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DATA ACQUISITION AND SIMULATION SOFTWARE AS TOOLS FOR MEDIUM VOLTAGE SWITCHGEAR ASSESSMENT AND OPTIMIZATION

MJERNO AKVIZICIONI SISTEMI I SIMULACIONI SOFTVER KAO ALATI ZA PROCJENU I OPTIMIZACIJU SREDNJENAPONSKE SKLOPNE TEHNIKE

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Abstract: This paper describes the advantages of using data acquisition systems and software modelling tools to support the assessment and therefore redesign of the existing medium voltage switchgear. A 38kV/630A load break linear puffer (LP) will be used as an example for this study. In house testing was conducted to capture important design parameters of the switch such as displacement, velocity of mechanical parts and gas pressure using various sensors and three different measurement setups. The first setup, which is primarily intended for no-load measurements, consists of a DAQ system equipped with different types of sensors - two rotational encoders, three laser-based distance sensors, six pressure sensors, contact separation measurement, and a high-speed camera integrated and synchronized with the measurement system. The second and third setups, which are suitable both for no-load and on-load measurements, are based on state-of-the-art DAQ systems, which use three piezo-electric based pressure sensors, two fibre-optic based pressure sensors, three laser-based distance sensors and a high speed camera synchronized with the measurement system. The data acquired by the measurement systems is used in combination with an in-house developed simulation software HV CB Simulation, which enables simulating and predicting various variables of switching devices. Moreover, high speed camera videos analysed with both commercial and in-house developed image processing software, visualize and reveal many otherwise inaccessible occurrences. In addition to a comprehensive analysis of the proposed data acquisition and simulation setups, three design improvements in the linear puffer design - increase of the opening speed, removal of the flexible conductors and the length increase of the puffer cylinder - are presented and discussed in this paper.

Keywords: load break switch, DAQ systems, simulation and modelling tools, image/video processing

Sažetak: Ovaj rad opisuje prednosti korištenja mjerno akvizicionih sistema i softverskih simulacionih alata u svrhu procjene te redizajna srednjenaponske sklopke. Kao primjer će biti korištena postojeća 38kV/630A sklopka - sa tzv. linearni pufferom (LP). Kako bi se procijenili važni parametri sklopke kao što su kretanje određenih mehaničkih dijelova, njihova brzina ili odgovarajući pritisci, korišteni su namjenski razvijeni softverski alati i tri različita mjerna sistema. Prvi mjerni sistem, primarno namijenjen za beznaponska ispitivanja, opremljen je sa različitim tipovima senzora - dva rotaciona enkodera, tri laserska mjerača udaljenosti, šest senzora pritiska, sistemom za mjerenje razdvajanja kontakata te brzom kamerom integrisanom i sinhroniziranom sa mjernim sistemom. Drugi i treći mjerni sistem, koji su pogodni za mjerenja pritiska i hodograma čak i u laboratorijama velike snage, sastoje se od modernih akvizicionih sistema koji su opremljeni sa tri piezo-električna senzora pritiska, dva fiber-optička senzora pritiska, tri laserska senzora udaljenosti i brze kamere posljednje generacije sinhronizirane sa mjernim sistemom. Podaci prikupljeni mjernim sistemima se kombiniraju sa namjenski razvijenim simulacionim softverom za simulaciju SN/VN prekidača HV CB Simulation koji omogućava simulaciju i predviđanje mnogih važnih varijabli sklopnih aparata. Također, video zapisi prikupljeni brzim kamerama i analizirani komercijalnim kao i namjenski razvijenim softverima za obradu slike otkrivaju i mnoge fenomene koji inače nisu uočljivi. Osim detaljne analize korištenih mjernih sistema i simulacionih alata koji potpomažu redizajniranje sklopke, u radu su predstavljena i diskutovana tri unapređenja u dizajnu linearnog puffera - povećanje brzine isklopa, uklanjanje fleksibilnih provodnika i produženje puffer cilindra - koja su detektovana i verifikovana korištenjem opisanih mjernih i simulacionih alata.

Ključne riječi: sklopka, prekidač, akviziciono-mjerni sistemi, alati za simulaciju i modeliranje, obrada slike/videa

INTRODUCTION

Load break switches (LBS) are widely used in distribution systems. They are typically operated in a voltage range of 6-38 kV and designed to interrupt currents from a few hundreds of amps to 1kA. LBS are often combined with fuses (fused ways), being an inexpensive and reliable solution for switching applications and providing a high degree of flexibility to the grid.

Several switching technologies exist in medium voltage (MV) switchgears to extinguish the arc, namely, vacuum interrupter (VI), rotating arc and puffer type [2].

