Leszek WOLSKI[1], **Wojciech MATELSKI**[1], **Karol SEWERYN**[2], **Paweł PAŚKO**[2]

Instytut Elektrotechniki (1), Centrum Badań Kosmicznych, Polska Akademia Nauk (2)

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Supercapacitors based driving system for space fast surface sample acquisition system

Abstract*. The paper presents the idea and implementation of the surface sample acquisition system with drive based on supercapacitors energy storage system in a reduced gravity environment. Selected control algorithms are presented in form of simulation studies and the most suitable is applied and tested experimentally.*

Streszczenie. *Przedstawiony artykuł opisuje koncepcje napędu próbnika gruntowego w kosmicznym środowisku o obniżonym ciążeniu. Zaprezentowano koncepcję konstrukcji oraz układu napędowego z wykorzystaniem superkondensatorów. W artykule umieszczono wyniki prac symulacyjnych oraz eksperymentalnych wybranej metody sterowania.* ***(Superkondensatorowy układ napędowy gruntowego próbnika kosmicznego)****.*

Keywords: surface sampling device, space exploration, fast drive, packmoon, supercapacitor.
Słowa kluczowe: próbnik gruntowy, badanie kosmosu, napęd impulsowy, packmoon, superkondensator.

Introduction

Space missions aimed at providing ground samples taken on other bodies to Earth are one of the ways to extend our knowledge of extraterrestrial materials and processes occuring on and under their surface. So far, several missions have been carried out to retrieve and transpose samples such as Apollo, Hayabusa or Phobos Ground. The European Space Association (ESA) is currently planning next missions, such as Phootprint, MarcoPolo-R, Hayabusa-2, OSIRIS-Rex or NASA is preparing Resource Prospector mission to the Moon.

Fig.1. Solar system planets. From the Sun on the left: Mercury, Venus, Earth, Mars, Jupiter, Saturn, Uranus, Neptune [1]

Fig.2. Phobos (left) and Deimos (right) - Mars moons [2]

The mission called Phootprint is proposed to be launched with an Ariane 5 on 2024 with early 2026 as backup date. Ariane 5 is a heavy launch rocket used to deliver payload into geostationary orbit. One of the top-level science goals is to understand the formation of the Martian moons Phobos (20x26 km) and Deimos (12x16 km) (fig.2) and put constraints on the evolution of the Solar System (fig.1). The mission would last about 3,5 years, including cruise, orbit mapping, 7 days on the surface, and sample return cruise time. The spacecraft would be powered by solar arrays. Because of the low gravity, the lander would be anchored to the surface during sample collection and launch back of the Earth Re-entry Capsule (ERC).A part of Phootprint mission/lander is the project aimed to ground sampling device, named PACKMOON.

There are three main aspects related to the investigation of new types of sampling tool solutions:
- High-amplitude dynamic force is the most effective way to pump energy into the end of crack.
- For safety reasons, the sampling tool must not anchor the lander. It means that the geometrical topology and associated device movement must be reversible.
- The sampling tool must not disturb the sample interior structure. Furthermore, the sample must be easily secured and released if needed.

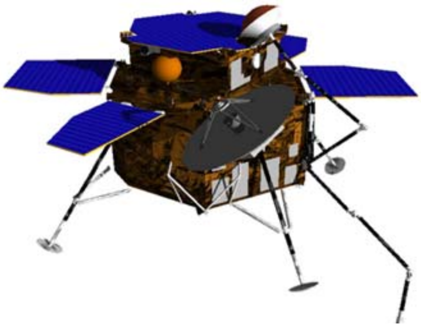

Fig.3. Phootprint mission lander [3]

The device called PACKMOON presented in figure 4, is a mechatronic system, that effectivly uses power to sample hard materials up to 7 MPa and is dedicated for low-gravity bodies space enviroment. PACKMOON can be used for taking ground samples on comets and asteroids, except for using it to sample rocks in planetary conditions. The sample taken by this device is most valuable for further scientific investigation and this is the goal for planned sample return missions, such as ESA’s Phootprint mission to Phobos Moon of Mars.

The principle of operation is based on insertion of two spherical, rotary jaws presented in figure 5, into regolith. During this process it is critical to minimize the mechanical interaction with lander (fig.3).For this reason the device consist of doubled mechanical subsystems, which operate in the same axis but in opposite directions.

Those systems are driven by electrical motors. Their shafts are directly coupled with special hammers, which can be seen in figure 4. The hammers repetitively hit the metal jaws, so they could break into the ground(change from the initial open state to close position, at which the sample is gathered).

