OPTIMIZING AND INTEGRATING ELECTROMECHANICAL ACTUATORS IN AGRICULTURAL EXCAVATOR BOOMS FOR ENHANCED EFFICIENCY AND BATTERY LONGEVITY

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OPTIMIZAREA ȘI INTEGRAREA ACTUATORILOR ELECTROMECANICI ÎN BRAȚELE EXCAVATOARELOR AGRICOLE PENTRU EFICIENȚĂ ÎMBUNĂTĂȚITĂ ȘI LONGEVITATE A ACUMULATORILOR

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ABSTRACT

The research optimizes electric consumption in agricultural excavator booms by integrating electromechanical actuators and Power-by-Wire technologies. Utilizing a PID controller reduces electric motor peak current consumption, enhancing battery longevity. The research, carried out on a reduced-scale experimental stand, reveals the potential applications of the excavator arm equipment in agriculture, such as the precise location of irrigation systems, arrangement of terraces for orchards or vineyards, setting up greenhouses, and efficient unloading/loading of bulk materials. These applications signify the versatility and adaptability of electrically powered excavators in addressing diverse agricultural needs, emphasizing the significance of the developed mechatronic system for enhancing efficiency and sustainability in agricultural practices.

REZUMAT

Cercetarea optimizează consumul electric în brațele excavatoare agricole prin integrarea actuatorilor electromecanici și a tehnologiilor Power-by-Wire. Utilizarea unui controler PID reduce consumul maxim de curent al motorului electric, îmbunătățind durata de viață a acumulatorilor. Cercetarea, derulată pe un stand experimental la scară redusă, promite aplicații potențiale ale echipamentului brațului excavator în agricultură, precum localizarea sistemelor de irigații, amenajarea teraselor pentru livezi sau vie, înființarea serelor și încărcarea/descărcarea eficientă a materialelor vrac. Aceste aplicații semnifică versatilitatea și adaptabilitatea excavatoarelor electrice în abordarea diverselor cerințe din agricultură, subliniind importanța sistemului mecatronic dezvoltat pentru îmbunătățirea eficienței și durabilității în practicile agricole.

INTRODUCTION

In view of global and EU efforts through the European Green Pact *(*** The European Green Deal)* to reduce greenhouse gas emissions, agricultural equipment will in future be powered by electricity *(Soofi et al., 2022)*. Thus, electrically powered agricultural tractors are increasingly present on farms to carry out various specific activities.

As has recently been shown *(*** Research and Markets, 2023)*, the electric agricultural tractor market was valued at $98.7 million in 2022 and is projected to reach $234.0 million by 2028, growing at a CAGR of 14.06% between 2023 and 2028. The price of tractors in agricultural operations is influenced by the trend of electrification and automation of agricultural machinery.

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The electric agricultural tractor has seen an exponential increase in interest among farmers, manufacturers and researchers in the agricultural industry *(Mao et al., 2022; Scolaro et al., 2021; Troncon and Alberti, 2020; Mocera et al., 2023; Dhond et al., 2021)*, with electric vehicle (EV) sales reaching record highs. The presence of electric tractors on modern agricultural farms is also influenced by farmers' desire to use renewable sources to power them. The presence of electric tractors allows the introduction of modern technologies such as GPS guidance, automation of work processes, technologies that increase the productivity of agricultural activities.

Depending on the application, electric tractors can be classified into: tractors for light duty, tractors for medium duty, tractors for heavy duty. In the top position in the electric agricultural tractor market are light-duty tractors *(Khatawkar et al., 2019; Matache et al., 2020; Jia et al., 2018; Moreda et al., 2016)*, with a share of 50.98% in 2022. The high demand for light-duty electric agricultural tractors is due to their low mass, better battery performance and low cost compared to heavy-duty tractors *(*** Research and Markets, 2023; Matache et al., 2020)*. Also, in some countries there are increasingly strict regulations on the use of conventional tractors that do not meet new environmental standards. The world's leading manufacturers of electric agricultural tractors include Deere Company, Mahindra Group, Kubota Corporation, Yanmar, Massey Ferguson, Farmtac, Dongfeng, Kioti Tractor, New Holland, etc. *(*** IRB Tranding Market Insights, 2023)*.

In agriculture, the tractor is the basic equipment and for various agricultural activities various pieces of equipment (implements) are attached to it such as: ploughs; seeders; mowers; cultivators, etc. *(Magnusson and Pettersson, 2023; Varani et al., 2021; Un-Noor et al., 2022)*. Implements are accessories that help farmers to increase their productivity and to be able to perform several types of work with the same tractor *(*** Dataintelo)*. Implement manufacturers have developed a type of implement that turns the agricultural tractor into an excavator (see Fig.1). Generally, these implements are mounted at the rear of the tractor and are equipped with a boom, handle and bucket, turning the agricultural tractor into a mini-excavator. More and more farmers are using this type of equipment for small projects on a farm such as: transplanting trees, moving manure, proper excavation operations; moving agricultural soil, digging ditches, levelling small areas, precise location of irrigation systems, arrangement of terraces for orchards or vineyards, setting up greenhouses, efficient unloading/loading of bulk materials, etc. *(*** Holt Ag Solutions)*. This equipment is recommended to be used for short seasonal works, in which case it reduces labour costs and ensures greater safety in execution, but for large works this equipment cannot be used in place of classic excavators *(*** Victory Tractor Implements, 2022; *** Diamond B Tractors & Equipment)*.