A linear puffer (LP) interrupter (Figure 1) typically consists of a compression chamber and an interruption chamber [3]. The

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puffer unit is connected to a spring-loaded mechanism that drives down the piston during opening. The piston movement compresses the SF_6 gas in the compression chamber while the nozzle and tulip guide the flow toward the interruption chamber. Both the acceleration of SF_6 gas through the nozzle and the capability of the gas to quickly restore its insulation level after switching result in a successful arc extinguishing, avoiding thermal and dielectric breakdowns [3].

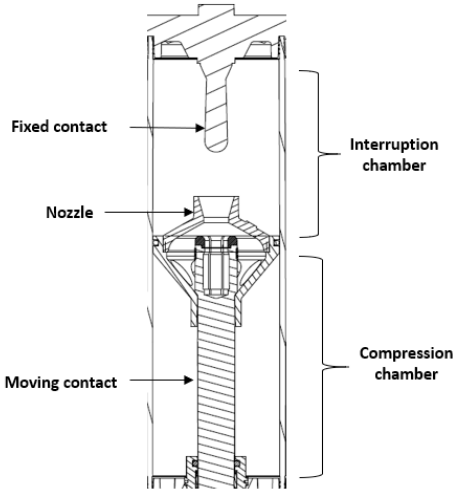


Figure 1: Schematic of the linear puffer switch.



Figure 2: Linear Puffer load break switch 38kV 630A

In order to increase the performance of a LP module and increase its breaking capacity, it is important to create a higher pressure in the compression chamber; hence a stronger gas flow in the interruption chamber to blow the arc [5]. This high pressure can be created by increasing the energy of the mechanical system for higher speeds. Other parameters, such as nozzle profile, also help building pressure and improve arc quenching [5] [6].

In the process of MV switch redesign, it is important to fully assess the mechanical and electrical performance of the prototypes. Accurate measurements of contact rods travel (and consequently their speed and acceleration) and pressure variations during opening and closing operations of the switch are key parameters that need to be accurately measured and analysed for successful redesign iterations.

Over the last decades, high speed camera recordings have been used as a complement of these measurements, revealing or confirming many phenomena that are difficult to understand by observing only measured electrical signals.

In this paper, the on-load and no-load in-house developed measurement systems used to evaluate the current linear puffer load break switch will be described and discussed. The collected data for no-load case will be initially used to validate the analytical model of the linear puffer in the simulation software. The measurement data and simulation tools are used to pinpoint the possible improvements of the switch. Although the presented linear puffer needs to be significantly redesigned to achieve the required performance, this paper will present only three improvements - the increase in mechanism speed, the removal of the flexible conductors and the increase of puffer cylinder length, while other improvements and results from on-load testing will be published in future publications.

The paper is structured as follows. Section 1 describes the measurement systems used for analysis of the LP . In the second section, high speed camera and motion analysis software are discussed in more detail. The third section provides a brief insight into the in-house developed high voltage circuit breaker simulation tool (HV CB Simulation). Section 4 discusses the proposed improvements of the LP, verified by simulation and measurement data. Conclusion and guidelines for future work are given in the last section.

1. DAQ MEASUREMENT SYSTEMS

The process of testing, redesigning and verifying the aforementioned 38kV/630A linear puffer (LP) is conducted on multiple no-load testing sites - in-house G&W laboratory in Bolingbrook (USA) and EnergoBos laboratory in Sarajevo (Bosnia and Herzegovina), while the on-load testing is to be conducted in Kema HV Laboratory in Chalfont, USA. Different sites and applications require different measurement approaches, taking in consideration that some of the measurement systems need to be mobile, while other need to operate not only in no-load but in on-load conditions etc.

In certain setups, we have tested multiple types of sensors in order to see which one performs the best.

For that purpose, three measurement systems are implemented and used:

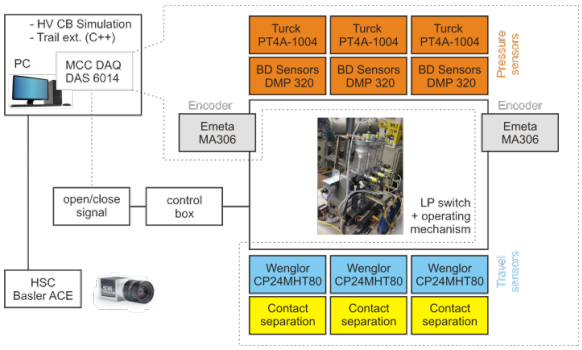
- **System No.1** - Measurement system in EnergoBos laboratory Sarajevo (Bosnia and Herzegovina). It is a stationary system, primarily designed for measurements and testing during no-load operations.
- **System No.2** - Measurement system in G&W laboratory Bolingbrook, USA. It is a portable system intended for no-load and on-load pressure measurement,

- **System No.3** - Measurement system in G&W laboratory Bolingbrook, USA. It is primarily intended for travel measurement and synchronization with high-speed camera.

