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Implementation of a Virtual Active PID Control in HIL Pantograph Tests

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Abstract

Railway vehicles obtain their electrical supply from the contact between the pantograph and the catenary, through which the network energy circulates. Understanding the characteristics of this contact is crucial, as the maximum speed of the railway must be regulated to prevent disruptions in supply caused by detachment between the pantograph and the catenary, leading to electric arcs that degrade the elements in contact. It is also crucial in the phenomenon of wear of the wiper material and the contact wire.

The quality of the current collection is measured by the average value and the standard deviation of the contact force. This study explores the feasibility of using an active pantograph to stabilize the contact force, thus improving the current collection quality. To achieve this objective, a PID control system is virtually implemented on a Hardware-in-the-Loop test bench. The developed system could be implemented in a pantograph test bench for future experimental validation. The main contribution is the experimental validation of a control design proposal applicable to pantographs to improve the current collection.

Keywords: catenary, pantograph, PID control, contact force, HIL test, active control.

1 Introduction

Transport is a sector that contributes most to global warming via greenhouse gas emissions [1]. Its contribution to economic development raises the number of displacements of people and products over time, but it also causes damage to the environment. Lowering emission policies have evolved in most sectors to reduce the number of emissions; transport has raised its emissions (from 32% to 45% in the European Union [2]). Among transportation systems, rail transport [3] (mainly powered by electricity) is the most efficient in terms of CO_2. Moreover, recent studies [4] report that high-speed rail reduces emissions even in the system's calculous construction phase. Therefore, improving the operation of railway transport systems (speed, power losses, safety, etc.) will increase their use and contribute to the decarbonization trend worldwide.

The pantograph is designed to maintain contact with the catenary by adjusting its position to accommodate variations in wire height, wind conditions, and other factors. The variations in the pantograph-catenary interaction (PCI) directly influence the current collection quality as well as the wear of the catenary. High contact forces will lead to excessive wear on the catenary, and low forces will lead to electrical arcs (also involving cable wear). Therefore, researchers have developed several strategies to minimize the PCI force variation.

On the catenary problem side, there are many modelling and simulation studies, as well as HIL test benches that seek to study better catenary configurations aimed at improving the PCI problem ([5]-[8]). The proposed solutions are intended to be used in new catenary installations since the replacement of already-built railway lines is expensive and prohibitive.

Regarding the pantograph, researchers have proposed active pantographs [9], which include control actions to correct deviations in the PCI force. Although several proposals exist for active pantograph implementations, the underlying concept is based on the classical closed-loop control scheme. PCI force needs to be measured, analysed, and compared with the desired behaviour.

Due to the complexity of the problem and the models that can be used, in recent years, control strategies have been oriented in two different ways. On the one hand, some research opts for the design of a simple control strategy (such as PID [10], or state feedback) applied to complex models, and on the other hand, those that use complex controllers (such as sliding [11], fuzzy [12] or optimal control approaches [13],[14]) from the field of nonlinear control applied to more simplified models.

The most complex point of the active pantograph is the actuator. This system must be coupled to a real pantograph not originally designed to accommodate this actuation mechanism. Therefore, it is imperative to consider the potential problems that the mechanism could cause when it becomes passive. Some alternatives have been analysed in the literature. It is concluded that the most effective system is the introduction of a correction force as close as possible to the contact strips [15], discarding other systems that allow modifying the pressure (it has very slow dynamics) or acting on other rod of the mechanism [16] (greater technical complexity and less effectiveness).

Most approaches only show simulation results due to the difficulties of getting experimental data. Nevertheless, in [15], the authors present a strategy that includes an angle-controlled wing on the pantograph head to generate an aerodynamic force, depending on the train speed, thanks to the wind. The advantages of this system are less driving power, less modification of the pantograph mass, technical clarity, and, most importantly, not interfering negatively with the pantograph operation in case the active system stops. It has the disadvantage of being more difficult to control because of its complex dynamics.

2 Methods

The main objective of this work is to improve the current collection of the pantograph-catenary system by applying active control in the pantograph. To this end, several objectives are established.

The first objective is to simulate an active control system that carries out this task through PID. The application of this control would have several advantages: i) to reduce the vibrations in the pantograph-catenary contact thus allowing to increase the speed of railway vehicles, ii) to reduce the contact force while avoiding detachments would reduce the wear of the materials without generating electric arcs which produce premature deterioration, iii) in the eventual implementation, it would require a low investment cost since this control could be applied without affecting the existing infrastructure, it would only be necessary to modify the pantograph. The second objective is adaptability to real cases, the scope of the study is limited to obtaining the control software. It is not intended to obtain a physical element to be installed in pantographs to carry it out, but the limitations that current actuators present (response time) are considered. In this way, this work represents a basis both for improving control and for the future integration of the hardware in the pantograph. The tests to validate the developed control will be carried out in the test bench developed by the research group. Figure 1 shows a scheme of the active pantograph system. Section 2.3 provides the details of the developed procedure.

