CE 5.0 operating system;
3. IGAP-420 WiFi communication equipment in "CLIENT" configuration

The dispatcher-type central point, to which the local point sends the measured information, is equipped with:

4. PC computer having configured database system - SQL Server 2012 Express and WiFi communication equipment IGAP-420 in configuration "ACCESS POINT".

The schema of the projected data flow can be seen in Fig. 5.1.

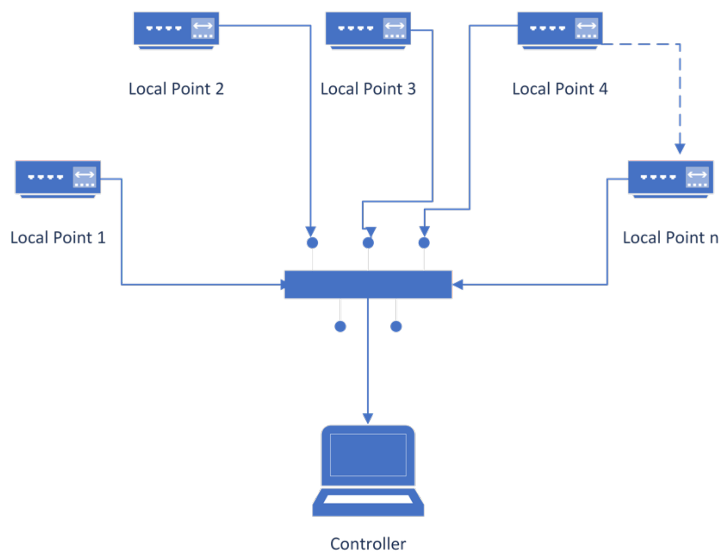


Fig. 5.1. *Data flow*

5.2. WP-5441 CONTROLLER SOFTWARE CONFIGURATION

In order to use wp-5411 controller it has been configured in terms of communication network and support for "debug".

5.3. COMMUNICATION POINT SOFTWARE CONFIGURATION

In order to ensure the communication of the local monitoring points with the dispatching application, it is necessary that the WiFi communication equipment from the local monitoring points be configured in the "CLIENT" mode and the one from the dispatcher in the "ACCESS POINT" mode.

5.4. CONFIGURATION OF COMMUNICATION PROTOCOLS

5.4.1 ModBus RT. U Example:

The structure of a message is of the form:

<ADR><FCT><DATA><CRC>

<ADR> - the address of the slave equipment (UMG-104);

<FCT> - the order code, 1 byte having the following possible values:

0x03 - reading the registry;

0x04 - reading the entrance registers;

0x06 - writing register;

0x10 - writing several kings;

<CRC> - control amount CRC16 (2 bytes);

<DATA> - information on the address of the registry(s), the number of registry offices and the content of the registry.

The format depends on the order code, so:

Command 0x03:
Application: address of the first register - 2 bytes
number of registry - 2 bytes
Answer: address of the first register - 2 bytes
number of bytes - 2 bytes having the value 2n, where n is the number of registers required;
the contents of the registers - n x 2 bytes, where n is the number of registers

0x04 command:
Application: address of the first register - 2 bytes
number of registry - 2 bytes
Answer: address of the first register - 2 bytes
number of bytes - 2 bytes having the value 2n, where n is the number of registers required;
the contents of the registers - n x 2 bytes, where n is the number of registers

0x06 command:
Application: registry address - 2 bytes
registry value - 2 bytes
Answer: Registry address - 2 bytes
registry value - 2 bytes

0x10 command:
Application: address of the first register - 2 bytes
number of registry - 2 bytes
number of bytes - 2 bytes having a value of 2xn where n is the number of registry;
registry value - n x 2 bytes, where n is the registry number
Answer: Registry address - 2 bytes
registry value - 2 bytes

In case of error the equipment responds with the function code having the most significant bit set, followed by the error code on a byte.

5.4.2 TCP/IP

5.5. ARCHITECTURE OF DEVELOPED SOFTWARE APPLICATIONS

5.5.1. Software application for the local monitoring and control point

The software application runs in the Windows CE operating system having the architecture shown in Fig. 5.2.

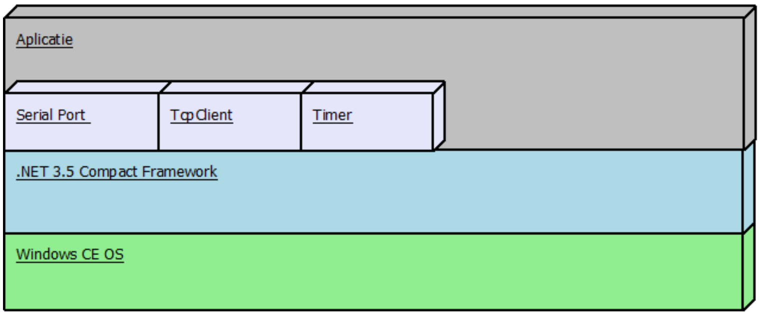


Fig. 5.2. *Monitoring and control application architecture*

5.5.2. Controller software application

The dispatcher application runs in the Windows operating system having the following architecture:

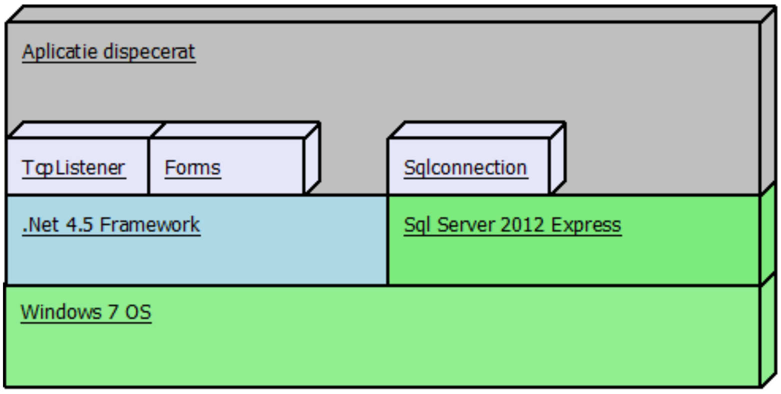


Fig. 5.3. *Dispatcher application architecture*

5.5.3. Database software application

The dispatcher application uses the SQL Server 2012 Express database system to store cell configurations, system events, and measured values.