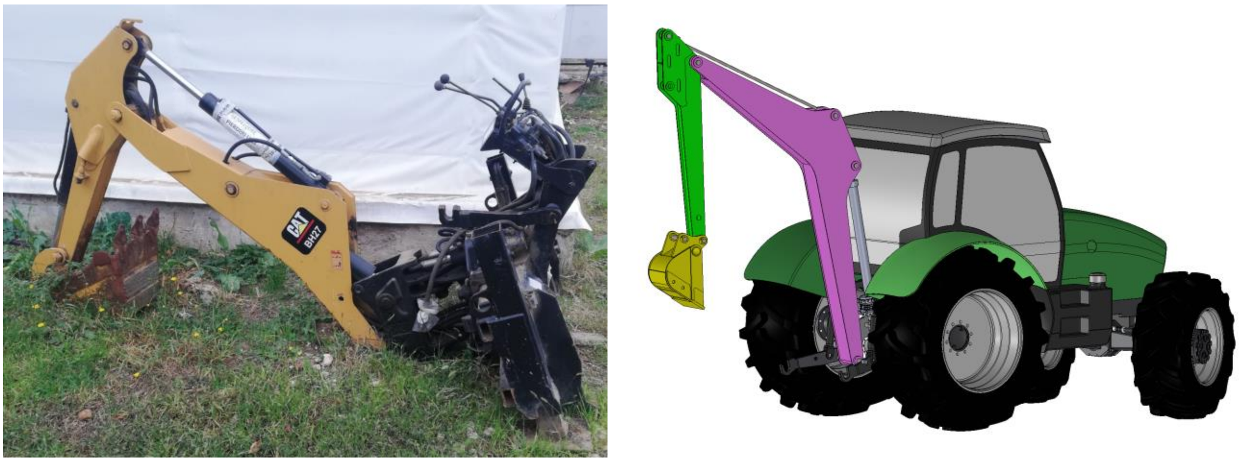

Fig. 1 - Excavator boom implement for an electric tractor

In the above context, there is a need for the development of couplings for electric agricultural tractors. While in the case of conventional tractors the tractor's hydraulic system or a power take-off is used to generate the energy needed to operate the hitch, in the case of electric tractors one wants to use the electrical energy from the tractor battery. The operation of the tractor battery for the coupling means, in the case of electrically operated couplings, to develop novel solutions for the operation of the coupling using electromechanical actuators.

PBW (power-by-wire) technologies, with distinctive design approaches, aim to extend the use of electromechanical actuators from aircraft control systems to the operation of various agricultural equipment. An electric actuator system using PBW technologies transports power between systems "through cables instead of traditional hydraulic lines, which improves performance.

Advantages of PBW actuators include: increased system safety and reliability due to the absence of flammable and hazardous hydraulic fluids; reduced weight, volume and complexity of power transmission; easier maintenance and lower associated costs due to the absence of hydraulic leakage; increased energy efficiency and improved dynamic characteristics *(Qiao et al., 2018)*. Another advantage of eliminating actuation of implements by electromechanical actuators for agricultural tractors is the elimination of the risk of soil or plant contamination from hydraulic oil leaks.

The field of electric tractor drive systems using electric power is a new field that is continuously developing. Like any new element, it has difficulties in implementing solutions on a large scale due to lack of experience and knowledge of drive solutions, energy storage, reliability and lack of trained technical staff to ensure maintenance work. The presented research examines the use of an electromechanical actuator in the actuation of a mini-excavator boom by testing it on a stand simulating digging activities.

MATERIALS AND METHODS

In order to study the actuation of implements using electromechanical actuators for electric tractors, the authors used an experimental stand to simulate digging processes for an excavator boom. The stand is built considering the geometry and the actuation mode of an excavator boom; the digging process is simulated by using weights that are placed at the boom level, as in Fig. 2. The experimental stand, shown in Fig. 3, is composed of four main subsystems: the boom, chassis metal structure subsystem; the actuation subsystem with electromechanical actuator; the actuator control subsystem; the motion and electrical energy monitoring subsystem.

