

Original scientific paper /Izvorni naučni rad

DESIGN, DEVELOPMENT AND IMPLEMENTATION OF A DISTRIBUTED MEASUREMENT SYSTEM FOR NO-LOAD PRESSURE MEASUREMENT IN HIGH VOLTAGE CIRCUIT BREAKERS

DIZAJN, RAZVOJ I IMPLEMENTACIJA DISTRIBUIRANOG MJERNOG SISTEMA ZA MJERENJE PRITISKA U VISOKONAPONSKIM PREKIDAČIMA TOKOM NO-LOAD OPERACIJA

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Abstract: This paper presents the design and development of a distributed measurement system for measuring pressure in high voltage circuit breakers (HV CB) and other switching apparatuses, during no-load operations. Instead of using traditional pressure transducers which require significant installation space, additional data acquisition cards and often demand for complex wiring, an in-house solution of pressure measurement is proposed. The system consists of miniature sensors, accompanied with a suitable amplifier, microcontroller unit and communication module, which may be distributed inside the interrupter unit in convenient locations. Due to the fact that the measurement values are transmitted digitally, measurement noise is significantly reduced while the wiring of the system is additionally simplified. The proposed measurement system is tested using two different interrupters (HV CB and a load break switch). The experimental results have demonstrated that the developed system is applicable, accurate, cost-effective, flexible and simple to use.

Keywords: distributed measurement system, pressure measurement, microcontroller, communication, high voltage circuit breaker

Sažetak: U ovome radu predstavljen je dizajn i razvoj distribuiranog mjernog sistema za mjerenje pritiska u visokonaponskim prekidačima i drugim sklopnim aparatima tokom no-load operacija. Umjesto korištenja tradicionalnih pretvarača pritiska koji zahtijevaju značajan prostor za instalaciju, dodatne akviziciono-mjerne kartice i često zahtijevaju kompleksnija ožičenja, predloženo je korištenje vlastitog sistema za mjerenje pritiska. Sistem se sastoji od minijaturnih senzora, odgovarajućeg pojačala, mikrokontrolerske jedinice i komunikacijskih modula koji mogu obiti raspoređeni na pogodan način unutar komora sklopnog elementa. S obzirom da se mjerene vrijednosti prenose u digitalnoj formi, mjerni šum je značajno umanjen, a ožičavanje kompletnog sistema je značajno pojednostavljeno. Mjerni sistem je testiran na dva različita sklopna elementa (visokonaponski prekidač i srednjenaponska sklopka). Eksperimentalni rezultati su pokazali da je razvijeni sistem primjenjiv, tačan, jeftin, fleksibilan i jednostavan za korištenje.

Ključne riječi: distribuirani mjerni sistem, mjerenje pritiska, mikrokontroler, komunikacija, visokonaponski prekidač

INTRODUCTION

Over the past years, the design process of high-voltage (HV) circuit breakers (CB) has become unthinkable without computer simulations [1]. The simulations are based on different mathematical models, which describe physical processes inside CB interrupter

chambers. Although the models can be of different complexity, most of them provide flexibility in terms of design parameter changes and analysis of influence on different physical quantities. This leads to fewer necessary development tests and therefore significant cost reduction. In order to simulate opening/closing operations of a CB, many physical input parameters are required. Some of them can only be determined in an empirical way, by combining simulations, experiments and measurements on real CB. Such measurements are also used in the design and optimization process of HV CB [2].

Experiments based on no-load operations often suffice for specific HV CB analysis. Thus, for experimental analysis,

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Paper submitted: October 2019 Paper accepted: November 2019

real prototypes can be replaced with more cost-effective models of CB, which still adequately represent the actual HV CB [2]-[4]. In addition, measuring physical quantities, such as pressure, during no-load operations is much simpler than during on-load. By using a custom designed measurement system [4], simultaneous measurements of contacts travel, coil current, oscillations of elements in the kinematic chain and pressure measurements in chambers of the interrupter unit can be conducted.

Currently, there is an increased interest in development of SF₆-free high voltage substations with CO₂ and CO₂ based mixtures [5]-[7], as per Kyoto Protocol of 1997 in order to reduce SF₆ emissions. The analysis of the gas flow and pressure changes inside specific volumes of the interrupter unit (HV CB or load break switch) during and after the arc quenching process is of upmost importance for the constructors of these devices, both for SF₆ and SF₆ alternatives.