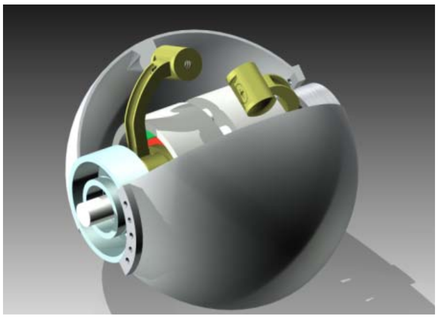

Fig.4. PACKMOON – CAD model of sampling device [4]

With the given machanical parameters of the sampler, including rotary mass and inertia, it is required for the hammers to accelerate to the speed of 90 rad/s, before achieving the angular displacement of 90 degrees. In this way, the kinetic energy transferred to the jaws is high enough to break the targeted surface. The time for taking a single sample is estimated at under 10 minutes. The main idea, as well as the detailed mechanical concept of the sampling device, and all necessary requirements for the drive are specified in the paper [5].

Fig.5. PACKMOON jaws in two opposite position [6]

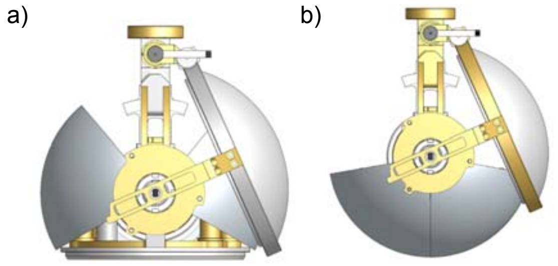

Fig.6. PACKMOON in: initial position (a), jaws closed (b) [6]

Fig.7. ILM50 motor kit used in PACKMOON drive [7]

Simulation results

In order to find the optimal drive control algorithm, the sample acquisition drive with the BrushLess Direct-Current Motor (BLDC) ILM50-14 machine, presented in figure 7, has been simulated using simulation program PSIM, which is available in The Electrotechnical Institute (IEL). The aplication offers a dedicated BLDC machine model, allowing the entry of the motor parameters from its datasheet.

This motor was chosen due to its high technical value, small dimensions (50 mm diameter, 23 mm length), small mass and high performance (high nominal power 180 W and 1.4 Nm torque). It is available as a rotor-stator installation kit for structural integration in the designed device. It is used for robotics, aerospace, automotive and military applications.

With direct connection of the ILM50-14 machine to the supply voltage of 24 V the current will reach 30 A, which can cause the damage of the machine. Anyhow, it is not effective, because increasing the current above 20 A gives only slight increasing of the developed torque. Therefore it is necessary to control the machine current, by controlling the duty cycle using Pulse Width Modulation (PWM).

The simulations have been carried-out for four types of modulation:

- simple PWM with constant carrier frequency;
- enhanced PWM (ePWM) with constant carrier frequency and velocity correction;
- hysteresis type PWM (hPWM), keeping the current within certain limits;
- level-time type PWM (letPWM), switching the current off after reaching the certain level and switching the current on after calculated time.

The simulated circuit contains the BLDC machine supplied from 24 V, the six transistor bridge controlled according to the Hall sensors signals, additional inertia and a number of indicators including incremental encoder. The basic schematic diagram of the simulation circuit is presented in figure 8.

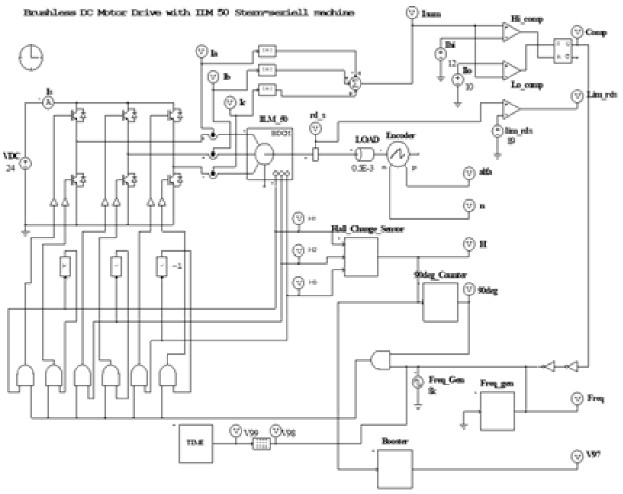

Fig.8. Components of the hammers drive control [9]

Presented diagram contains all the necessary devices for simulating different types of PWM by enabling or disabling the appropriate parts. The simulations have been carried out with the parameters derived from the data sheet of the ILM50-14 machine with star-serial connections. The inertial load is set as $0{,}5 \cdot 10^{-3}$ kgm^2. Additionally the model has been equipped with angle sensor signalizing 90° and speed sensor indicating 90 rad/s.