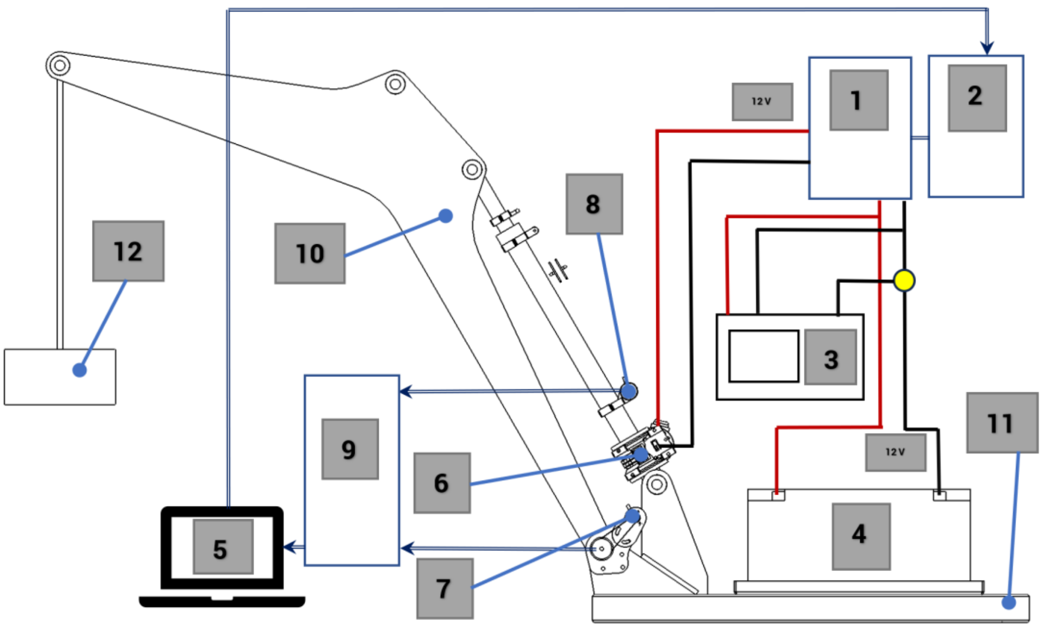

Fig. 2 - Experimental stand block diagram

Block diagram of the experimental stand, shown in Fig. 2, is composed of the following elements: 1 - relay block and PWM (Pulse-width modulation) 12 V /40 A; 2 - CONTROLINO MAXI 100-100-100 12 V controller; 3 - HIOKI PW 3198 electrical energy analyser; 4 - Deep Cycle Gel battery, voltage 12 V and 153 Ah; 5 - PC for control and data recording; 6 - electromechanical actuator powered at 12 V with 5000 N actuation force; 7 - rotary encoder E40S6-50-3-T-24 for determining the angular position of the boom; 8 - rotary encoder system E40S6-50-3-T-24 for measuring the speed of movement of the electromechanical actuator; 9 - data acquisition board - Arduino MEGA 2560 R3 (100 Hz experimental data acquisition frequency and 0.1 seconds plotting interval); 10 - excavator boom - welded metal structure; 11 - experimental stand chassis - welded metal structure; 12 - test weight.

The movement of the boom is achieved by the electromechanical actuator (Fig. 4) which is controlled by the PC via the Controlino PLC controller connected to the relay and PWM block (PWM DC Motor Speed Controller HHO-RC, 40 A continuous current and 2000 W maximum power).

The simulation of loads during digging is performed with the help of masses having different values (1.56, 6.25, and 12.5 kg), in total 20.31 kg. The PC control allows to change the direction of movement and speed of the electromechanical actuator with the help of relays. Movement monitoring is performed by means of two systems: a rotary encoder system mounted by means of a toothed belt transmission with a ratio of three on the excavator boom shaft, which records the angular position and angular speed of the excavator boom; a rotary encoder system mounted between the actuator rod and the actuator housing, which by means of a toothed belt measures the displacement and speed of the electromechanical actuator.