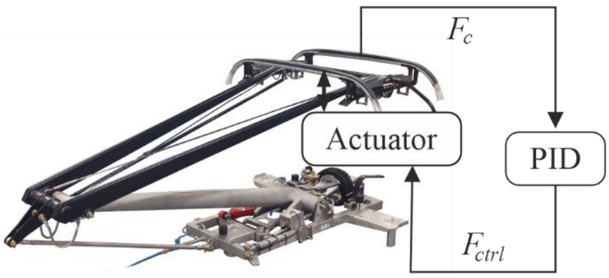

Figure 1: Active pantograph system.

2.1 Application of PID in an active pantograph

A proportional-integral-derivative (PID) controller is used to regulate the pantograph-catenary contact force (F_c). It must receive the difference between the contact force and the reference $\left(F_{ref}\right)$ as input.

The output is the vertical force that the actuator of the active pantograph must apply: F_{Ctrl} (1). The PID offers responses in real time, allowing immediate action.

$$F_{Ctrl}(t) = K_P \cdot e(t) + K_I \int_0^t e(\tau)d\tau + K_D \frac{de(t)}{dt} \quad (1)$$

where $e(t) = F_c(t - T_{act}) - F_{ref}$.

There are two important factors in the controller: the dynamic response and the delay, T_{act}. The last is the time that the electronics requires to: i) update the input, ii) calculate the output and iii) launch the control signal. The dynamic response is assumed to be a first-order system with time constant, $T_{res}/3$, and unit gain.
The transfer function of the pantograph-catenary contact can be considered unknown due to the great complexity of its dynamic. For this reason, the adjustment of PID parameters (K_P, K_I, K_D) cannot be performed by process function analysis.
In this work, the adjustment has been carried out by manually modifying the parameters of the PID controller and the response time of the virtual actuator.

2.2 Current collection quality

The UNE-EN 50367 standard states that a valid way to measure the quality of current collection is through the average value (F_m) and the standard deviation (σ) of the contact force. The average force limits for high-speed vehicles $(v > 200km/h)$ powered by alternating current is:

$$\begin{aligned} F_{m,min} &= 0.00047 \cdot v^2 + 60 \\ F_{m,max} &= 0.00097 \cdot v^2 + 90 \end{aligned} \tag{2}$$

where v is the is the travel speed of the train in km/h.

The maximum standard deviation allowed is:

$$\sigma_{max} = 0.3 \cdot F_m \tag{3}$$

The objective of the active pantograph system is to regulate the contact force to reduce its standard deviation and its mean value. Following UNE-EN 50317 standard, the contact force is passed through a low-pass filter with a cutoff frequency of 20 Hz of twelfth order. In this work, the improvement in the current collection has also been measured as a percentage of the dynamic behaviour achievable without the application of the PID control.

2.3 Experimental setup

The test method is hardware in the loop. The experimental setup consists of a real pantograph DSA-380 which is used in high-speed velocity trains. A linear actuator (LinMot PS10-70x400U) simulates the vertical position of the contact point between the catenary and the pantograph. The force transducers (HBK U2B) with nominal force of 500 N are between the linear actuator head and the contact strip of the pantograph. The signal measured by the force transducer is filtered, conditioned, and sent to the real-time controller, National Instruments cRIO-9040. This controller sends the force to a PC which runs the mathematical model of the catenary, and outputs the vertical position that the contact point will have in the next step. The new position is sent via EtherCat to the servo drive (LinMot E1400) of the linear actuator, which follows the reference, closing the simulation loop. This process repeats every 2 ms.

To calculate the vertical position from the measured contact force, the working group has its own software: PACDIN. This program complies with the EN-50318 standard for the validation of simulation codes for the pantograph-catenary system and can recreate the dynamic interaction between the pantograph and the overhead contact line. Figure 2 shows the main elements of the experimental setup and represents the loop process. Details of the test bench can be found in [7].