5.5.4. Offline value processing software application

The application works in the LabVIEW graphical programming environment and relates to the entire software architecture of the system as follows:

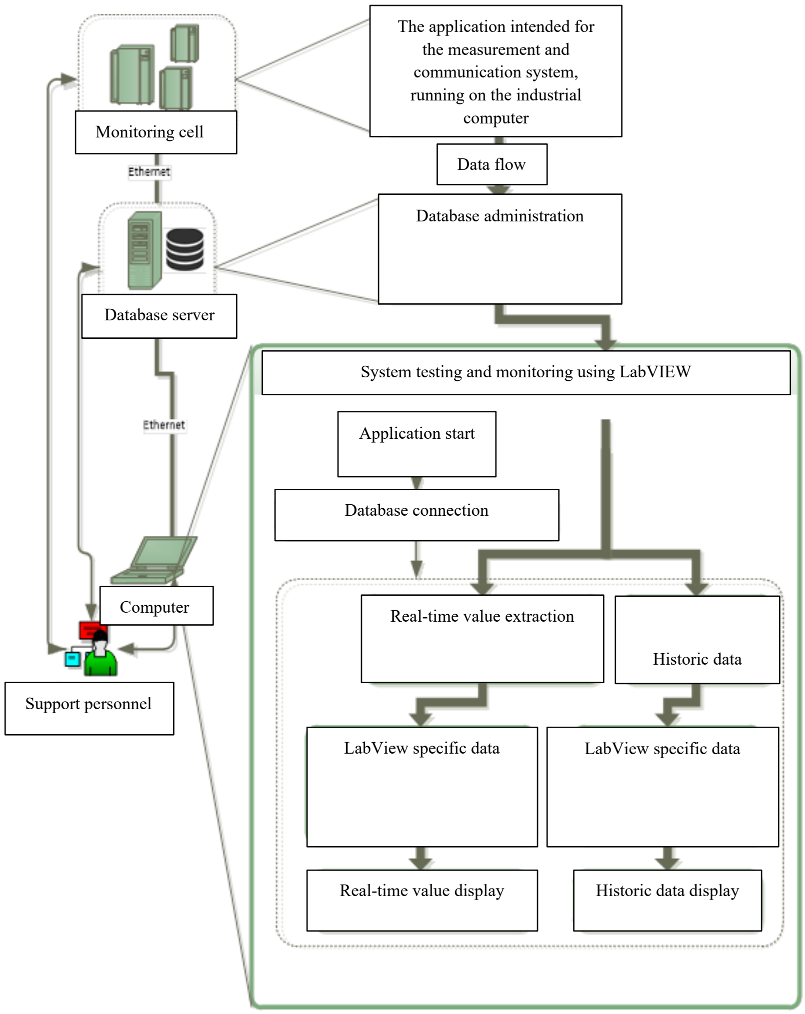


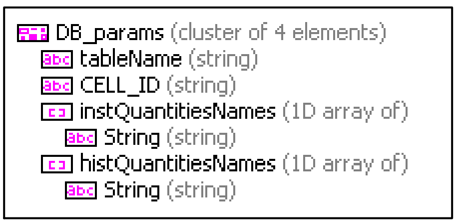
Fig. 5.5. *Complete system software architecture*

Building blocks of the LabVIEW monitoring and testing software application

► Create a list of measured sizes
► Connect the application to the database
► Sizing the buffer components related to the displayed windows
► Time synchronization and instantaneous size readings for a local point
► Query the database for time labels, at instant sizes
► Query the database for sizes related to a local point, in the case of the size history

This subVI makes up an SQL statement in order to read from the database the size values corresponding to the measuring cell having the specified ID. The request is made for the case of the size history, requesting the records contained within a specified time frame.

Input/output parameters



```
startDateTimeRec (typedef 'LVDateTimeRec.ctl'[non-strict])
  startDateTimeRec (cluster of 10 elements)
    fractional second (double [64-bit real (~15 digit precision)])
    second (long [32-bit integer (-2147483648 to 2147483647)])
    minute (long [32-bit integer (-2147483648 to 2147483647)])
    hour (long [32-bit integer (-2147483648 to 2147483647)])
    day of month (long [32-bit integer (-2147483648 to 2147483647)])
    month (long [32-bit integer (-2147483648 to 2147483647)])
    year (long [32-bit integer (-2147483648 to 2147483647)])
    day of week (long [32-bit integer (-2147483648 to 2147483647)])
    day of year (long [32-bit integer (-2147483648 to 2147483647)])
    DST (long [32-bit integer (-2147483648 to 2147483647)])
```

```
endDateTimeRec (typedef 'LVDateTimeRec.ctl'[non-strict])
  endDateTimeRec (cluster of 10 elements)
    fractional second (double [64-bit real (~15 digit precision)])
    second (long [32-bit integer (-2147483648 to 2147483647)])
    minute (long [32-bit integer (-2147483648 to 2147483647)])
    hour (long [32-bit integer (-2147483648 to 2147483647)])
    day of month (long [32-bit integer (-2147483648 to 2147483647)])
    month (long [32-bit integer (-2147483648 to 2147483647)])
    year (long [32-bit integer (-2147483648 to 2147483647)])
    day of week (long [32-bit integer (-2147483648 to 2147483647)])
    day of year (long [32-bit integer (-2147483648 to 2147483647)])
    DST (long [32-bit integer (-2147483648 to 2147483647)])
```