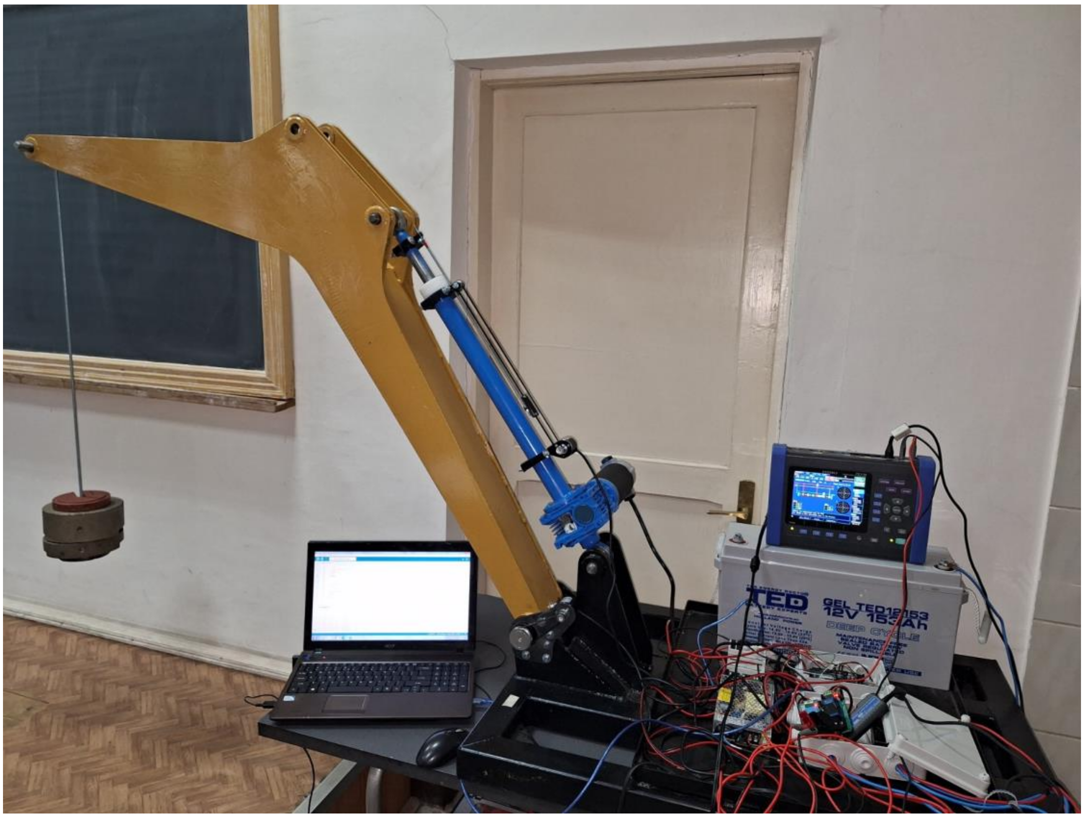

Fig. 3 - Experimental stand

The monitoring system of the electrical energy consumed by the electromechanical actuator is realized with the HIOKI PW 3198 current analyser. The HIOKI PW3198 power quality analyser has the measurement accuracy Voltage: ±0.1% of nominal voltage; Current: ±0.2% rdg. ±0.1 % f.s. + current sensor accuracy; Active power: ±0.2 % rdg. ±0.1 % f.s. + current sensor accuracy *(*** Hioki E.E. Corporation)*. The equipment, throughout the tests, collected data on supply voltage, current and electrical energy absorbed by the electromechanical actuator. The data stored in the storage medium of the equipment were analysed with the PQ ONE software which allows the presentation of the values of the electrical energy absorbed by the electromechanical actuator in graphical or tabular form *(*** Hioki E.E. Corporation, 2023)*.

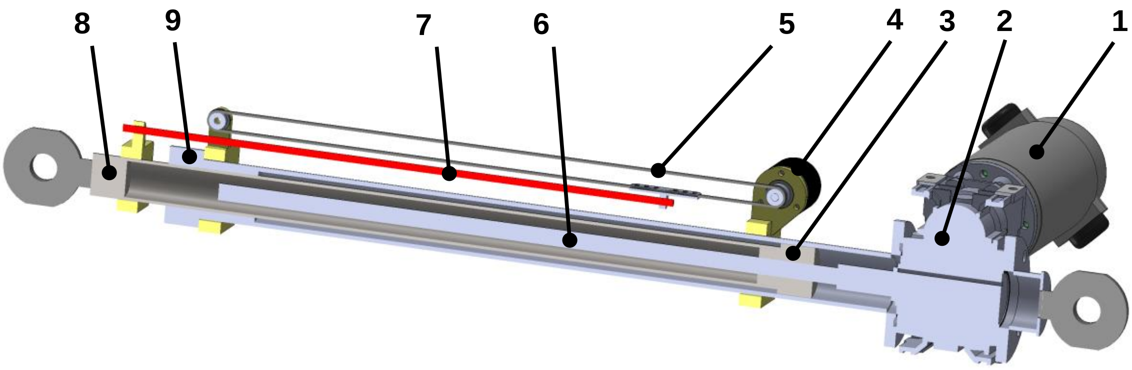

Fig. 4 - Electromechanical actuator section view

The electromechanical actuator (Fig. 4) consists of the following components: a 12 V / 250 W / 3000 rpm permanent magnet DC motor (PMDC Motor) (1), a PCM040U worm gear reducer (2) with a transmission ratio i = 60, a BSH 12 x 04 ball nut (3), an E40S6-50-3-T-24 rotary encoder (4), a 2GT-6 mm toothed belt transmission (5), and a C7 12 x 04 ball screw (6). The operation involves the electric motor transmitting rotational motion to the ball screw, subsequently converted into translational motion by the ball nut, connected to the actuator drive rod (8). The translational motion is monitored by a toothed belt transmission, transforming it into rotational motion at the encoder level. The encoder's rotation, with a pitch diameter of 12.22 mm, results in a 12.22 mm displacement of the actuator drive rod (8) relative to the fixed part of the actuator (9).

RESULTS

On the excavator boom with a 20.31 kg load attached, three experiments were conducted, that is 3 case scenarios were implemented. The first two result sets "1" and "2" comparatively illustrate the dynamic variations of various system parameters for constant control voltages with values of ± 12 V and ± 5 V, in intervals of 25 seconds with 5 second pauses. The two sets of dynamic variations of the parameters presented in Fig. 5 vary due to the control input (voltage); in the first case (”1”), the command is directly applied, while in the second case (”2”), a one-second delay (a ramp function) is employed. In the latter case, the command value gradually increases, reaching its maximum value after one second.