Dynamical changes of pressure are of special importance at some typical locations inside the interrupter unit of HV CB, such as [8]: inside the compression chamber (CC), inside the heating chamber (HC), the chambers used for cooling the gas and along the nozzle, as illustrated in Figure 1. In one of the previous papers [9], the authors have introduced a pressure transducer for pressure measurement inside HV circuit breaker model, developed exclusively for no-load operation. The pressure transducers were designed and manufactured in collaboration with EnergoBos ILJIN d.o.o., Faculty of Mechanical Engineering and Faculty of Electrical Engineering Sarajevo. The transducers were embedded in the existing measurement system [4] for the HV CB model installed in "EnergoBos laboratory for experimental testing on models and prototypes of high-voltage SF₆ circuit breakers". The carried out tests have confirmed that the developed transducers,

in spite of their cost-efficiency and simplicity, still satisfy the technical requirements.

Some of the drawbacks of the implemented system were identified as part of the future work [9], namely:

- the existing dead-zone of the sensor measurement should be reduced, in order to measure pressure under 1.4 [bar] absolute,
- measurement noise should be reduced,
- investigate the possibility to embed the in HV CB model components e.g. in a HV CB nozzle, which would require additional reduction of transducer dimension,
- reduce a number of wires inside the HV CB model.

In this paper, the aforementioned issues have been addressed. Firstly, the dimensions of the sensors have been reduced so that they may be installed in the HV CB nozzle. According to the authors' best knowledge, there are not many papers [8]-[10] dealing with the pressure measurement along the nozzle. Secondly, a unique distributed measurement system has been proposed and developed. In the current setup, the transducers do not require a data acquisition card (DAQ), but each sensor has its own small DAQ system as part of the accompanying microcontroller unit. Therefore, the number of wires is reduced due to the fact that now each sensor system is connected to the 2-wire communication bus. Lastly, the amplifier design is modified in a way that both the dead zone and of the amplifier measurement noise are reduced.

The paper is structured as follows. The first section presents the proposed distributed design system. The experimental results and the introduced improvements are discussed in the second section. Conclusion and guidelines for future work are given in the last section.

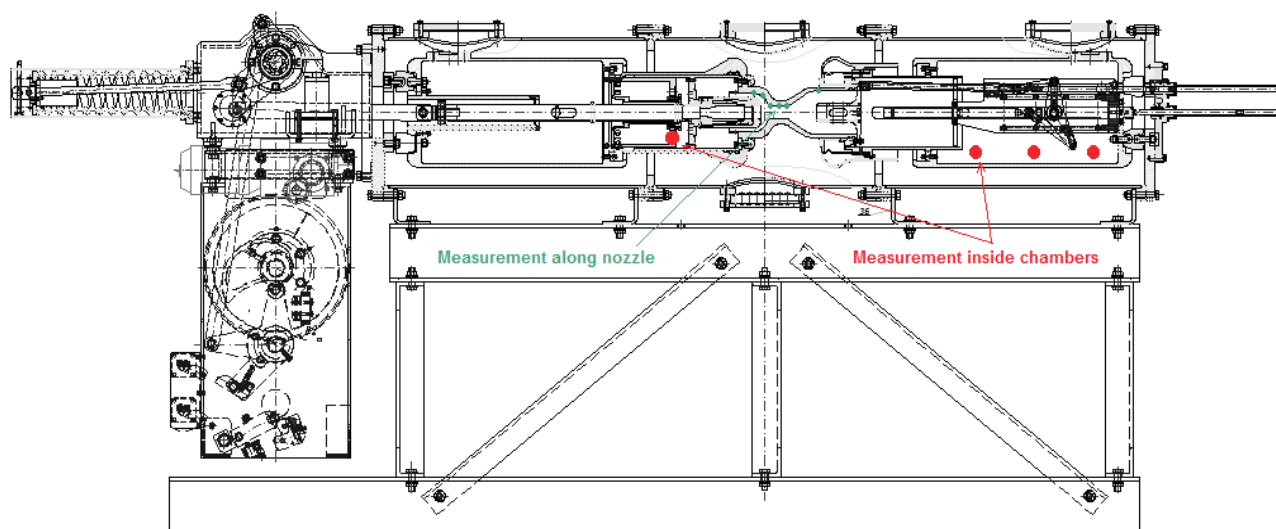


Figure 1: Pressure measurement in the HV CB model - previous measurements [9] were conducted inside Compression and Heating Chamber (CC and HC), marked with red dots. Current measurements require installing pressure sensors within a limited space (along the nozzle), marked with green dots.

1. PROPOSED SOLUTION

1.1. Analog pressure transducer

In one of our previous paper [9] we have proposed the analog transducer for pressure measurement in HV CB. This transducer had the following properties:

- pressure range 0-20 [bar] range (absolute),
- ability to operate in vacuum (with sustained load),
- short response time (<4 [bar/ms]),
- accuracy better than 0.05-0.1 [bar],
- medium: air/SF6 gas,
- working temperature up to 50 °C,
- cost-effective solution,
- ability of installation and operation of the transducer inside the HV CB model with permanent operating pressure of 7 [bar].