Simple PWM with constant carrier 2 kHz frequency

To generate the PWM current pulses the Freq_Gen module has been used. The frequency was set as 2 kHz. The duty cycle was 87%. This value was chosen experimentally to reach the desired rotational speed of 90 rad/s on the angular way of 90°.

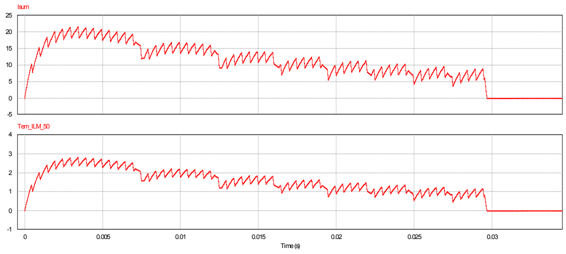

Fig.9. Current and torque during start with 2 kHz carrier [9]

The current is of the triangular shape, which is related to the varying time constant. The maximum current value reaches 21,6 A and its rms value in the first sector is 17,9 A. The maximal torque is 2,83 Nm.

Simple PWM with constant carrier 8 kHz frequency

In the next experiment the PWM carrier frequency has been set to 8 kHz. The results are presented in figure 10.

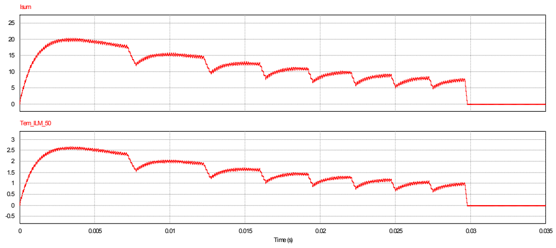

Fig.10. Current and torque during start with 8 kHz carrier [9]

With 8 kHz PWM the resulted time to reach the velocity of 90 rad/s is practically the same – 29 ms. The maximal current is in this case 20 A and the rms value in the first sector is 18 A. The shape of the current is more smooth with the triangular waveform amplitude of 0,5 A. As in the previous case the current decreases when the velocity arises and in the last sector the maximal current value is 7,5 A.

Enhanced PWM with constant carrier frequency and velocity correction (ePWM)

In the next experiment the user designed C-block PWM_Gen module has been used to generate the PWM current pulses. The duty cycle has been corrected to achieve the similar current value in all sectors. The PWM carrier has been set to 5 kHz and the duty cycle increased in time to compensate the electromotive force. The obtained results have been presented in figure 11.

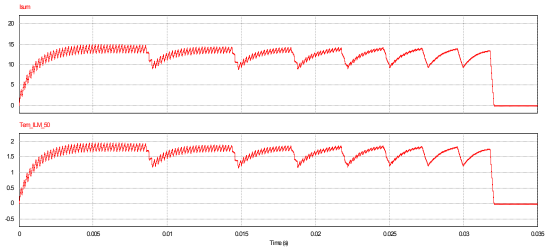

Fig.11. Current and torque during start with ePWM [9]

Hysteresis type PWM (hPWM)

In the next experiment the hysteresis type of PWM has been used. In this experiment the part consisting of the three phase current sensors, Hi_comp and Lo_comp currrent comparators and flip-flop Comp has been activated. The obtained results have been presented in figure 12.

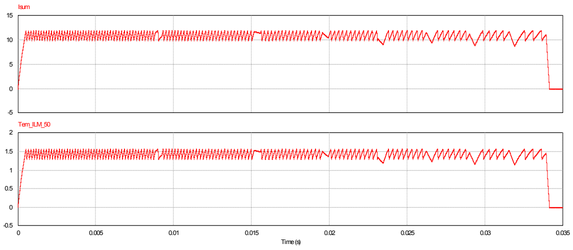

Fig.12. Current and torque during start with hPWM [9]

The hysteresis limits are 10,7 A and 12 A. The current dips related to sector changes are negligible, and the rms current value is 10,6 A in all sectors. The switching frequency changes from 6 kHz in the first sector to 1,8 kHz in the last sector. The torque changes in all sectors are within 1,3 ÷ 1,5 Nm limits. The rms value of the torque is equal 1,4 Nm and the velocity increases in practically linear way.