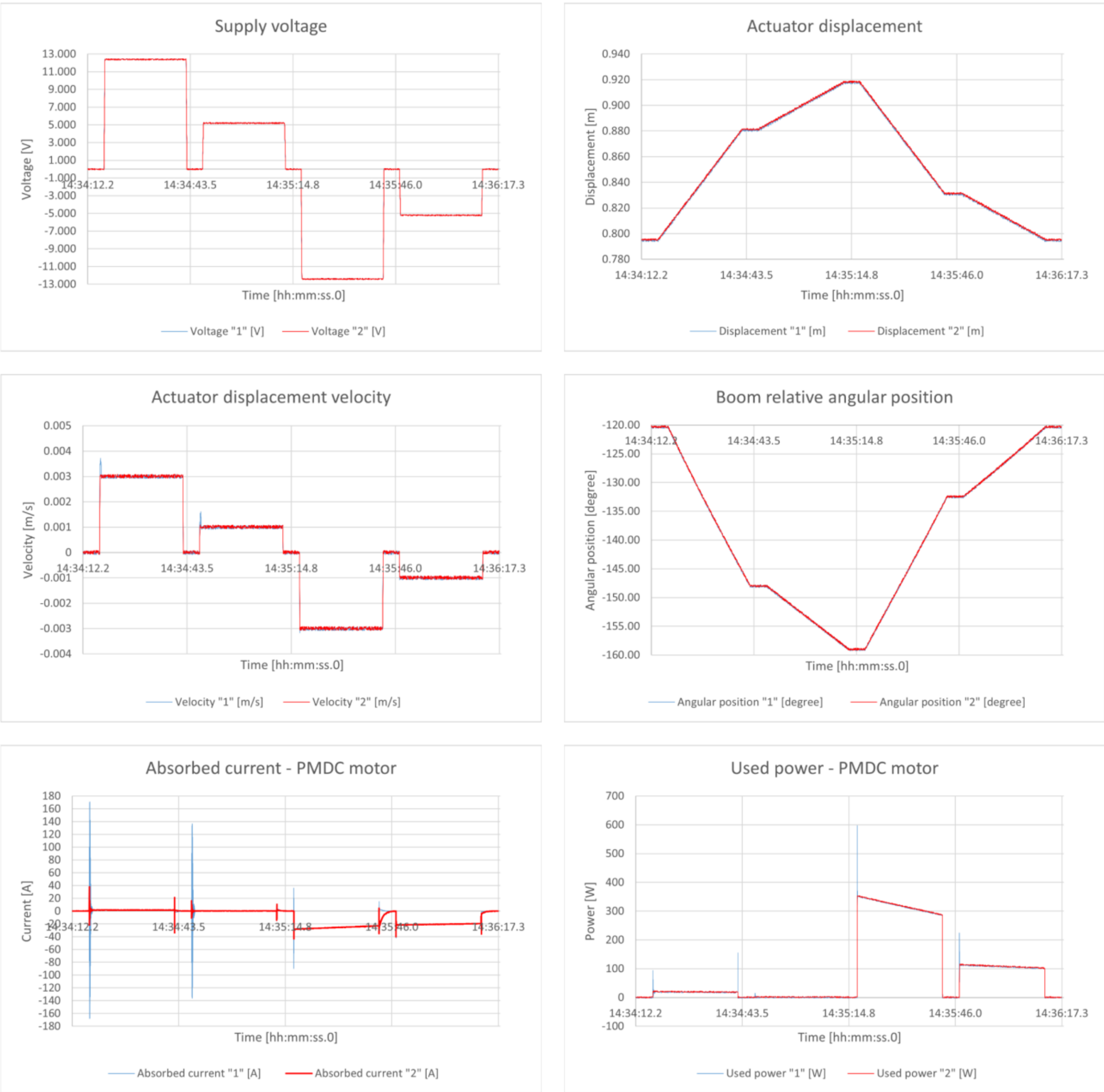

Fig. 5 - Dynamic variation of the system parameters corresponding to the experiments in cases no. "1" and "2"

In Fig. 5, one can notice how the ramp function used for system control voltage in case "2" has a positive influence on the system. Specifically, in comparison with the system in case "1", the graph depicting the instantaneous current absorbed by the PMDC motor shows that at system startup, the absorbed current is much lower, as is the case with the absorbed power. In the remaining graphs variations are negligible.

In the third experiment (case no. "3"), the system's power supply voltage was continuously controlled by a PID controller, tasked with regulating the rotation speed of the excavator boom. The PID controller was implemented in software using the "Arduino PID Library - Version 1.2.1" by Brett Beauregard *(Beauregard, 2017)*, and for plotting the graphs, the "Matplotlib 3.8.2" library *(*** Matplotlib 3.8.2 documentation)* was used.

The automatic control system's performances are depicted in Fig. 6, providing an overview of these performances in the top row graphs, where the control setpoint is compared with the relative angular velocity of the boom, on the left, while the instantaneous control error is presented on the right. Details of these variations are shown in the graphs below, revealing that the absolute control error of the automatic control system has a maximum value of 6.32%.