All three systems will be explained in more detail in the following paragraphs.

The block diagram of the System No. 1 is shown in Figure 3.a), while its physical appearance is presented in Figure 3.b). This stationary system is based on two mature PCI-slot data acquisition cards, namely PCI-DAS6014 from Measurement Computing, which allow up to 16-bit 200kS/s on 16 analogue channels. In addition, each of the cards has 8 digital output/relay channels. This system has also been used for no-load testing of 420kV HV CB model of Iljin Electric, South Korea [7]. Two acquisition cards and completely separated systems allow simultaneous analysis and measurement on two different devices. One half of the data acquisition system, used for testing of LP is equipped with:

- 6 pressure sensors (piezoresistive 3x BD Sensors DMP320, 3x Turck PT4A-1004, all measuring 0-4 bar absolute, response time under 1ms),
- 3 laser-based distance sensors (3x Wenglor CP24M-HT80 40-160mm laser distance, 2kHz sampling rate),
- 2 heavy duty incremental rotational encoders (2x Emeta MA306, 3200 pulses per revolution),
- 3 contact separation signal measurement,
- high-speed camera synchronization signal,
- open/close signal for tripping the coil and operating the mechanism of the switch (using separate dedicated LP control box).



a)



b)

Figure 3: a) Block diagram of DAQ System No.1, b) Measurement system and tested LP device with installed sensors

System No.1 is primarily intended to be used for no-load analysis and prototype testing purposes. Its main advantage is that it is fully compatible with the HV CB Simulation software (more details in Section 3) hence it allows combining measurement and simulation data in real time. All channels are sampled with 10kHz sampling rate and the results are fully synchronized. One measurement example is shown in Figure 4.

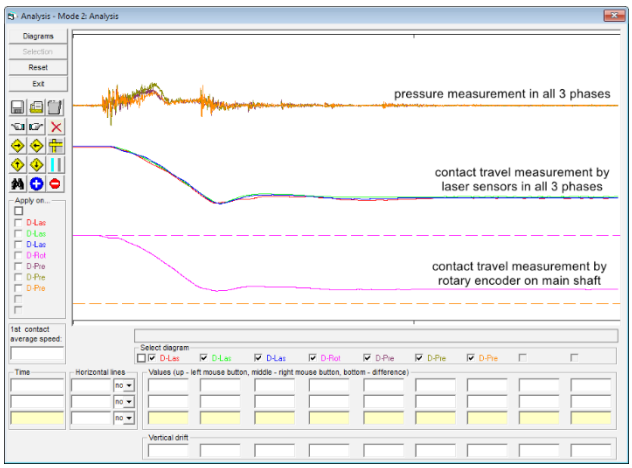
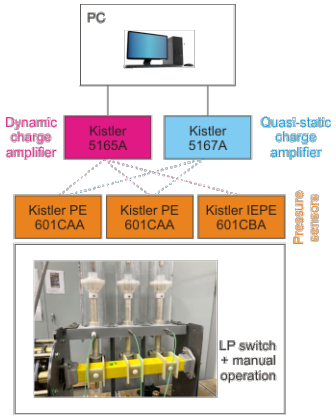


Figure 4: Example of measurement results on System No.1 achieved through HV CB Simulation

The block diagram of the System No. 2 is shown in Figure 5.a), while its physical appearance is presented in Figure 5.b). This system is primarily intended to be mobile and used for pressure measurement during on-load testing in HV laboratory with piezoelectric-based pressure sensors, which are known for their high temperature resistance (up to 700° C) and significant noise immunity, compared to the standard piezo-resistive counterparts.



a)



b)

Figure 5: a) Block diagram of DAQ System nr.2, b) actual system

Piezo-electric based pressure sensors from Kistler come in two variants - PE (such as 601CAA) which generate electrical charge and require a signal conditioner in order to be acquired (e.g. with a DAQ card and PC), or IEPE (such as 601CBA) which have their own integrated charge to voltage converter. Piezo-electric based pressure sensors may be interfaced using either a dynamic charge amplifier (e.g. 5165A) which is convenient for measuring dynamically changing pressure signals or quasi-static (5167A) which are used for measurement of relatively slow changing pressure signals. It is important to note that the choice of amplifier (dynamic or quasi-static) has to be made according to the bandwidth of the measured pressure signal. Although the spectrum analysis of the simulated pressure signal revealed that both of these amplifiers can be used, or in other words that bandwidth of the dynamic amplifier, especially in its lower part of the spectrum, is wide enough, we opted to test both amplifiers in no-load conditions. The experiments (Figure 6) prove that both types of amplifiers may be used for pressure measurement in the aforementioned HV LP.