The hysteresis control method of the drive current control has the best properties of the tested solutions. It allows for reaching the desired level of velocity with the lowest possible current level without overcharging the machine. But there are serious drawbacks of this method – it needs an additional complex current control circuitry and it needs another set of current limits for backward movement.

Non-standard level-time type PWM (letPWM)

Considering the drawbacks of the hysteresis method, another non-standard control method has been developed – level-time type PWM, switching the current off after reaching the certain level and switching the current on after calculated time. This type of current control needs only minimal amount of the additional components – one current sensor, controlling the source current instead of phase currents and one comparator. The maximum pulse current level is controlled by hardware and the duty cycle and consequently the rms value of the current is software controlled.

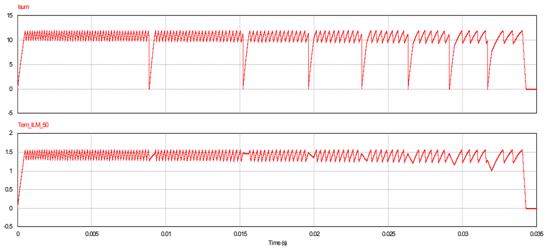

Fig.13. Current and torque during start with letPWM [9]

The results are similar to these obtained using hysteresis PWM algorithm. The time to reach the velocity of 90 rad/s is the same 33 ms. The cut-off current level is 12 A, and the current waveforms are similar to generated by hysteresis PWM. With time delay between consecutive current pulses set to 50 μs the current rms value is 10,8 A. The rms current value can be changed by changing the time delay between pulses and e.g. for the rms current of

5 A, allowing for small velocity movements, the time delay is 900 µs. The current generated in this case and the appropriate sector change signal are presented in figure 13.

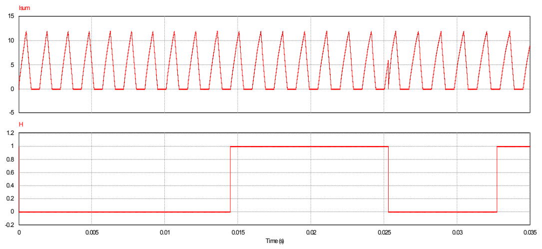

Fig.14. The current and sector change signal for duty cycle giving 5 A rms current with letPWM [9]

Taking into account the minimal amount of the additional components and the possibility of controlling the rms value of the current by the software, the drive control using the level-time PWM algorithm is the most suitable solution for the sample acquisition drive.

Experimental model

The full PACKMOON test kit includes: power supply unit (PSU), main computer (PMC), driver controller (DCM), electrical energy storage (EES), hammers motor driver (HMD) and hammers motors, as shown in figure 15. The model stand of hammers drive systems consists of the following modules: two inverter modules, two drive controllers, energy storage module (EES) with 100 mA constant current charger.

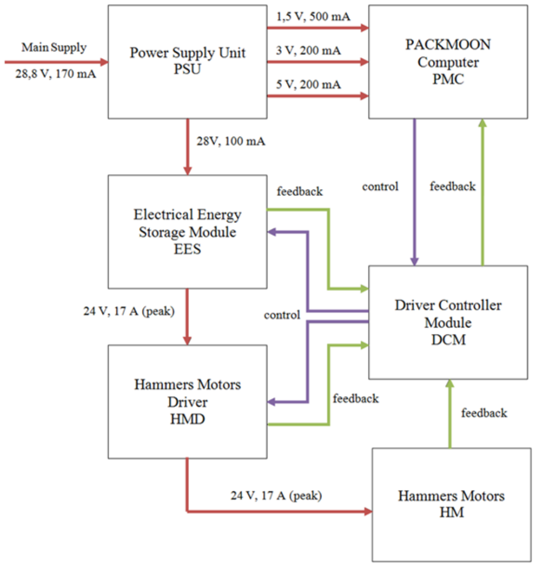

Fig.15. Block diagram of the Control System [8]

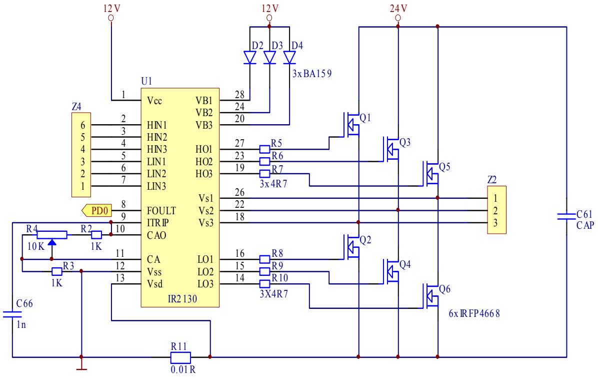

Fig.16. Simplified schematic diagram of the inverter driver [8]