The response time and cost-effectiveness were stressed out as the most important factors by the investor. The measurement range 0-20 [bar] was not mandatory since the expected measurements were inside the 5-12 [bar] range. However, it was important for the transducer to be capable to withstand vacuum as well as higher pressures, which occur either during the filling of the model with SF6 gas or in normal operation. In addition, unlike most commercial solutions, the transducer should be able to measure pressure even in scenarios when its housing is inside the HV CB model (or other switching apparatus), which means it is under measuring pressure as well.

The miniature resistive bridge based pressure sensor Smartec SPD300ABto05 [11] was chosen as the main element of the developed pressure transducer. This sensor property (measurement relative to an inside vacuum chamber) allows to design a pressure transducer which may withstand non-atmospheric pressure and vacuum.

Integrated industrial voltage amplifier Analog Microelectronics AM401 [12] was used for amplifying small voltage signals from the bridge. Figure 2 provides the designed electronic schematic. The whole sensor and printed circuit board (PCB) are enclosed into M16 and M20 screws. The corresponding technical drawings and 3D models are shown in Figure 3.

The sensors were calibrated, tested, installed and used for pressure measurement inside HV CB model in EnergoBos laboratory. More details about the implementation and experimental results can be found in our previous paper [9].

One of the challenges of the implemented system [9] was how to transfer electrical signals and lay the wires inside the pressurized HV CB model. Each transducer required at least three wires (GND, VCC and VOUT), thus, for example 5 transducers require 15 wires, or at least 7 wires if VCC and GND signals are common for all sensors. Another challenge was that the designed transducer (although rather small) is too large to install along the HV CB nozzle. To this end, we proposed a novel distributed measurement system, which will be explained within the next section.

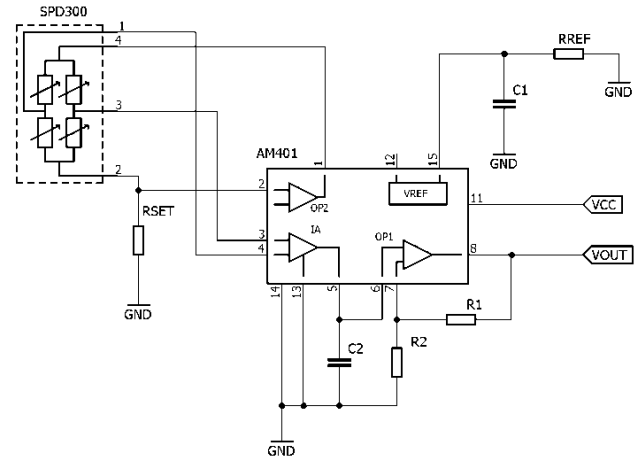


Figure 2: Schematic of the previously proposed analog pressure transducer. [9]

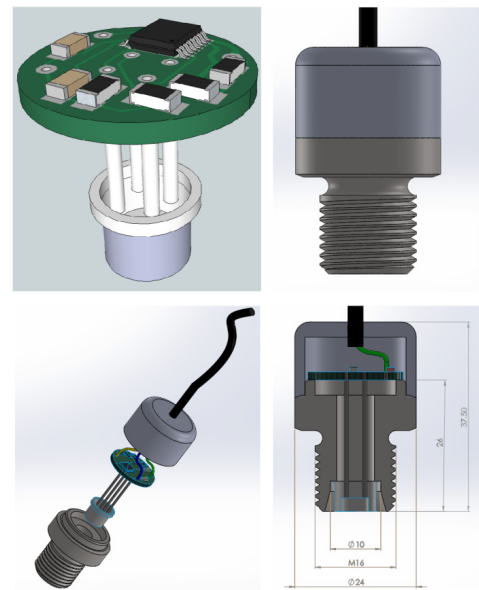


Figure 3: Cross-section and 3D model of the previously proposed pressure transducer. [9]

1.2. Distributed measurement system

Due to the fact that the chosen sensor SPD300ABto05 [11] is relatively small (around 10mm in diameter) it can be easily installed into HV CB nozzle. Unfortunately, the voltage generated on the powered resistance bridge is only a few millivolts, therefore it is impossible to transfer these electrical signals by more than a few centimeters without inducing a significant amount of measurement noise. This means that the amplifier needs to be as close to the sensor as possible. The standard filtering methods (either hardware or software) are challenging to implement because the dynamic response of the transducer is equally important. Common software-based or hardware-based filtering, for example using digital or analog low-pass filters, is unacceptable due to the fact that the actual pressure measurement dynamics has to be preserved and should not be affected by filtering methods.