Place and connectivity in the LabVIEW application

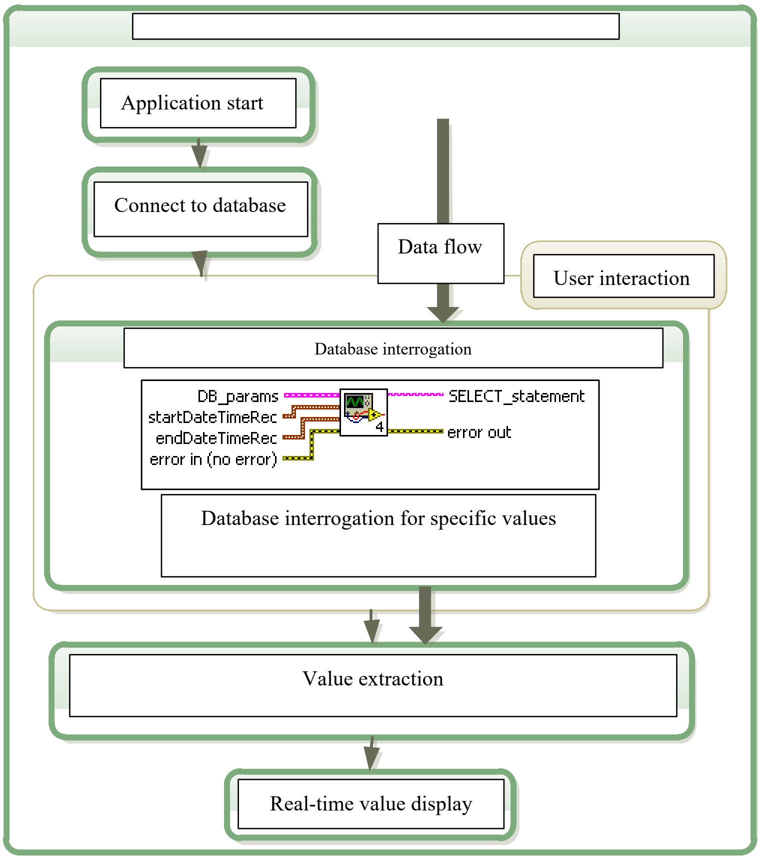


Fig. 5.11. *Organization chart for querying the database for size history*

- ► Convert date and time to database format
- ► Viewed measurement point selection
- ► Vector selection specified size from arrays of read columns
- ► Compile data collection for instant size display

CHAPTER 6

EXPERIMENTAL DETERMINATIONS

6.1. TESTING OF HARDWARE COMPONENTS

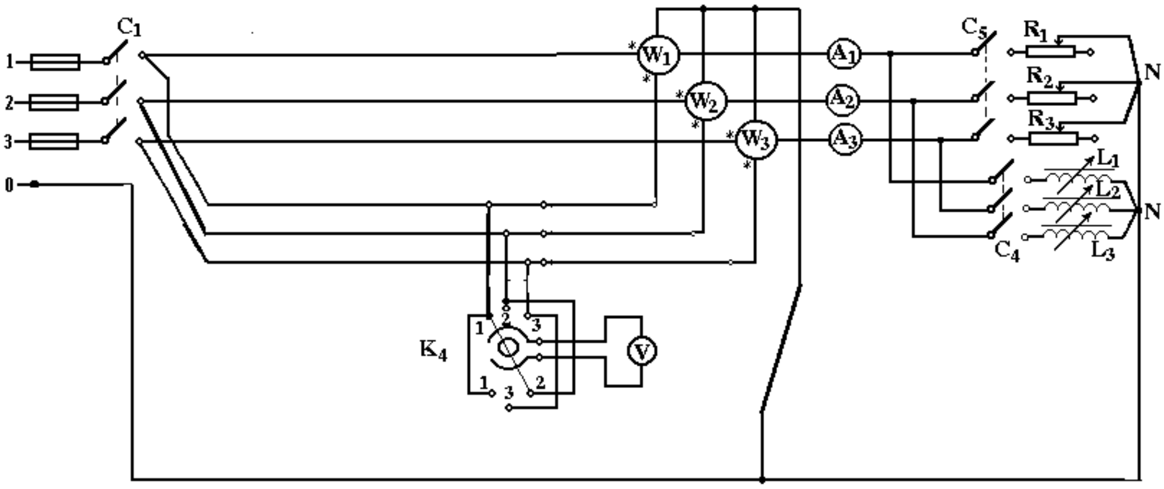


Fig. 6.1. *Test facility*

The experimental realization of the input circuits for the current intensity and for the smart meter can be seen in Fig. 6.7 and Fig.6.8