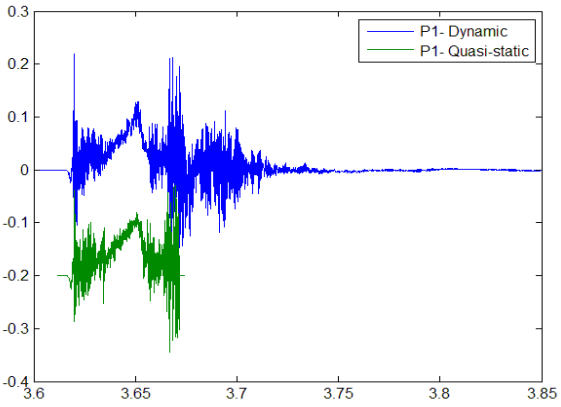
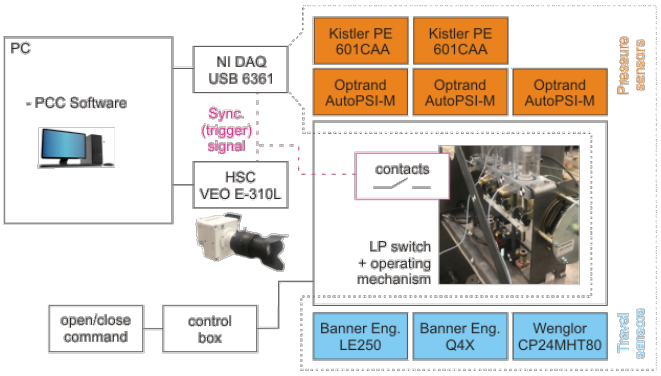
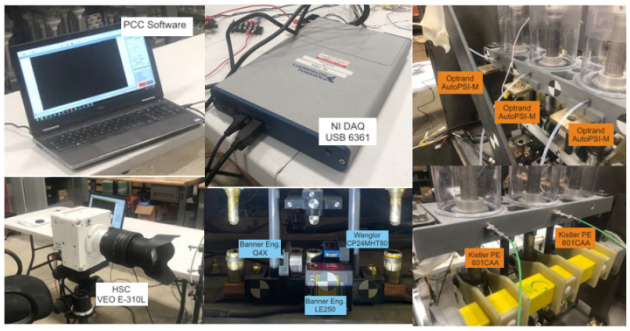


Figure 6: Measurement results on System No.2 - comparison of measurement using dynamic and quasistatic amplifier.

The block diagram of the System No. 3 is shown in Figure 7.a), while its physical appearance is presented in Figure 7.b). This system is based on a more modern National instruments USB 6361 which has 16 analogue channels, supporting up to 16-bit 2Ms/s sampling rate. This system is primarily intended to be used for testing of other types of pressure sensors (namely the on-demand developed Optrand AutoPSI-M), testing different types of laser-based distance sensors (Banner Engineering LE250 and Q4X - 310, and Wenglor CP24-80) and achieving strong synchronization with high speed camera. It is important to note that unlike Kistler piezo-electic based pressure sensors, Optrand sensors use modulated light for detecting deformations of pressure membrane, therefore by using fibre optic cables to transmit signals they offer superior electrical insulation. In addition they can sustain higher temperatures, which is very important for on-load testing in vicinity of electrical arc.



a)



b)

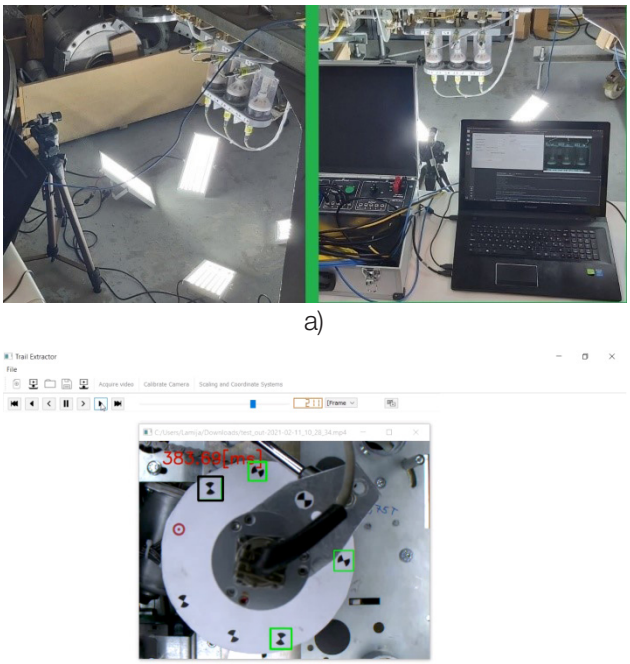
Figure 7: a) Block diagram of DAQ System nr.3, b) actual system