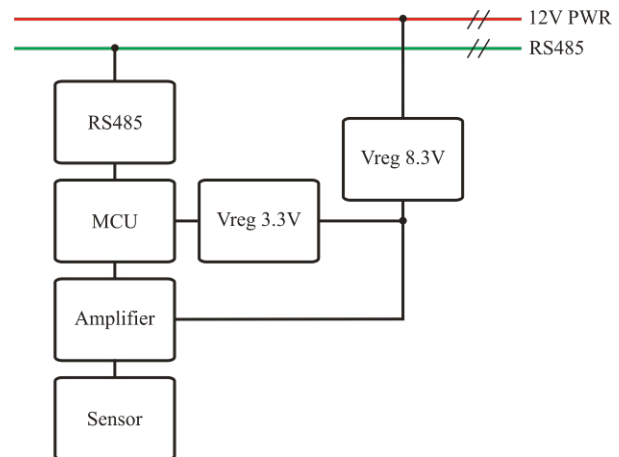
The best way to acquire and transmit the pressure measurement signal without noise is to convert the analog signal to a digital value. This means that the sensor should be close to the amplifier and the analog-to-digital (AD) converter at the same time. Having this in mind, as well as the dimensional constraints of the interrupter unit, we proposed and designed a device named DSP-Box. A DSP-Box is a small interface between the sensor on one side and a personal computer (PC) on the other side of the communication channel. The DSP-Box architecture is presented in Figure 4.a). It is essentially based on a microcontroller (MCU) and a communication module. The MCU acts like a miniature data acquisition (DAQ) device, which samples and converts the analog data into digital, communicates with the PC and transfers the acquired data.

The fact that the sensors should be able to measure the pressure using 10 kHz sampling frequency, would imply significant communication bandwidth to transfer all the samples in real time. For example, 10.000 16-bit samples per second (ksp/s), for 5 sensors connected on the same communication bus, would require a bandwidth of at least 800 kb/s. Additional sensors require bandwidth of a few Mb/s. However, for applications such as measuring pressure during opening/closing operation of the HV CB model or load break switch, the operations never last more than one second. Therefore the acquired data does not need to be transmitted immediately, but could be saved locally in MCU RAM memory, and transmitted to the PC when needed. This implies that a slower and more robust communication protocol could be used, but the MCU should be able to locally save the temporary measurement data.

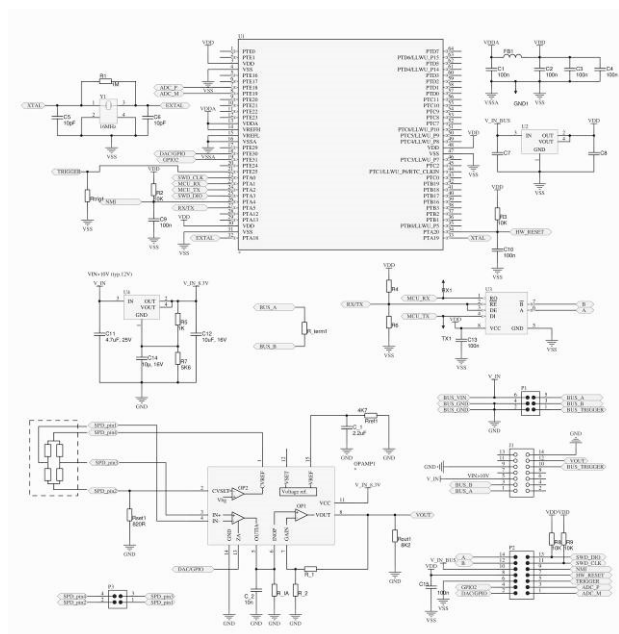
As for the MCU, NXP ARM Cortex-M0+ based MKL17Z-256VLH4 was chosen [13]. It has 32KB of RAM memory, which allows storing 16.000 of 16-bit analog samples. Since one part of RAM should be free for normal operation of the MCU, only 20KB of RAM is reserved for immediate storage of 10.000 two-byte samples. The MCU has an embedded 16-bit AD converter (max sampling frequency 818 ksp/s), 12-bit DA converter, and a (low power) UART communication module.