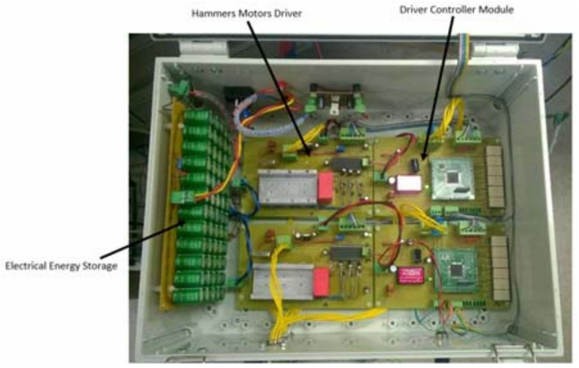

Fig.17. Components of the hammers drive system [8]

Electrical Energy Storage module (EES) was built as matrix of parallel-series conected supercapacitors, type DRE226S0EK25RR with rated capacity of 22 F each, in 12 rows and 5 columns, producing totally 9,17 F with maximum energy about 4 kJ (the total usefull energy in this application is about 2 kJ). The maximum repetitive current that can be used from this EES is more than 40 A. For each hammer duty cycle energy consumption is about 10 J. As a part of test system the EES charger, with current limiter with set to 100 mA, is used. Due to the very low charging current, aproximately 20 mA per column, the voltage balancing system is not required. EES is one of the most important parts of the system in cases of limited supply power. From the main source of power it is possible to achive less then 3 W (28 V and 100 mA) but motor drive needs about 400 W (24 V and 17 A). That is the reason to use supercapacitor based EES battery, and of course, it requires charging before each work cycle. The main components of hammers drive have been presented in figure 17.

Fig.18. The experimental breadboard during sampling operation

As motor driver fully the integrated one chip International Rectifier IR2130 is used. It doesn't need any additional auxiliary voltage and its design is ideally suited to the needs of the proposed control system. The inverter driver has been presented in figure 16. The motor inverter is connected to, and controlled, by AT90CAN128 processor.

The output stage consists of six IRFP4668 unipolar transistors with drain current up to 130 A, drain–source voltage 200 V, and series resistance 8,0 mΩ. The main control program has been designed, so that it can be easily transferred to a CPLD programmable unit like Altera or Xillinx. The view of the completed hammers drive system is presented in figure 17.

Experimental results

The results obtained using simulation tools have been verified experimentally using the model stand which contains: the experimental breadboard presented in figure 18 and the hammers drive presented in figure 17 with level-time current control algorithm described earlier. The phase current waveforms measured during tests are presented in figure 19.

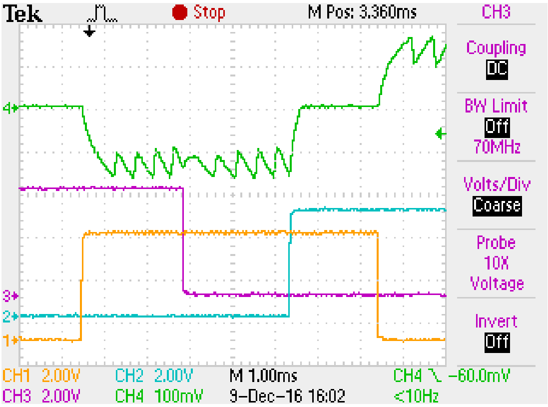

Fig.19. Experimental phase current waveforms [9]

The current is measured using green channel of the oscilloscope with sensitivity 10 mV/A. The cut-off current level is set at 15 A. The experimental waveforms are in perfect agreement with the simulation results presented in figure 13. Three other oscilloscope channels are connected to the Hall sensors, showing the actual rotor position and velocity. The macro-scale measurements of the machine start are presented in figure 20.