2. HIGH SPEED CAMERAS AND TRAVEL EXTRACTION

The main challenge when using displacement sensors and encoders for mechanical motion analysis of the switch is to accurately measure the movement of the part that is more than often difficult to reach deep inside the switch. In other cases, parts of interest are within visual range, but it is extremely difficult to mount the sensor to directly measure the desired movement. Therefore, the movement of the parts is usually recorded indirectly e.g. instead of measuring linear movement of the contact rod, angular In other cases, parts of interest are within visual range, but it is extremely difficult to mount the sensor to directly measure the desired movement. Therefore, the movement of the parts is usually recorded indirectly e.g. instead of measuring linear movement of the contact rod, angular movement of the operating mechanism needs to be acquired. When measuring the rotation of a driving shaft, torsion, bending and small gaps in the power train are inevitable, which induce measurement errors. Sometimes the parts even have combined movement (e.g. linear + rotational) and these measurement challenges are even more emphasized. This is where high-speed cameras are highly useful.

Two different approaches will be presented in the paper:

- analysis using a Basler Ace acA640-750uc high speed camera with in-house developed video acquisition and processing software, codename “Trail extractor” (Figure 8.a) and 8.b)),
- analysis using state-of-the-art high speed camera (Phantom VEO E-310L) in combination with a commercial video acquisition and processing software “TEMA” (Figure 9.a) and 9.b)).



a)

b)

Figure 8. a) Basler ace HSC measurement setup, b) in-house developed software for trajectory extraction

The HSC Basler Ace acA640-750uc can provide up to 751 FPS at a relatively low resolution (640x480) and small ISO, thus it requires a strong light source (up to 20.000 lm). Moreover, the camera itself does not have any internal memory hence it is limited by its USB/Ethernet connection to a PC and it may transfer only a limited number of video frames before its starts dropping them. At first glance it may seem like a significant drawback, but fortunately the MV/HV switch opening/closing operations usually last only few thousand frames which can be transferred from camera to the PC without frame dropping. The Basler software SDK, combined with OpenCV/C++ image processing library is free of charge, very flexible when it comes to frame/video acquisition and processing, thus it requires some C/C++ programming skills.

The state-of-the-art version HSC (Phantom VEO E-310L) provides 3200 FPS in 1280 x 800 resolution and up to 39800 FPS in usable 256 x 256 resolution. It has a higher ISO which does not require extremely strong scene illumination, and it even has 36GB of internal memory thus allowing it to store 7.5 seconds of a video captured at a highest resolution/framerate without the PC.

Once the HSC video is acquired, the following tasks need to be addressed:

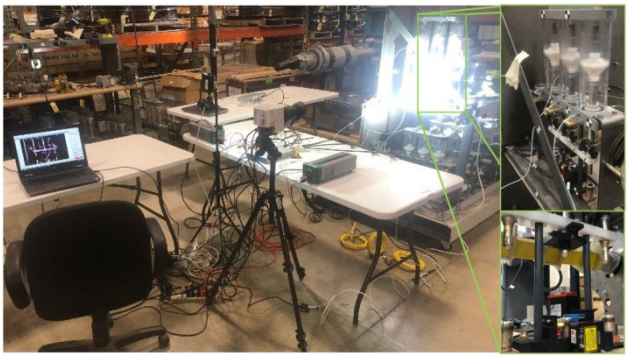
- synchronization challenge - the entire HSC video should be synchronized with a known and precise event (preferably contact travel),
- travel extraction challenge - a desired (and/or marked) part of the image should be tracked in consecutive frames,
- world space reprojection challenge - even if the object is correctly tracked in image space ("in pixels"), the object coordinates need to be projected/transformed in real world coordinates.

There are two different approaches that may be used for solving the synchronization problem. Both approaches rely on using the camera "trigger" digital input to start/trigger the frame capture. Although in industrial applications (e.g. on conveyor belts) an image is captured every time an external sensors detect the presence of an object, in MV/HV switch applications the entire video capture is triggered with one pulse, and the consecutive frames are captured based on internal camera clock signal. The first approach uses the data acquisition system as a "master" during data acquisition - the DAQ card sends the pulse to the camera and the camera "separately" captures the video with the predefined framerate, while the DAQ is capturing sensor signals using a dedicated programme (such as HV CB Simulation) or some other similar software. In the second approach, the camera is acting like a "master" device and controls the acquisition. In this case, the camera is pre-set up to acquire a specific number of pre and post frames, use a specific frame rate, and provide time synchronisation of measured signals by the configured sensors. This can be a convenient setup since it is simple to wire-up and synchronize, but sensor sampling is constrained with the camera sampling rate.