RS485 was chosen as the communication interface. It is widely used in industrial applications for its robustness in presence of noise, and it is simple to implement on a number of platforms, ranging from small MCUs to PC. [14]

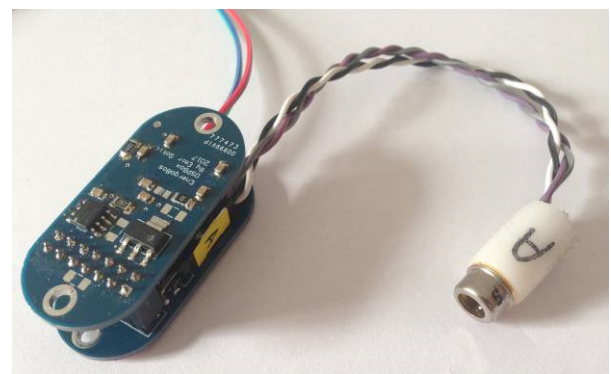
In order to unify the power supply rails, and reduce the power supply noise, each of the DSP-Boxes is equipped with voltage regulators, providing 3.3V for the MCU and communication module, and 8.3V for pressure transducer amplifier. The architecture of the DSP-Box is illustrated in Figure 4.a), the complete schematic is shown in Figure 4.b), while the actual physical implementation is given in Figure 4.c).



a)



b)



c)

Figure 4: DSP-Box: a) architecture, b) schematic, c) physical implementation

1.3. Control module

One of the most important challenges in the design of such distributed measurement system was to synchronize all the DSP-Boxes. The first obstacle was that the quartz crystal which is commonly used for providing system ticks for the MCUs cannot be used in pressurized chambers (such as HV CB). Moreover, due to imperfections of the crystals and relatively high operating frequency of the MCU (48 MHz), multiple systems could operate in slightly different time and the measurements would not be perfectly synchronized, even under atmospheric pressure.

One of the options was to use the internal RC clock of the MCU, but this clock source is not reliable for accurate operation [13]. Accurate sampling time is important for acquiring the analog measurements using the desired 10 kHz sampling rate. If an external reference clock was used, it would have been required to increase the number of wires for connecting the system.

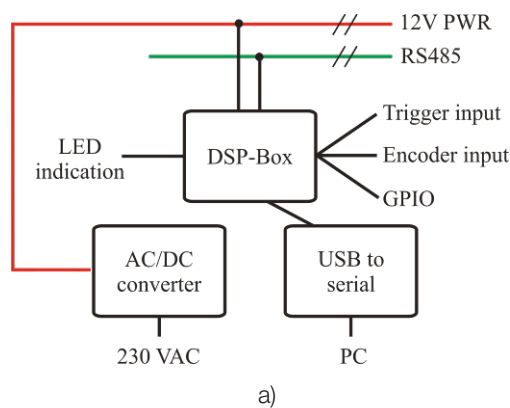


Figure 5: Control module: a) architecture, b) physical implementation

To this end, we propose the use of RS485 communication lines both for generating the ticks for the AD conversion, as well as for the communication and transfer of the measurement data. Unfortunately, the measurement system is planned to be used mostly on Windows operating machines, therefore accurate real-time acquisition

with PC generated ticks could not be used. The solution was to reconfigure one of the DSP-Boxes to be a master, crystal-driven tick generator, called Control Module (CM). The CM is used to generate synchronization ticks to the DSP-Boxes on the communication lines, and actually represents a differently configured and programmed DSP-Box. The simplified structure of the Control Module is depicted in Figure 5.a). In addition to the DSP-Box, with dedicated inputs/outputs for external components, it contains an AC/DC converter and an USB to TTL serial converter. The actual physical implementation of the CM is shown in Figure 5.b).

The complete architecture of the distributed measurement system is presented in Figure 6. It consists of the PC, a Control Module, and multiple DSP-Boxes distributed on a communication and power supply bus.

As all the other DSP-Boxes, the Control Module can be conveniently used for the configuration of the acquisition parameters of the system, and for interacting with external signals (trigger inputs, encoders etc.).

The software structure of the DSP-Boxes and Control Module will be explained in the next section.

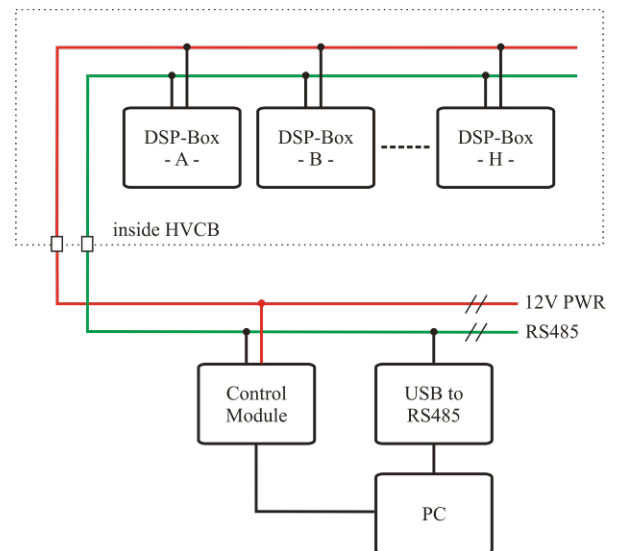


Figure 6: Complete distributed measurement system architecture

1.4. Software implementation

The operation of the system consists of three parts:

- application on the DSP-Boxes,
- application on the Control Module,
- application on the PC.