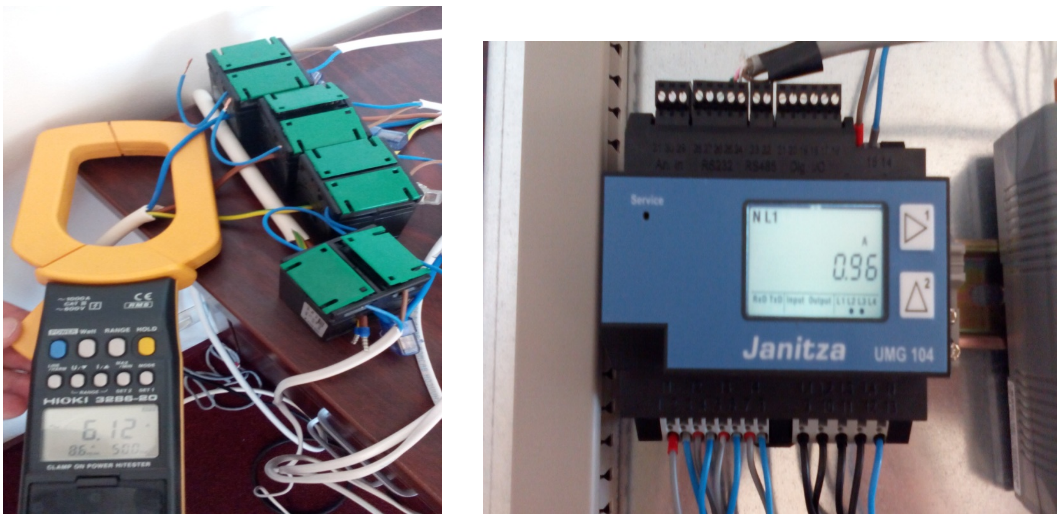


Fig.6.7 Experimental realization of circuits

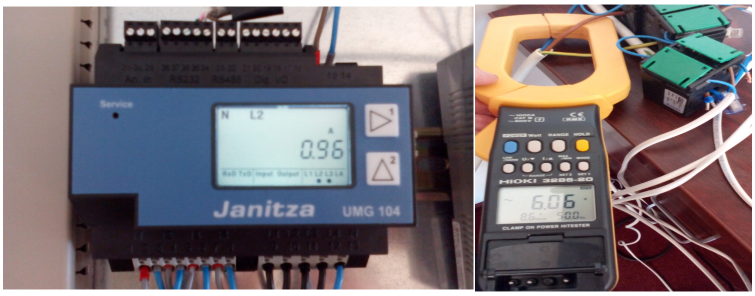
→ **Experimentation functions measuring constructive solution 1**

a. Electrical voltage measurement function

The results are shown in the following figures.

Measurement of voltage phase U_{1N} :
measured U_{1N} = 211,7 V; standard Ue_{1N} = 212,8 V
-

b. Electric current intensity measurement function
Current measuring transformers with the transformation ratio were used
I_{1n}/I_{2n} = 30A/5A = 6
Example: Phase 2

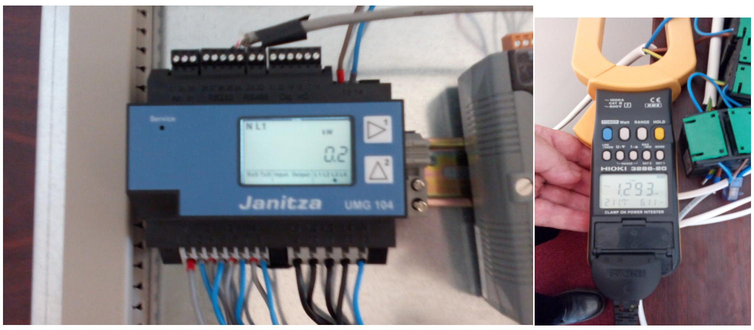


Indication of the numerical counter $I_{2}s$ = 0,96A Current I_2 measured multimeter = 6,06A

When calculating the conversion ratio indicated and taking into account the classes of apparatus as accurate, the results shall be entered in permissible values.

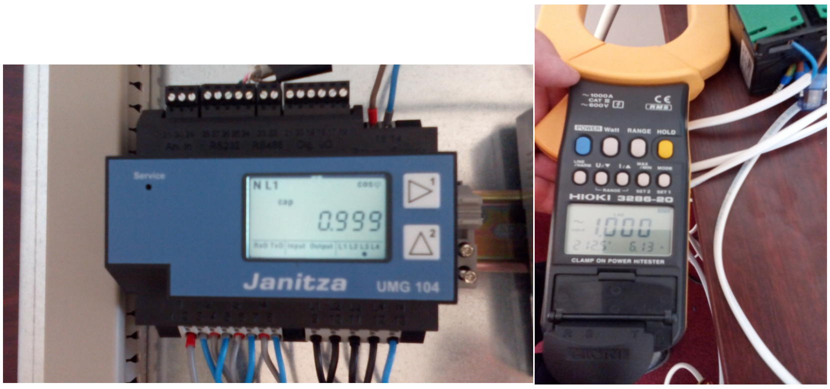
c. Active power measurement function

Faza 1



The power indicated by wattmeter W1 : P1s = 0,2kW →P1 = 1,2 kW
The power indicated by standard P1 = 1,293 kW

d). Experimentation function measuring power factor



Indication of the numerical counter and the standard measuring meter

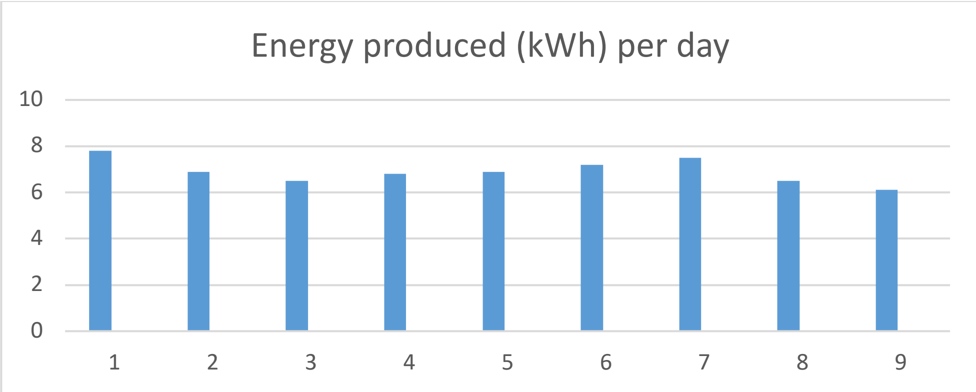
→ **Experimentation of components and functions measuring constructive solution no. 3**

The testing of the hardware components for variant 3 was done according to a scheme that includes solar (4 photovoltaic panels) and wind (a wind mini-generator) – Fig.6.4. The solution adopted for experimenting with the system is the direct measurement (using the integrated meter) of the energy produced.