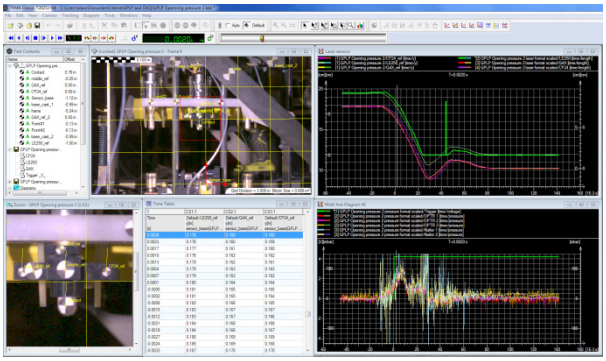
Once the video is acquired and synchronized with the rest of the measurements, the first challenge is to track the point(s) of interest. Points of interest need to be extracted from video frames by image processing algorithms. Usually, template or colour matching algorithms [8] and their variants are used for tracking the points of interest. However, best results are obtained by employing tracking markers (quadrature, Aruco and similar [9]) on objects prior to acquiring the video, if possible. In either case, the tracking problem is not trivial to solve - it is extremely challenging if high precision is required and poor lighting and low video quality are present.

One of the most important and difficult parts of travel extraction is the transformation of image space to world space coordinates. First, the camera is introducing lens distortions, which require calibration [8]. Secondly, and more important, the movement of the point of interest in 3D space is not acquirable with a single 2D camera without relatively strong initial assumptions e.g. that the point of interest is moving in a single plane, that the plane position is known at least in relative position to another reference plane and that the world coordinates of reference points in image space are known in advance. Although most of the aforementioned problems are considered to be solvable in image-processing community, they are far from being trivial. Our team is working on a trajectory extraction program based on C++ OpenCV image processing library, but the software application is still in its development phase and it is not user friendly yet (Figure 8b). In addition, we are using a state-of-the-art trajectory extraction software TEMA. Its graphical interface is shown in Figure 9b). It is a powerful software, which is a complete commercial solution for video processing and motion analysis, but it is also fairly expensive.

Travel recordings with laser sensors and TEMA software were measured and compared. Figure 9.b) presents the travel distance of the moving contact during the LP opening operation assessed with 3 different laser sensors and 3 different tracking points on TEMA software. Quadrant markers were used to track the moving contact and the plane of laser reflection on TEMA since it has a dedicated algorithm for tracing them. Using a dynamic centre of coordinates linked to a quadrant marker located on the laser's mounting brackets it's possible to compare measurements between video and lasers. Discrepancy of travel measurements with some laser sensors (LE250) and (CP24) was shown in Figure 9.b. LE250 showed an unusual large peak after contact separation at t = 46[ms] while CP24 sensor signal had abnormal stairs shape behaviour through the whole acquisition time. On the other hand, the Q4X laser shows a smooth behaviour of the travel recording measurement and has a great overlap with the tracked point measurement in TEMA as well. The results verified the accuracy of some laser sensors and helped pick the more suitable one for the next power testing.



a)



b)

Figure 9. a) Phantom VEO HSC measurement setup, b) TEMA commercial software interface

3. HV CB SIMULATION SOFTWARE

HV CB Simulation is an in-house developed computer software for simulation of high voltage circuit breakers based on a simplified enthalpy flow and physical arc model [10] and presented in [11]. The software has been continuously developing over the past years enabling simulation not only of SF6, but also alternative media circuit breakers [12]. Furthermore, circuit breakers with any number of chambers and different types of valves can be simulated [13] even taking into account discharge coefficients of the valves [14]. The software also provides possibilities of simulation of nozzle ablation [15] and contact erosion [16]. The latest version of HV CB Simulation provides several output results, which can be used for analysis during the development process of new apparatus or improvement of existing one. The output results include contact travel, pressure rise in all chambers, gas mass flows, arc voltage, nozzle ablation, contact erosion, etc.

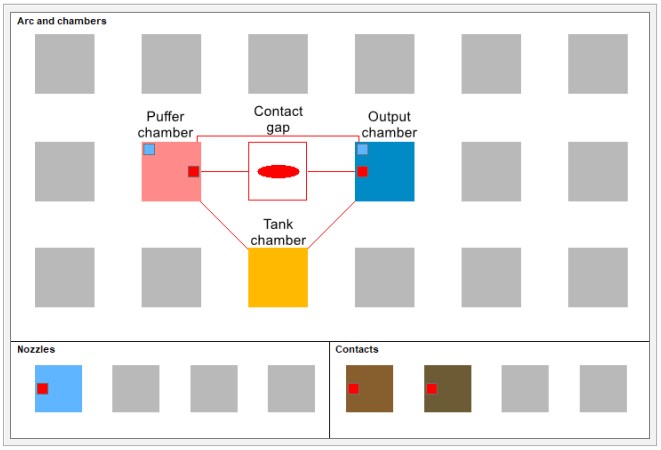


Figure 10. Schematic diagram of interrupter unit in HV CB Simulation

The interrupter of the aforementioned linear puffer is modelled with three chambers (puffer chamber, output chamber and tank chamber), 2 arcing contacts and 1 nozzle. Figure 10 shows the schematic of the interrupter model in HV CB Simulation software.