Each of aforementioned applications will be briefly explained.

The application on the DSP-Boxes consists of the following core parts: configuration of the input/output pins, communication interface, AD and DA converters. A single character unique address is assigned to each of the DSP-Boxes (from A to H). Each of the DSP-Boxes listens the communication bus and, if it is addressed, it interprets the command and provide a suitable reaction. There are few commands that a DSP-Box understands: unlock, prepare for acquisition, acquire, send the data from the buffer. Each of the DSP-Boxes after power-up waits for its configuration, namely how many samples it is supposed to acquire. Then, it waits for the signal to prepare for the acquisition, after which it waits for character-ticks on the communication bus. Each tick starts an AD conversion and the result is stored in internal RAM memory of the MCU. After a desired number of samples is acquired, the DSP-Box stops acquiring new samples, and waits for the master to query for the acquired data. To prevent accidental reaction of other DSP-Boxes during measurement data transfer, each of the DSP-Boxes need to be “unlocked” by a unique sequence of 10 characters before it starts interpreting the command. Address Z represents a broadcast address, and all DSP-Boxes will react to it. This address, however, should be only used to start the acquisition on all DSP-Boxes simultaneously.

The Control Module is programmed mostly using timer interrupt routines to guarantee accurate real-time performance. It receives the input commands from the PC regarding the operating mode (number of samples ranging from 1 to 10.000, and sampling frequency ranging from 1 Hz to 10.000 Hz). Then it waits for the “prepare” signal from the PC. After the “prepare” signal is received, everything is ready for acquisition. Acquisition starts after an external interrupt signal is set - it could be the trip coil voltage signal, or pressing a pushbutton, depending if the measurements needs to be synchronized with another process or not. During the acquisition, the Control Module sends a character on the communication bus each $T=1/f_s=100\text{ }\mu\text{s}$ (in case of $f_s=10\text{ kHz}$ sampling), which is used to synchronize the acquisition on all DSP-Boxes. In addition, the Control Module may be used to acquire other measurement signals simultaneously, such as encoder measurements.

The PC application is used to coordinate the measurements between the operator, Control Module, and DSP-Boxes. Its graphical user interface is shown in Figure 7. It is used for configuring the communication with the CM and DSP-Boxes, using RS485 (baud rate 500ksp/s), configures the CM and DSP-Boxes (sample rate and number of samples), triggers the acquisition, and retrieves measurement results. Each measurement result is stored in a file with date and time stamp, and it is convenient for additional visualization and processing. Moreover, the measurement files are compatible with HV CB Simulation software [15].

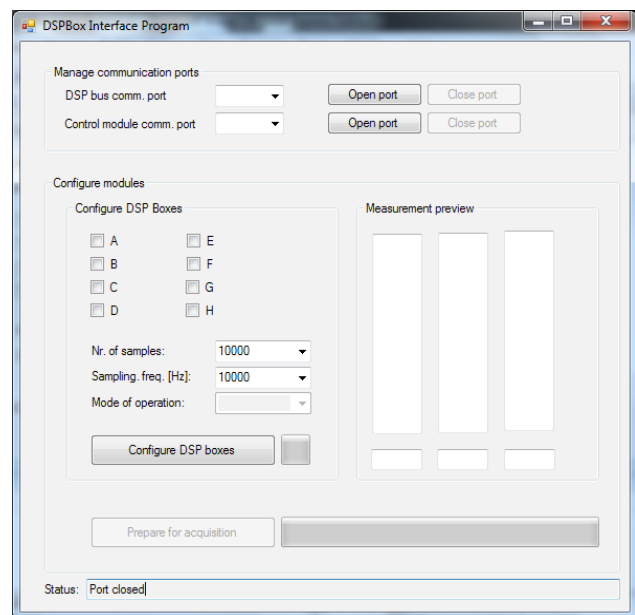


Figure 7: PC application GUI

2. EXPERIMENTAL RESULTS

2.1. Experimental setup nr.1

All the sensors were calibrated and tested using similar procedure as shown in [9]. Afterwards, six sensors were embedded within the HV CB model nozzle in EnergoBos Laboratory (Figure 8.a)). They were distributed alongside the nozzle as shown in Figure 8.b).