Fig. 6.4. Scheme testing constructive solution no. 3

During the experimentation period, the following energy was recorded:

During the day	1	2	3	4	5	6	7	8	9
Energy produced (kWh)	7,8	6,9	6,5	6,8	6,9	7,2	7,5	6,5	6,1
Total produced energy (kWh)	63,2								



6.2. TESTING OF SOFTWARE COMPONENTS

6.2.1. Data transfer tests

The transmission of data between two specific equipment, used as receiver/transmitter, was achieved.

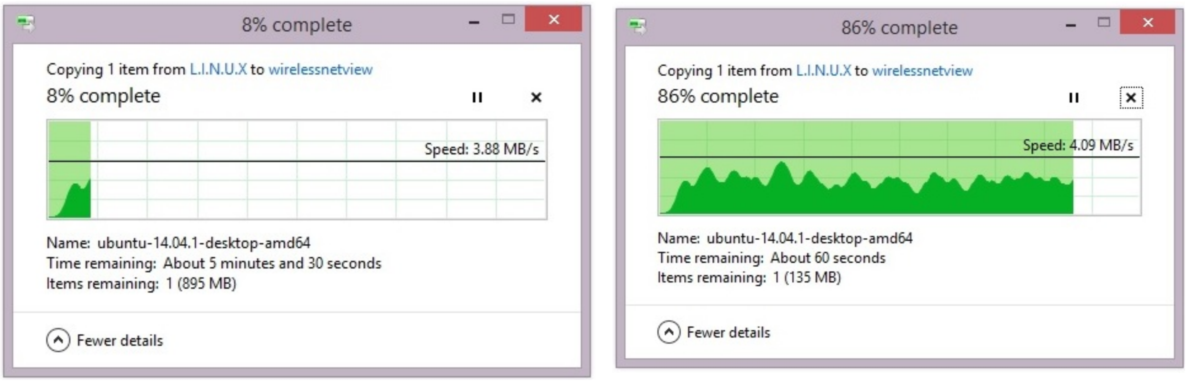
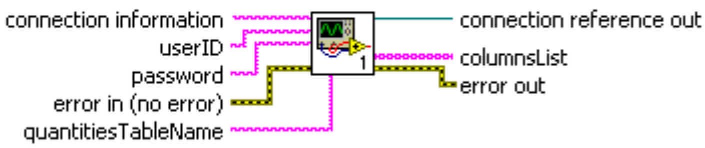


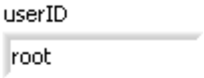
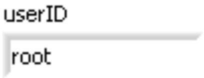
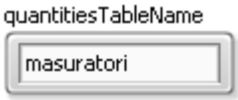
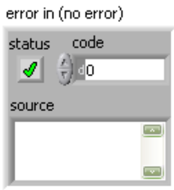
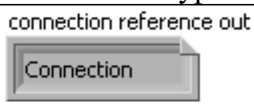
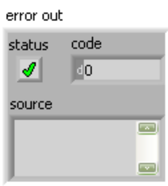
Fig. 6.8. *Data transfer testing*

6.2.2. Test of offline application

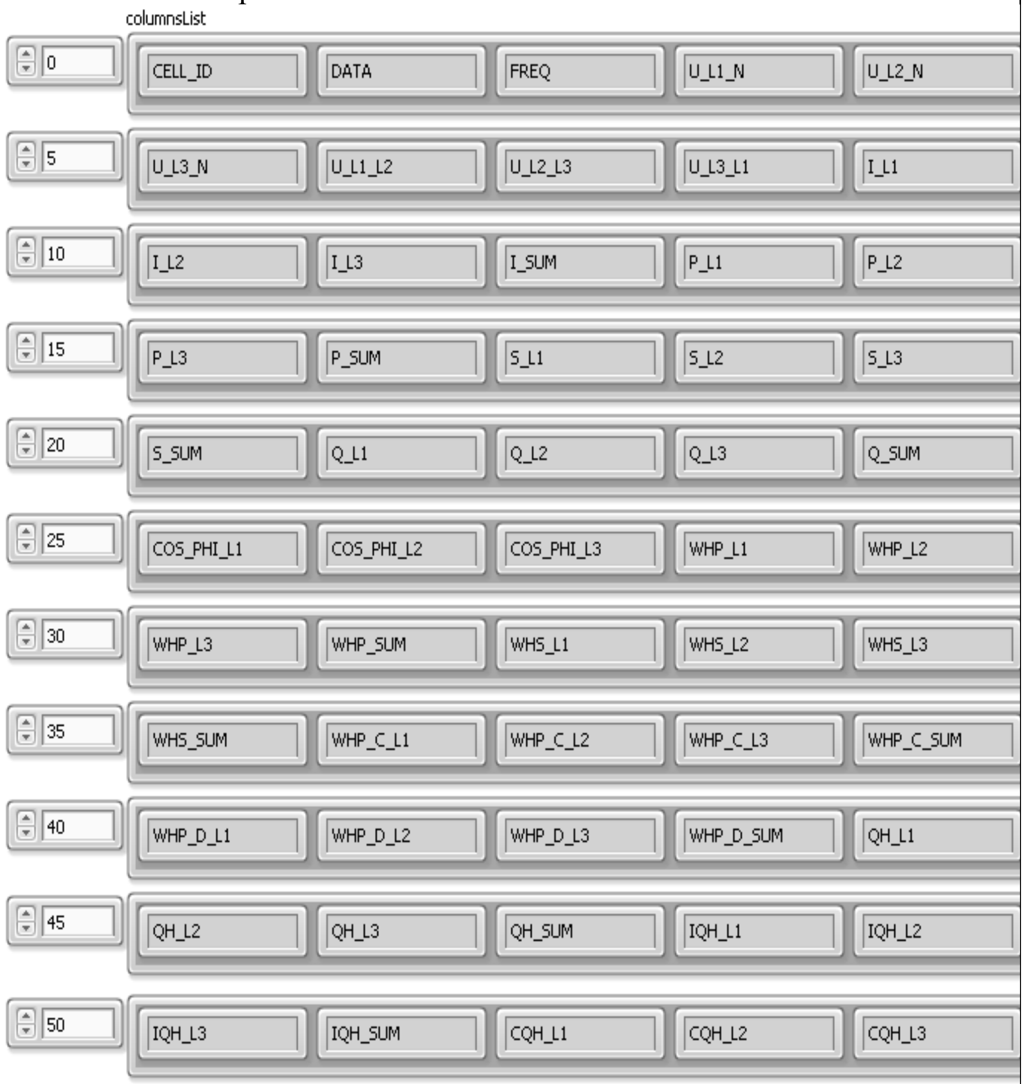
For the detection of programming errors, within the offline application, the program was run step by step, to adjust the ranges and to correct the breakpoints. LabVIEW's test probes are used for troubleshooting. Example of results:

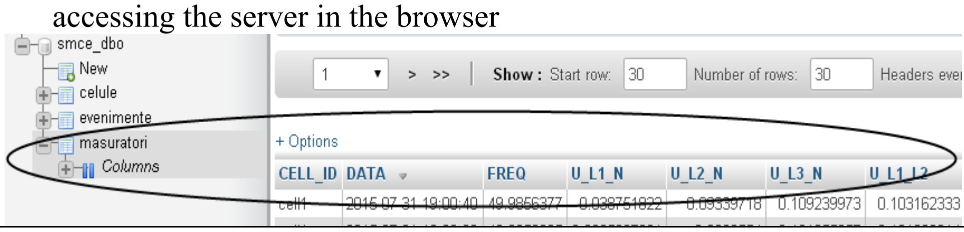
***Table* 6.1** *Test results 1 DB_connectToDb*

Description and connections	Connects the application to the database, with the information entered by the user and provides a reference to the connection, as well as the list of table column names containing the measured sizes **DB_connectToDb.vi** 
Input parameters	• connection information MySQL_ENOPT

	○ Description: The name of the connection created based on the MySQL driver; has a predefined value, which will not change by the user ○ Data Type: string •  ○ Description: user's name ○ Data Type: string •  ○ Description: user's name ○ Data Type: string •  ○ Description: user's password ○ Data Type: string • . ○ Description: Name of the table in the database, which contains the measurements ○ Data Type: string • . ○ Description: the status of the error at the input, its code and source, if there is any error; Code 0 means "no errors" ○ Data type: cluster (record)
Output parameters	• . ○ Description: the reference to the newly created connection, transmitted for use by other subroutines ○ Data Type: reference (handle) • . ○ Description: list of columns in the table whose name is entered as a parameter ○ Data Type: string vector • . ○ Description: the status of the output error, its code and source, if there was any error; Code 0 means "no errors"

<table>
<tr><td></td><td>• Data type: cluster (record)</td></tr>
<tr><td>TEST 1: input test data</td><td>○ Application data


•</td></tr>
<tr><td>TEST 1: output data</td><td>○ Subroutine output data


○ Extracted from the SQL client application window as it appears when accessing the server in the browser

</td></tr>
</table>

TEST 1: result	✓ Test passed

The following are the results regarding the testing of the software package together with the database.