4. DATA ANALYSIS AND INTRODUCED LBS DESIGN CHANGES

In order to improve the breaking performance of the load break switch, certain changes in the design of the apparatus need to be made. Mainly, the breaking performance is expected to be better with higher pressure rise in puffer chamber and with higher opening speed. A series of experiments were performed to assess the initial performances of the switch.

In the first phase of experiments, the possibility to increase the opening speed by increasing the preload of the switch springs was investigated. In total 3 experiments were conducted:

a) without additional preload (initial setup),
b) with additional preload of 2.5 mm,
c) with additional preload of 5 mm.

The measured contact travel and pressure measurements in phase 1 are shown in Figure 11.

The obtained results are as expected: higher preload leads to increased speed of contacts, which leads to increased pressure in puffer chamber. Table I shows comparison of average speed v10 and pressure peak values for 3 experimental setups. The speed was increased by 12% for additional preload of 5 mm.

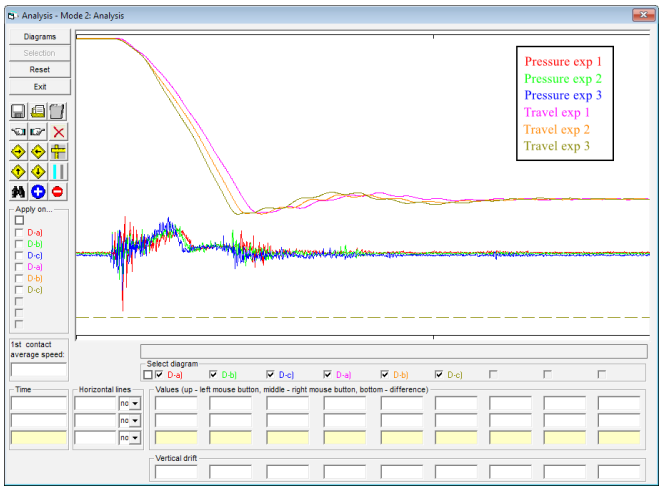


Figure 11. Travel and pressure measurements with different spring preload

Table I: Comparison of speed and pressure

	v10 speed (m/s)	Pressure maximum (MPa)
a) without additional preload	2.37	0.105
b) additional preload 2.5 mm	2.42	0.107
c) additional preload 5 mm	2.66	0.110

In addition, these experiments were also used in order to validate the switch model in HV CB Simulation software.

Therefore, it is interesting to observe the comparison of simulation and measurement results in all phases. Figure 12 shows comparison between measured and simulated contact travel and pressure rise for the first experiment without additional preload. The comparison presented in Figure 12 shows good agreement between the simulation and the measurement during the whole contact travel, except the last part of the travel, where the simulation does not take into account the rebound due to reaching of end travel.



Figure 12. Travel and pressure measurements compared with simulation results

The comparison of pressure measurements shows a similar shape in all three phases, while the best fit with simulation results shows in phase 2. The difference between pressure measurements in each phase is a result of small gaps in the power train, which are much more pronounced on the pressure measurements and cannot be directly identified on the contact travel. The results shown on Figure 12 confirm very good match between simulation results and measurements. Similar simulations were done in order to predict the behaviour of LP due to other intended changes in design.

The second set of experiments included one of the major changes - removing the flexible conductor connections, shown in Figure 13. Experimental measurements were done for both cases, with and without flexible conductors, as shown in Figure 14. By comparing the measured results, it is clear that by removing the flexible conductors the opening speed v10 is increased by approximately 4% in average. The downside is the more pronounced rebound because of the flexible conductors damping effect. The removal of flexible conductors opens other design possibilities, such as adding double flow principle to the switch (if necessary), which is frequently used for breaking of higher currents. It is important to note that the removal of flexible conductor connections requires redesigning other parts of the switch, due to changed current flow, but this is out of the scope of this paper.