Unfortunately, due to a bad mechanical connections, three of the sensors were damaged during first operation of HV CB model, thus Figure 8.c) shows only the captured pressure measurements of sensors E, D and G during opening operation in no-load condition. Taking into the consideration that the main topic of this paper is the distributed measurement system, and is not the analysis of pressure measurement, all the pressure measurements will not be presented. After repairing and reinstalling the sensors, a more elaborate discussion on the actual measurement result on pressure measurement alongside the HV CB nozzle will be provided, as part of our future papers.

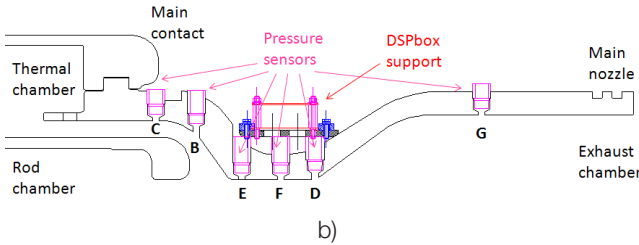
Figure 8.c) shows that the distributed measurement system operated as expected. Although the measurements are clearly readable due to the fact that pressure fluctuations are large (a quarter of the measurement range), a close inspection of the diagram reveals that the noise level is not insignificant (± 20 [mbar]).

2.2. Experimental setup nr.2

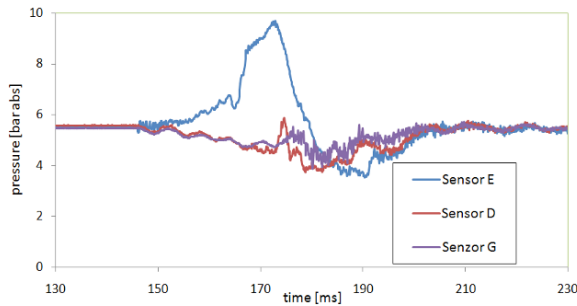
EnergoBos Laboratory required pressure measurements inside chambers of a different switching apparatus. The analysis and modelling of pressure variation of air, instead of normally used SF₆, inside the load break switch was needed. The load break switch and the measurement configuration are illustrated in Figure 9.



a)



b)



c)

Figure 8: Sensor installation along HV CB nozzle a) mounting, b) pressure sensor positions, c) measurement results

It is important to notice that in this setup, the DSP-Boxes are mounted at the exterior of the mechanical system and do not endure higher pressure. However, a few modifications were required for DSP-Boxes:

- the dead-zone should be minimized because in this setup sensors need to measure pressures lower than 1 [bar] absolute,
- the measuring pressure range should be reduced to 0-4 [bar] absolute,
- the noise should be reduced as much as possible.

The dead zone is eliminated by adding a voltage drift to the operational amplifier, as shown in Figure 4.b). A small, low-impedance reference voltage (approx. 300mV) needed to be introduced to the pin ZA (zero-adjustment) of the AM401. The best approach was to use the existing digital to analog converter (DA) on the MCU to generate the required voltage.

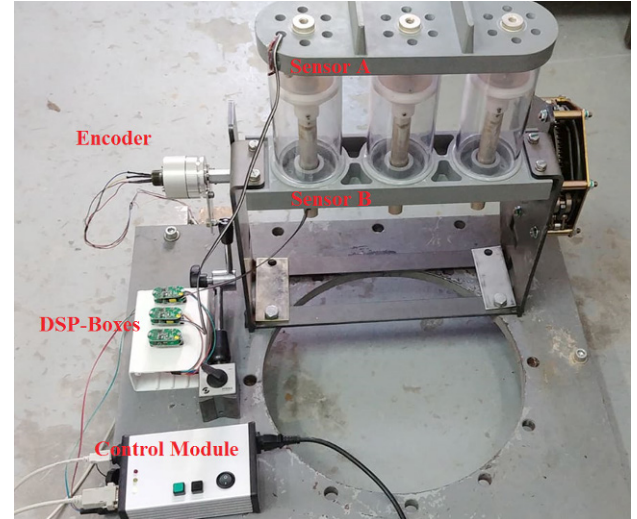
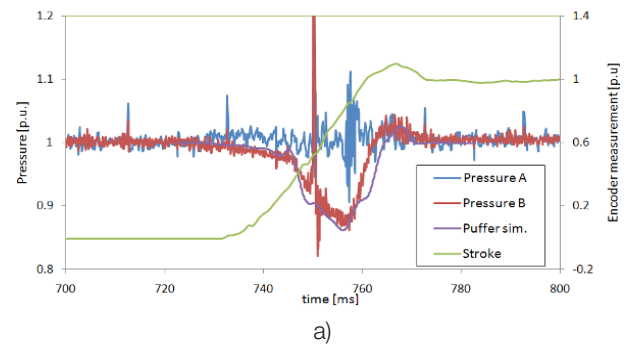