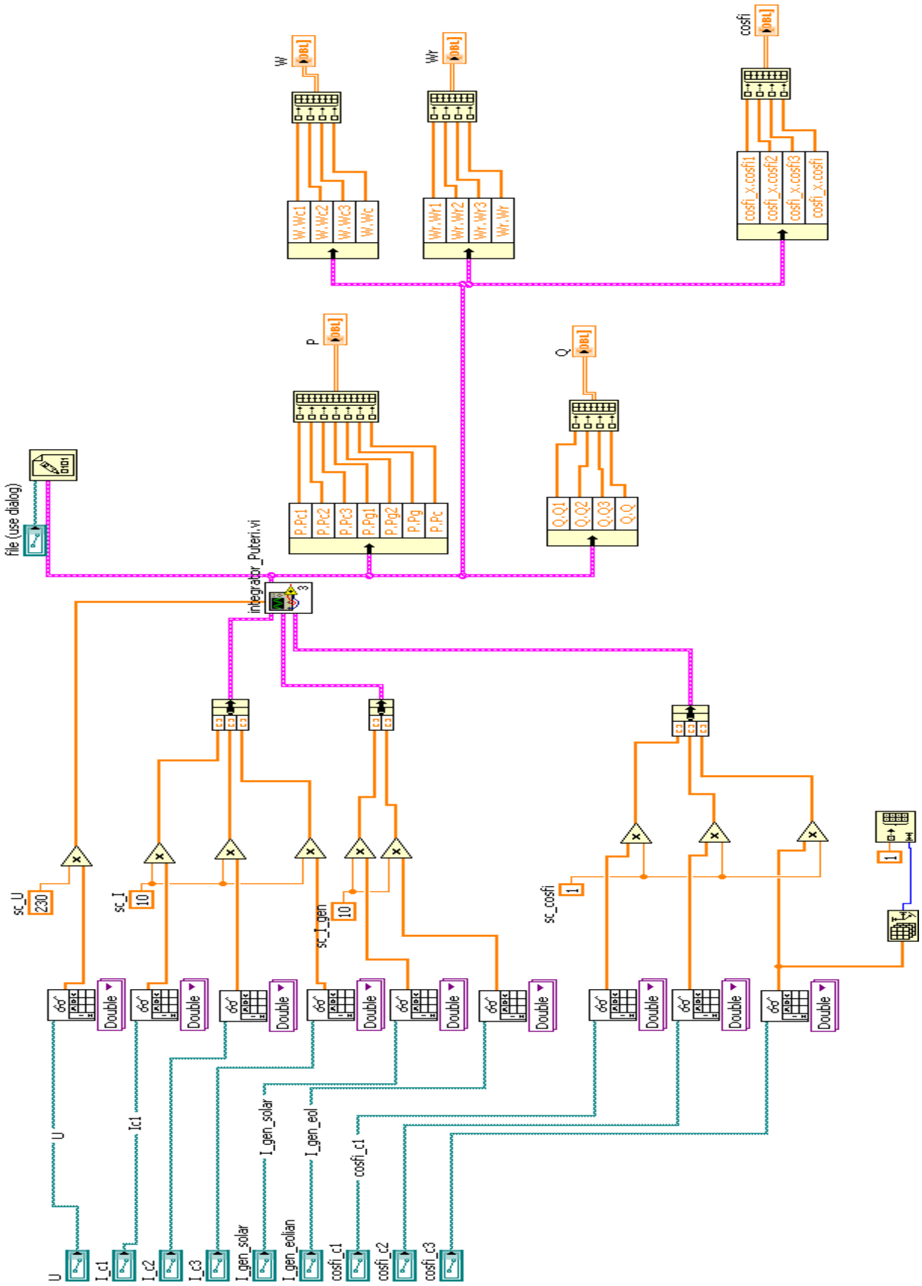


Fig. 6.9. Reading test sizes for U, I and power factor, scaling them, determining derived quantities (powers, energies) and preparing for display

The results of the tests on the dispatcher software are shown in the following figures.

Fig. 6.13. Instant measurements

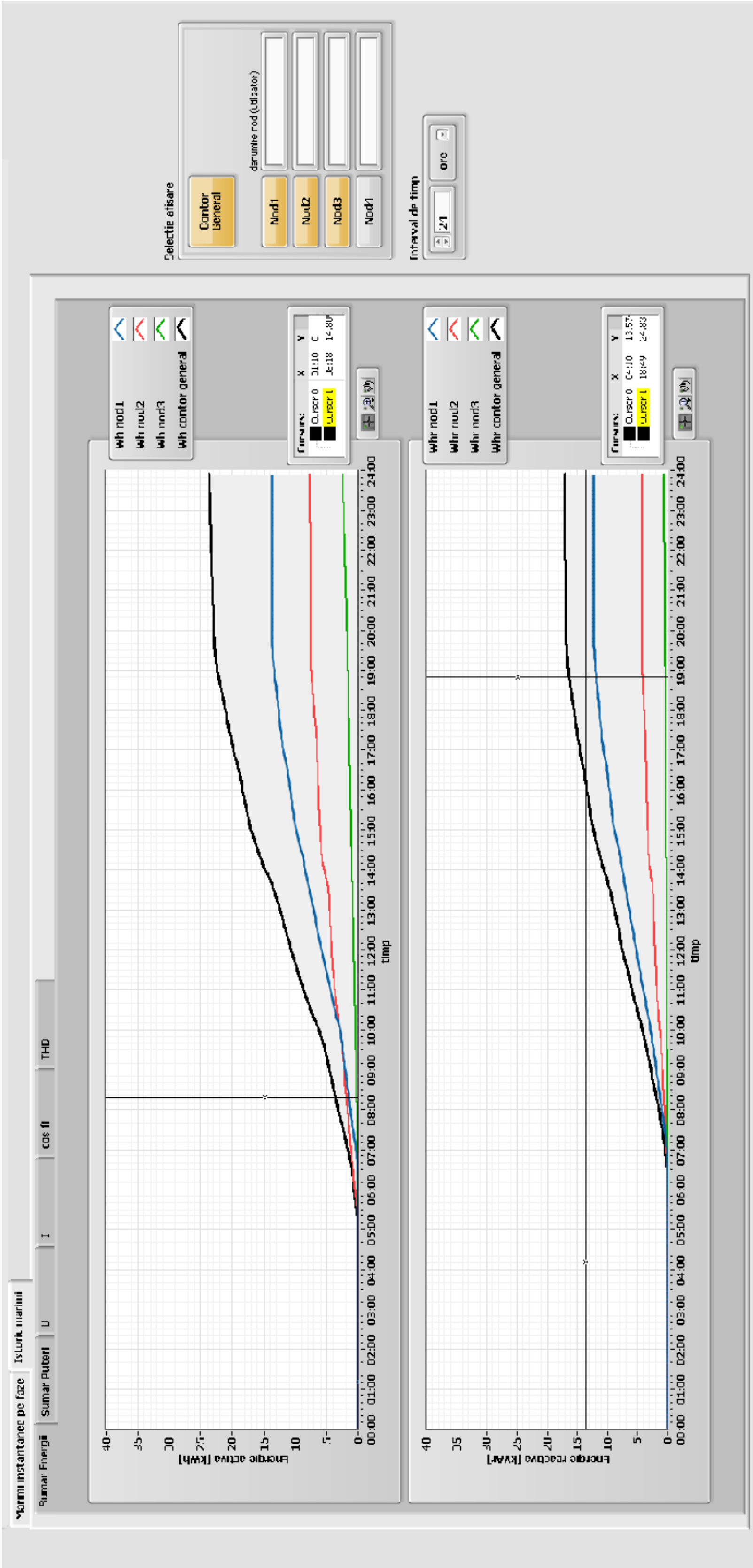


Fig. 6.14. Energy measured in a day

6.2.3. Testing the operation of the assembly representing the completed installation

The thermography was done using a Fluke TIS60 thermal imaging camera, and the thermogram was processed to indicate the fault points.

The results of the thermal imaging tests are shown in Fig.6.21. and Fig.6.22.