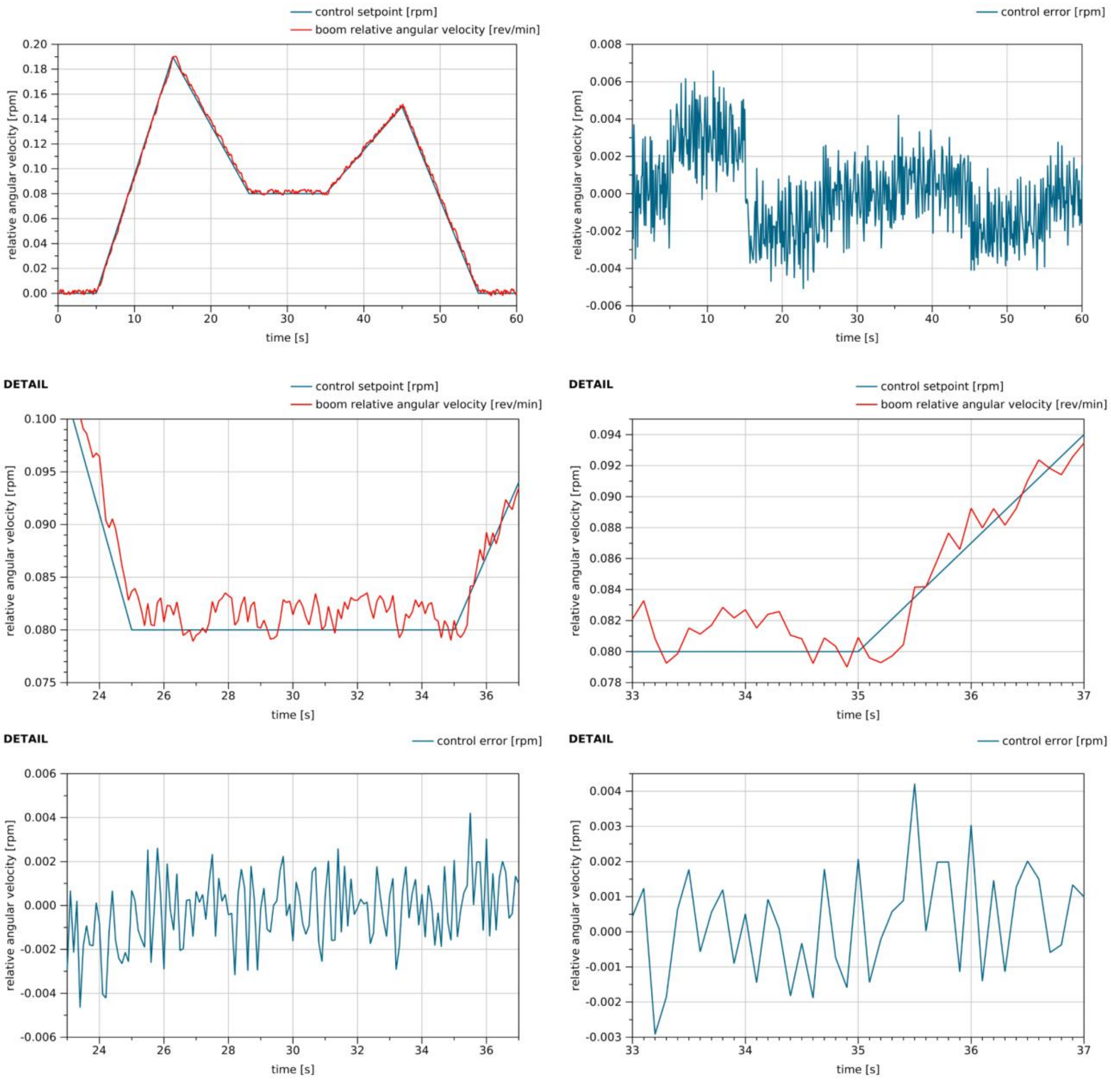

Fig. 6 - Dynamic performance of the system equipped with a PID controller - case no. "3"

Also, in Fig. 6, one can notice how the mechanical clearances within the mechatronic system controlling the excavator boom have a negative impact on the system's control performance.

These small mechanical clearances cause the error to asymmetrically oscillate around the 0 value, and the significant inertia of moving masses influences the control error, forcing it to briefly exceed the prescribed value.

The dynamic variation of the system parameters corresponding to the experiments in case no. "3" are presented in Fig. 7.

Moreover, in the graphs of Fig. 7, one can see how the control voltage continuously varies, except for the first and last 5 seconds when the voltage has low values and the current has high values, while the power consumed by the system has low values. This behaviour occurs when the PID controller tries to keep maintain system stability around the value of 0 for the displacement velocity and is caused by mechanical clearances and the inertia of moving masses. Such behaviour can potentially be avoided by implementing an automatic tuning of the PID controller and minimizing mechanical clearances.