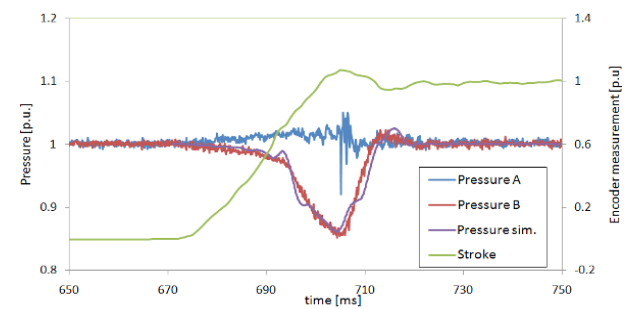
Figure 9: Distributed measurement system installed on load break switch (courtesy of G&W Electric)

The pressure range was easily modified by changing the values of the resistors R_1 and R_2 (Figure 4.b)), which determine the amplification of the signal at the second amplifier stage.

Due to the fact that the amplification is increased, the noise was amplified as well. In order to reduce the noise, several approaches were tested, implemented and analyzed. The effects are discussed in Table I. After addressing all the improvements given in Table I, the noise is significantly reduced, as it can be seen comparing Figure 10.a) and Figure 10.b). The SNR is significantly increased so the noise is within the ± 5 [mbar] range, which is satisfactory for this type of measurement.



a)



b)

Figure 10: Pressure measurement a) before, b) after reducing measurement noise

Table I: Effects of different actions to measurement noise reduction

Action	Effect
Using 12V battery supply instead of switching power supply	Extremely significant
Shortening up wires from sensors to amplifiers	Low
Shielding wires from sensors to amplifiers	Moderate
Separately twisting up signal and power supply wires from sensors to amplifiers	Moderate
Adding additional capacitors to power supply lines (MCU and amplifier)	Significant
Replacing a ferrite bead between Vcc and Vref lines	Low
Lowering resistance at output of first amplifier stage	Extremely significant

The results in Figure 10 illustrate the pressure changes inside the chambers of the load break switch shown in Figure 9 during the closing operation. Due to the fact that the actual pressure measurements for the load break switch (in Figure 9) are confidential, pressure and encoder measurement are presented in normalized values.

The simulation conducted in HV CB Simulation [15] for the load break switch shows very good concurrence of simulation and measurement. Small disparity noticeable in Figure 10 can be attributed to small error in travel measurement. Namely, the travel/velocity measurements are not perfectly accurate, thus the pressure computations have induced errors.

3. CONCLUSION AND GUIDELINES FOR FUTURE WORK

The paper presented the procedure of the design, development, testing and implementation of a distributed measurement system for pressure measurement, specifically developed for pressure measurements inside HV CB model chambers and alongside nozzle in no-load operations. We have improved one of our previous designs [9] by reducing the number of wires, dimensions of the sensors, the induced noise, removing the dead-zone. In addition, the proposed measurement system can be considered standalone, because it does not require additional DAQ cards.

The experimental results have demonstrated that the developed system is cost-effective, miniature, flexible and simple to use. Nevertheless, due to the fact that every sensor and amplifier has different characteristics each transducer must be treated separately, which could pose a problem when there is a need for production of large

number of transducers. In addition, the research laboratory must provide at least the minimum requirements for production, calibration and testing of such sensors.

As a part of the future work, we plan to develop a semiautomatic calibration system which would enable automatic sensor calibration using existing pressure references, and further investigate temperature effects. Although the transducers operate mostly on room temperature, it is not yet clear whether the temperature variation will significantly affect transducer measurements. Moreover, we plan to use the distributed system to analyze the pressure fluctuation along the nozzle during no-load operation of an HV CB model, using different gases (SF₆, CO₂ etc.).

Due to the fact that the DSP-Boxes are a versatile solution, they can be easily configured to measure other physical quantities using different sensors. Thus, as part of our future research, we plan to measure mechanical strains of HV CB model parts using strain gauges, as well as try to use pressure sensors with higher sensitivity.

ACKNOWLEDGEMENTS

The research presented in this paper is partially funded by the Ministry of Civil Affairs Bosnia and Herzegovina as support for H2020 project preparation "Envi-Break – Alternative Concepts for Environmentally Compatible Gas Circuit Breakers".

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BIOGRAPHY

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