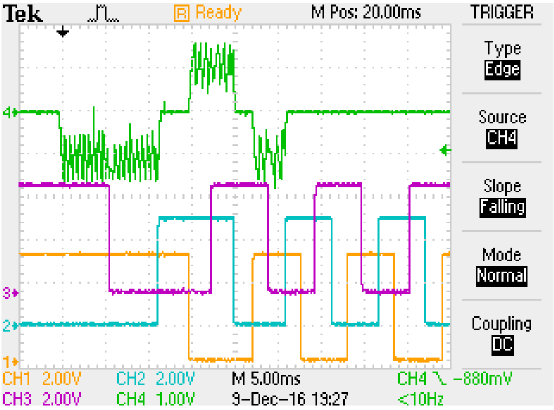

Fig.20. Phase current and Hall sensor changes during start [9]

The rms current value is about 10 A and the sector change time in the end of the starting sequence is less than 2 ms, which gives the velocity of about 100 rad/s. As was expected after simulation works, the ILM-50-14 machine supplied with level-time current control algorithm is able to reach the desired velocity during 90° movement.

The reversal movement needs the reduced rms value of the current. It has been achieved by longer time interval between current pulses. The simulation results of this case were presented in figure 14. The experimental phase current waveforms during few sectors reverse movement are presented in figure 21.

Conclusions

The requirements for this stage of the project have been successfully achieved. After thorough investigation using simulation tools the chosen configuration of the electrical drive for the sample acquisition system has been realized and tested.

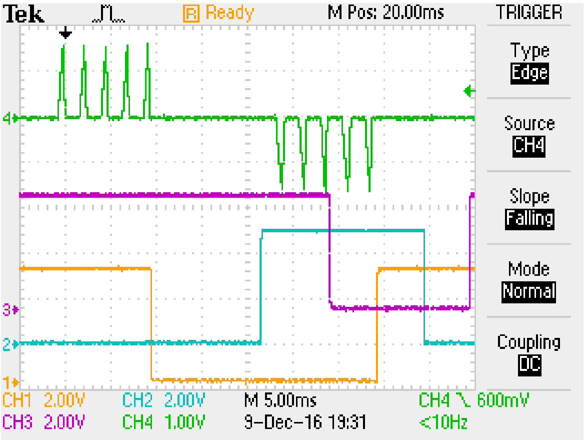

Fig.21. Phase current and Hall sensor changes during few sectors reverse movement [9]

As the most appropriate control algorithm the non-standard level-time type PWM (letPWM) was selected and apllied. The tests proved that BLDC machine ILM 50- 14, selected in the previous stage of the project, is able to generate the appropriate torque to reach the velocity higher than 90 rad/s on the angular way of 90°.

The supercapacitor based electrical energy storage has been designed and tested. The tests proved the suitability of this kind of the storage for work with BLDC motor drive. The storage capacity was tested with one drive and according to the test results should allow for more than 50 hits of two hammers. An example of angular displacement of the sample jaws is shown in the figure 22. The PACKMOON prototype is presented in figure 23.

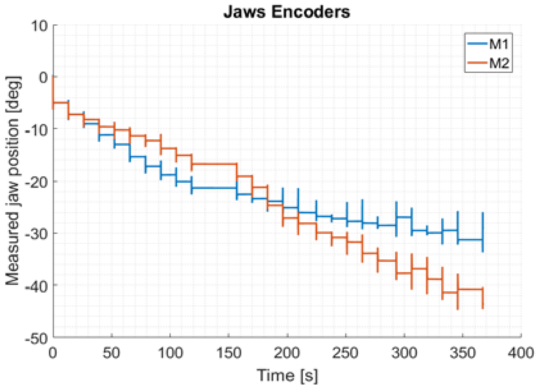

Fig.22. Example of measured jaws position using hammer drive during sampling

Fig.23. PACKMOON - prototype of sampling device

***Autors**: mgr inż. Leszek Wolski, Instytut Elektrotechniki, Zakład Przekształtników Mocy, Bałtycka Pracownia Technologii Energoelektronicznych (BAPTE), ul. Czechosłowacka 3, 81-336 Gdynia, E-mail: leszek.wolski@iel.pl; mgr inż. Wojciech Matelski, Instytut Elektrotechniki, Zakład Przekształtników Mocy, Bałtycka Pracownia Technologii Energoelektronicznych (BAPTE), ul. Czechosłowacka 3, 81-336 Gdynia, E-mail: wojciech.matelski@iel.pl; dr Karol Seweryn, Centrum Badań Kosmicznych, Polska Akademia Nauk, ul. Bartycka 18a, 00-716 Warszawa, E-mail: kseweryn@cbk.waw.pl; mgr inż. Paweł Paśko, Centrum Badań Kosmicznych, Polska Akademia Nauk, ul. Bartycka 18a, 00-716 Warszawa, E-mail: ppasko@cbk.waw.pl.*

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