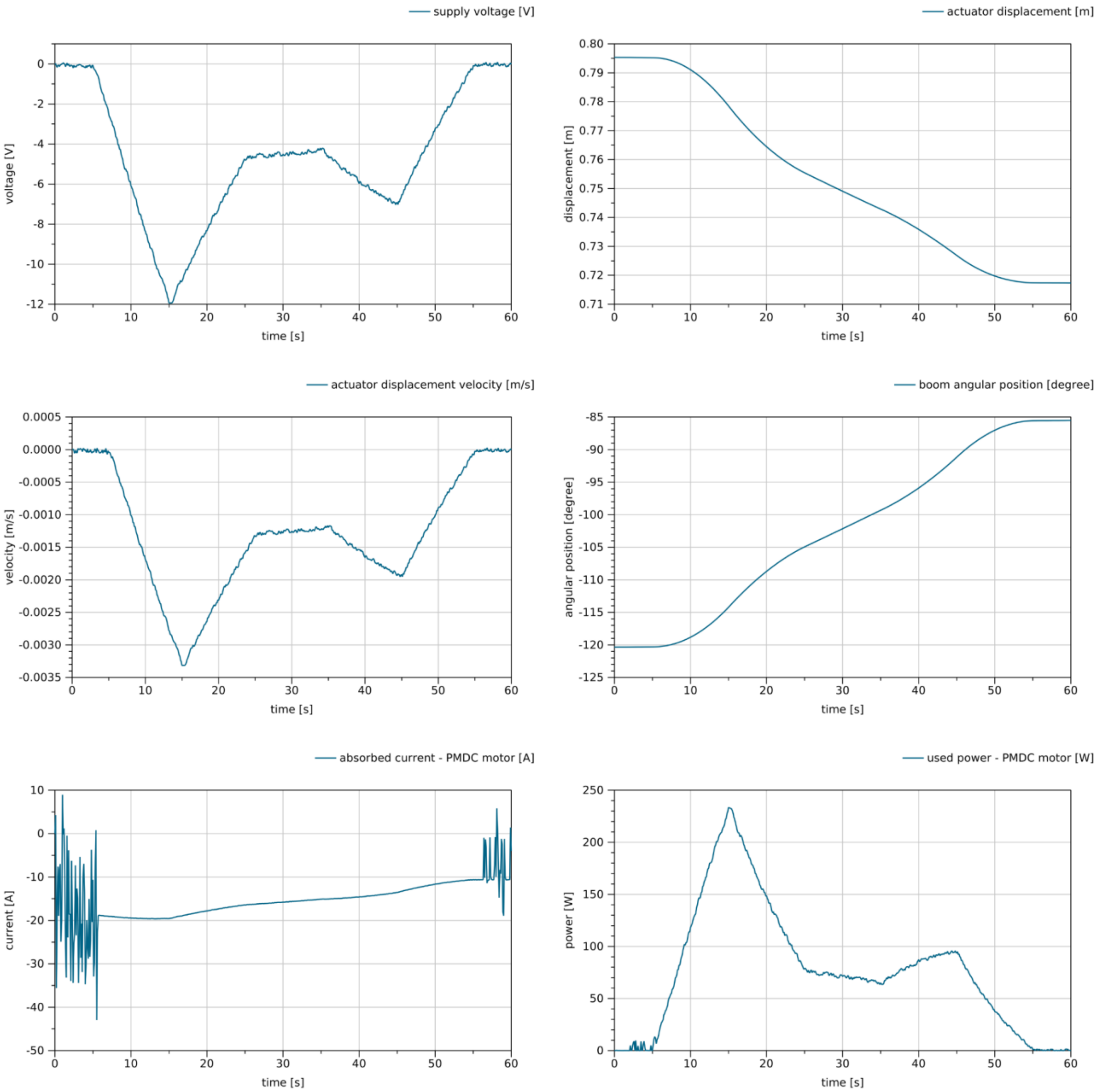

Fig. 7 - Dynamic variation of the system parameters corresponding to the experiments in case no. "3"

Also in Fig. 7, compared to Fig. 5, one can notice that the peak power consumed by the system has lower values, although a direct comparison cannot be made, and most importantly, the current absorbed by the electric motor no longer exceeds the value of 40 A, leading to an extension of the number of charge and discharge cycles of the battery.

Fig. 8 displays the energy used by the system in cases no. "1" and "2"; on this figure, one can see that the energy consumed by the system in the first two cases is virtually identical. Any small differences can be attributed to measurement errors and the slight influence of the ramp function on energy consumption.

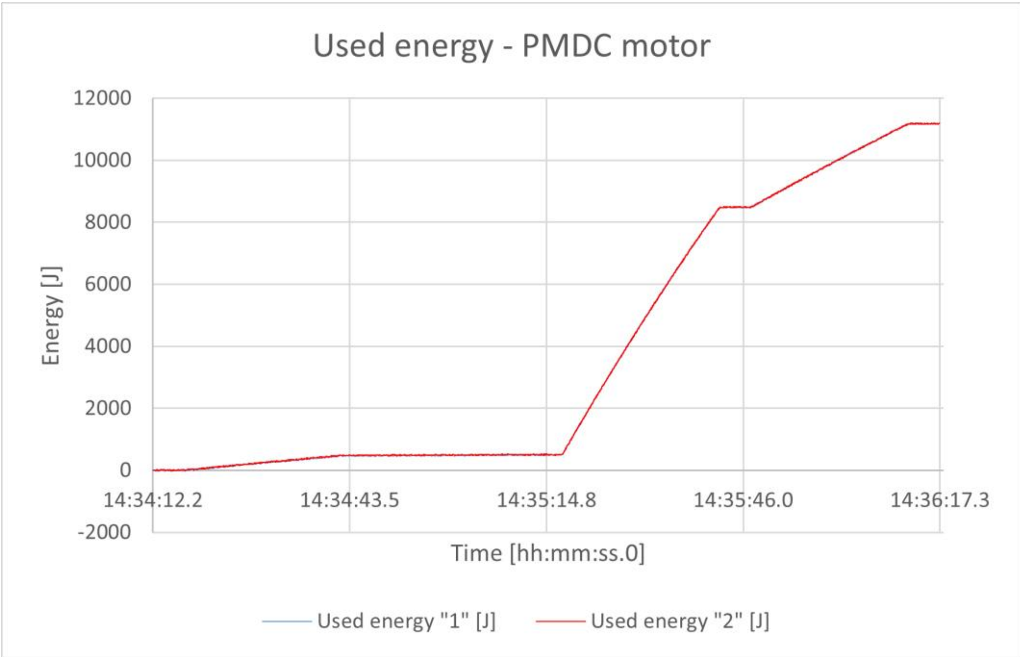

Fig. 8 – The energy used by the system in cases no. "1" and "2"