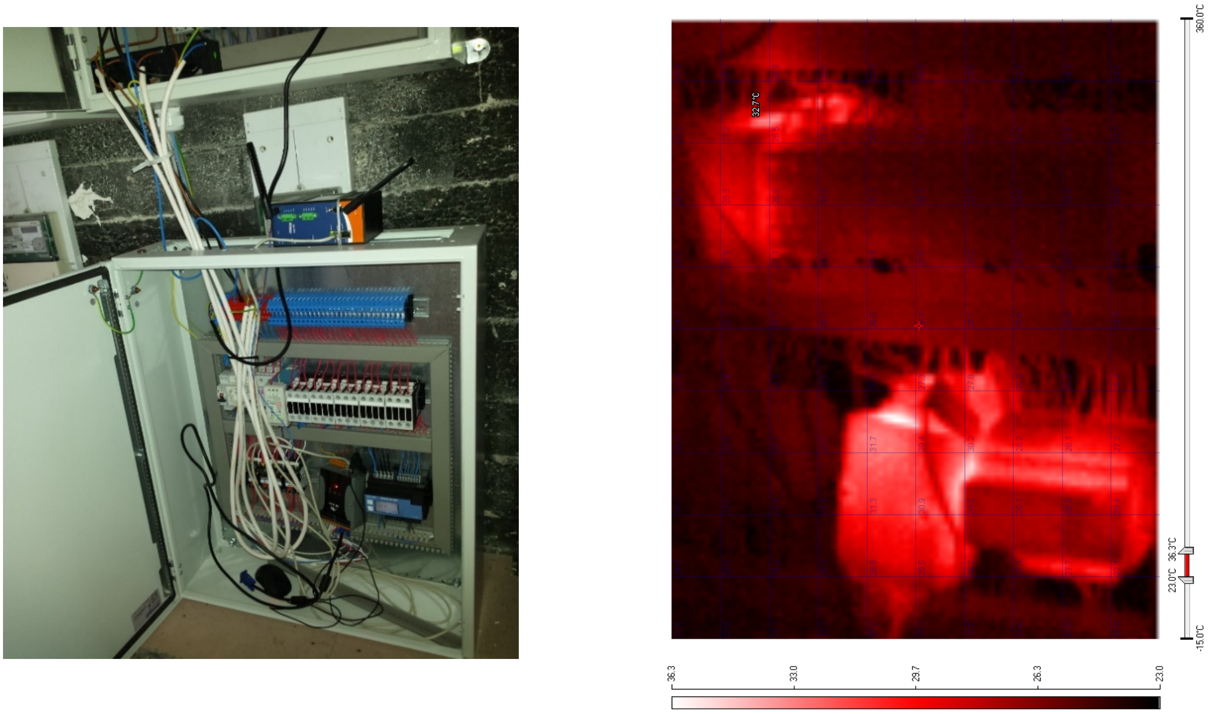


Fig. 6.21. *Thermal testing of constructive solution no.1*

CONCLUSIONS

General conclusions

The work addresses the complex issues of monitoring and optimizing electricity consumption at a small industrial consumer.

The intelligent system developed starts from "off the shelf" components, but gradually argues every choice made based on the constraints specific to each place of consumption and integrates all these elements to provide the best solution for the small industrial consumer. Modern consumption monitoring systems based on both classical and intelligent electronic meters are analyzed in turn and then these are extended with reliable solutions to compensate the power factor as well as to dampen the effects of harmonics.

The main contributions of the thesis are in the methodology of interconnection of the monitoring and consumption elements that led to the realization of an installation in three constructive solutions:

- Solution no.1 - Functions for measuring the parameters of the electricity consumed by a small consumer of industrial type, using a three-phase smart meter. Possible local commands to the equipment in the technological chain, data transmission to the dispatching point that ensures data management and optimization of consumption in real time are ensured;
- Solution no.2 – includes the equipment specific to solution no.1 to which is attached a module that ensures the fulfillment of the quality parameters of the electricity regarding the power factor and the elimination of the harmonics from the waveforms of the currents and electrical voltages;
- Solution no.3 – includes the equipment specific to the constructive solution no.2 together with equipment that ensures the introduction on request, following the optimization process, of the energy coming from the renewable sources of the respective consumer.

In addition to the developed hardware solution, the functionality of the entire system has been completed with the development of a database that stores both real-time measured values and offline processed values. The software solution was extended with the development of a client-server communication network and a LabVIEW application for processing and displaying the recorded data.

The validation of the hardware solutions and of the realized software elements was achieved by direct comparison of the results with the measured quantities in a test sequence that complies with the provisions of cenelec norm - EN 50160. The tests were performed both at the subassembly level and at the level of the entire system by thermography during operation.

Personal contributions

Personal contributions materialized in three important directions:

- **Conceptual:** studying the main techniques for monitoring and optimizing energy consumption for a small industrial consumer in the context of smart grids;
- **Experimental:** realization of an installation in three constructive variants with a wide spectrum of applicability;
- **Technology:** interconnection of several different technologies and creation of the software solution to harmonize the functionality

The following desiderata have been pursued and realized, which are also the original contributions in the field:

1. Elaboration of an extensive study, based on the completion of an important number of current bibliographic references, regarding the current technologies that ensure the operations of measuring the parameters specific to electricity, their tracking in real time and the temporal optimization at industrial consumers.
2. Elaboration of a study on the main techniques for compensating the power factor and improving the effects of harmonics in waveforms.
3. Study and presentation of the main characteristics of relational databases.
4. Design and realization of a smart installation, in three constructive variants, designed to measure and monitor the electrical quantities specific to the consumer's network, as well as to optimize consumption and introduce electricity from renewable resources.

5. Creation of relational databases for storage of measured sizes and offline processing quantities.
6. Development of software solutions for recording and transmitting measured quantities.
7. Development of software components for processing and displaying measurement sizes using labview environment.
8. Develop a client server architecture for measuring and transmitting data.
9. Development of a subassembly testing methodology for each variant of the pilot plant.
10. Development of a methodology for testing the entire facility.

Future directions of research

Given the complexity of the system developed for the future, I proposed to extend the offline processing software solution with a statistical processing module that would display elements that characterize the measured values over 24 hours and the improvement of the information security elements regarding the transmission and reception of data.

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ANNEX 1 – Pilot wiring diagrams

ANNEX 2 – Database testing report