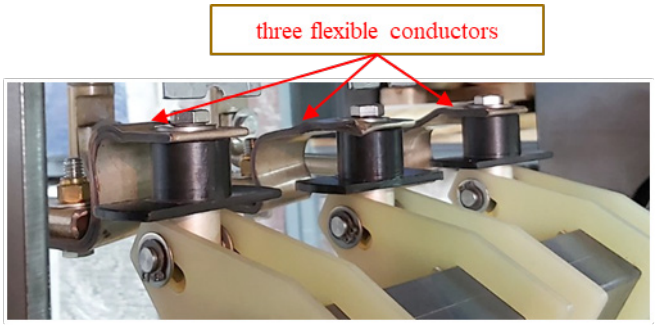


Figure 13. Flexible conductors on initial design



Figure 14. Travel measurements with and without flexible conductors

Both of the presented experiments (Figure 11-14) were conducted in Sarajevo using measurement system No. 1. Based on the results of the previous experiments, other series of experiments were done in Bolingbrook by measure-

ment system No. 2. The flexible contacts were removed, and a new (stronger) operating mechanism was used. The most significant change in the design was increasing the length of puffer cylinder.

Figure 15 shows travel and pressure measurements of initial and new design. Although recorded on different measurement systems, the results are still comparable. The comparison shows that the resulting movement is faster, as expected, due to stronger mechanism with higher opening spring energy. The downside is the more pronounced rebound, which can be addressed to missing of flexible conductors. This problem can be solved by adding shock absorbers to the system.

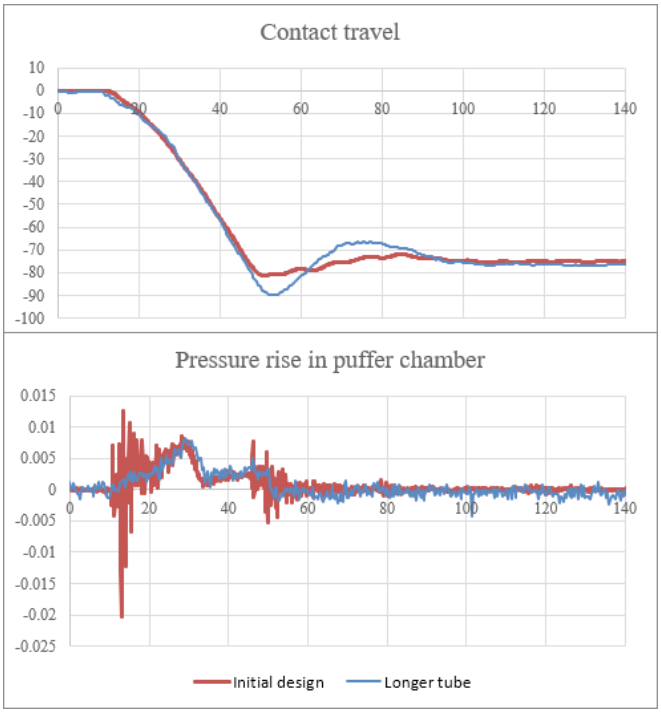


Figure 15. Comparison of travel and pressure rise in puffer chamber

It is interesting that, although the contact speed is higher when comparing to the initial design, the pressure rise in the puffer chamber remained almost the same. This can be explained by two changes that oppose each other in the pressure rise: faster travel increases the pressure but the longer puffer cylinder leads to less puffering, and therefore lowers the pressure. Consequently, the longer puffer tube enables increasing total contact stroke, which should lead to further pressure increase. In addition, higher contact stroke will positively affect the dielectric behaviour of the LP. It is clear from Figure 15, that the system No. 2 is more immune to noise than the system No. 1, due to the fact it uses a more modern data acquisition cards and different type of sensors.

5. CONCLUSION

Different measurement setups from EnergoBos Sarajevo and G&W Electric USA testing laboratories were presented and explained in the paper. In addition, an in-house developed high voltage circuit breaker simulation software (HV CB Simulation) was introduced. These tools proved essential in the process of medium voltage switchgear redesign.

The most important indicators of the switch performance, such as including pressure and moving contact travel measurements of the linear puffer load break switch were measured and compared with simulated results of the HV CB software during no load tests. Good agreement was shown upon this comparison.

Moreover, measurement results showed that the opening speed should be increased and that there is an important discrepancy in contact movement due to flexible conductors. Therefore, three successful improvements to the existing 38kV/630A load break linear puffer (LP), supported by aforementioned measurement and simulation results, were made. Namely, the opening speed of the switch was increased by adding spring preload, the flexible conductors were removed and the length of the puffer cylinder was increased. The measurement results clearly illustrate the increase of the switch performance.

As part of future work, we will focus on further usage of the presented measurement systems and simulation software, both during no-load and on-load operation, as important tools for switch improvement and optimization. Currently, we are analyzing other influencing parameters and approaches such as ablation, double flow integration and different mechanism energies during on-load measurements for load break switch redesign.

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