Fig. 9 displays the energy used by the system in case no. "3". Although the time variation of energy consumed by the system in this case is, on the right half of the graph, relatively similar to the time variation of energy consumed by the system in cases “1” and “2”, they cannot be compared because they have different operating cycles.

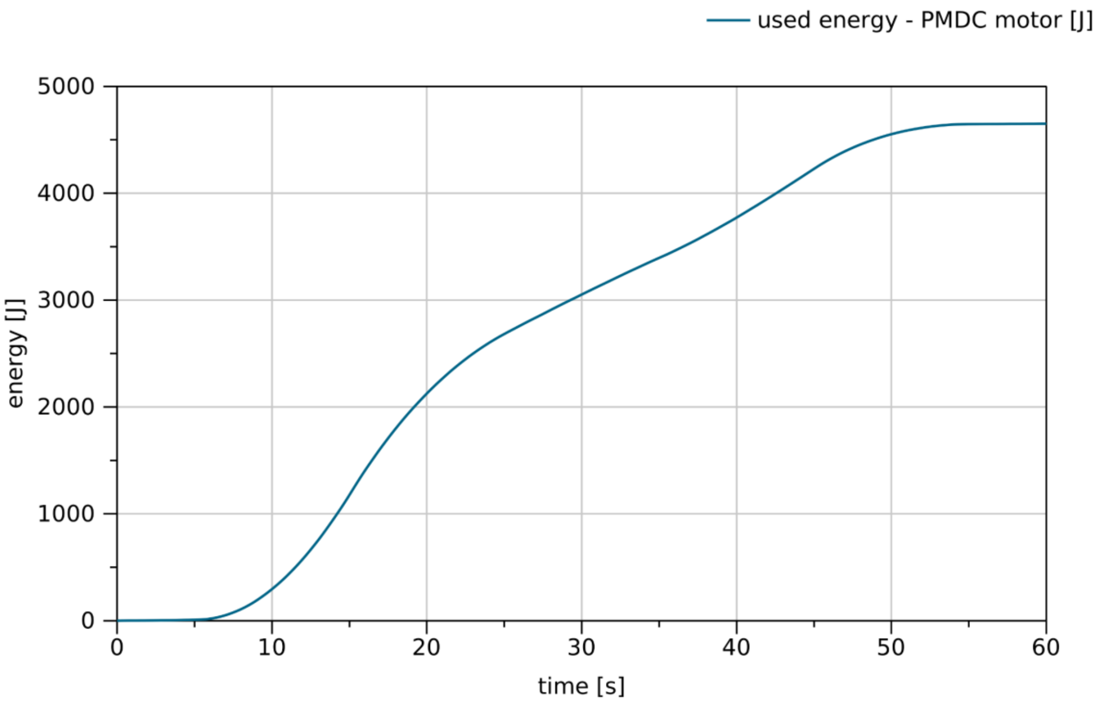

Fig. 9 – The energy used by the system in case no. "3"

CONCLUSIONS

The research highlights the feasibility of optimizing electric consumption in agricultural implements, specifically focusing on electrically powered excavator booms. By proposing and implementing an electric drive solution with electromechanical actuators, the article establishes a foundation for enhancing the efficiency of electrically powered agricultural machinery. The integration of Power-by-Wire (PBW) technologies, highlighted in the research, showcases the feasibility of using electromechanical actuators in agricultural equipment. The advantages of PBW, such as increased safety, reduced weight, and improved energy efficiency, show the feasibility of extending these technologies beyond aircraft control systems to enhance agricultural machinery.

Notably, the study reveals that the reduction in the current absorbed by the electric motor, particularly observed when utilizing a PID controller, contributes to improved battery longevity. The findings emphasize the crucial role of controlling the motor current in enhancing the overall efficiency and extending the lifespan of electric vehicle batteries.

In conclusion, the results presented in this article shed light on the dynamic performance of the mechatronic system controlling the excavator boom under various experimental conditions. The comparison of different control scenarios, including the direct application of commands and the use of a ramp function and a PID control revealed the impact of mechanical clearances and mass inertia on the system's control accuracy. The implementation of a PID controller demonstrated improvements in system stability, with potential benefits in terms of power consumption and the lifespan of the battery. However, challenges such as asymmetric oscillations and brief deviations from the setpoint were identified, underscoring the importance of automatic PID tuning and the reduction of mechanical clearances for enhanced system performance. These findings contribute valuable insights to the ongoing research in the field of mechatronic systems for electrically powered excavators and agricultural machinery, emphasizing the significance of addressing mechanical uncertainties for optimal control and energy efficiency.

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