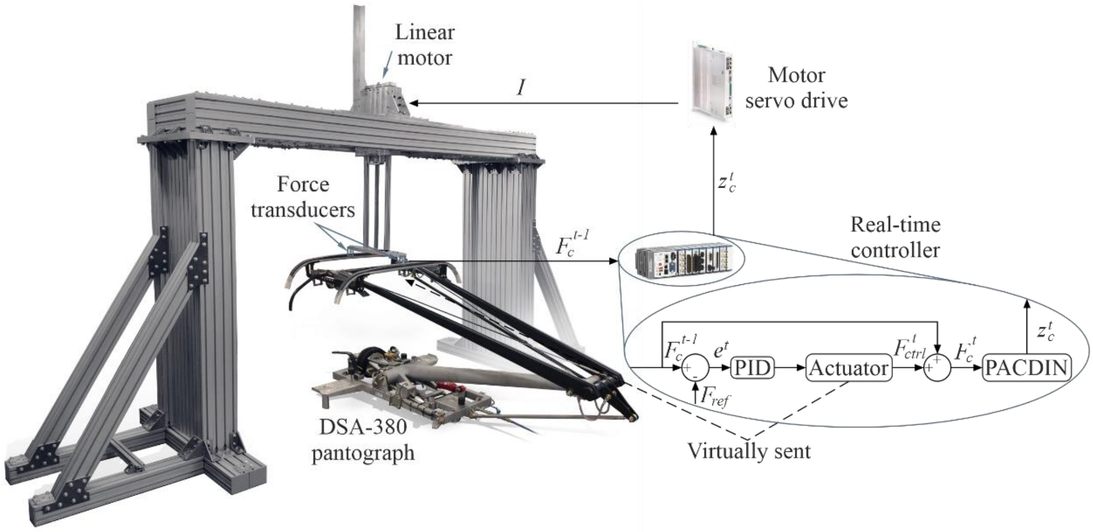

Figure 2: HIL test setup.

2.3.1 Implementation of the PID control

The PID evaluates the control force in the instant t as follows:

$$F_{Ctrl}^{t} = K_P \cdot e^t + K_I \cdot \sum_{\tau=0}^{t} e^{\tau}\,\Delta t + K_D \frac{e^t - e^{t-1}}{\Delta t} \tag{4}$$

where $e^t = F_c^{t-1} - F_{ref}$, the superscript refers the time instant. Since the PID evaluates the control force in each loop, in accordance with equation (1), the actuator delay is $T_{act} = \Delta t = 2\ ms$.

In this work, the parameters of the PID (K_P, K_I, K_D) have been adjusted manually. For each tested value, the current collection quality has been measured following the procedure described in section 2.2. It is not yet intended to obtain a physical element to be installed in pantographs to carry it out, however, the study also includes as a parameter the response time of a possible actuator in anticipation of a future implementation.

3 Results

The contact force measured corresponds to the catenary model based on the C350 Spanish line, with a span length of 65 m. The average force, the standard deviation and the improvement in the current collection correspond to the 10 central spans, thus fulfilling the requirement of the standard UNE-EN 50318. Figure 3 represents: i) the catenary, ii) the initial slope of the contact force necessary to achieve a progressive start of the lineal motor in the tests, and iii) the spans analysed. The vehicle speed is assumed to be 300 km/h.

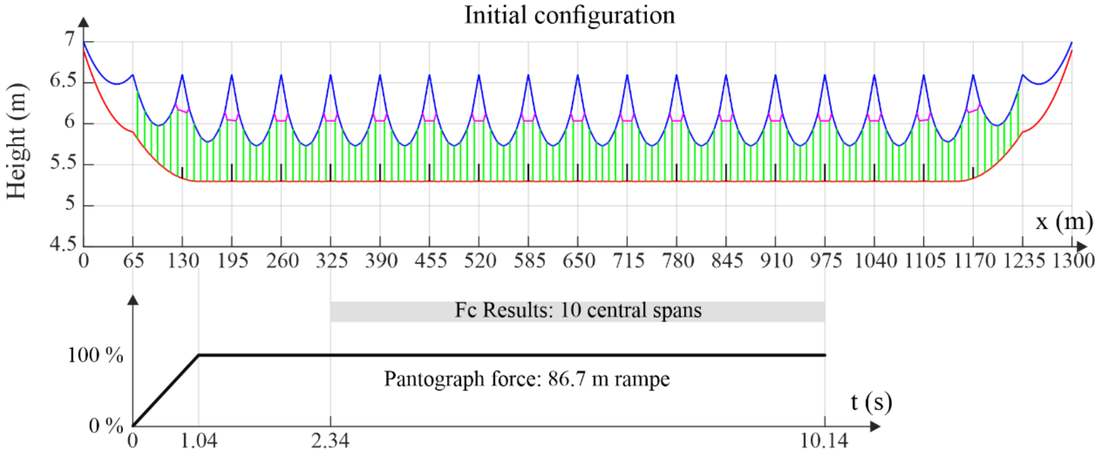

Figure 3: Catenary analysed.

Figure 4 represents the results in a test without control. The graph shows the measured force with the load cells, and the force that is input into the simulation program to obtain the position of the contact point. The magnitudes are filtered with a cutoff frequency of 20 Hz. The first 1.04 seconds, both forces are different since the force applied by the linear motor increases progressively to avoid undesirable dynamic effects. The quality of current collection is obtained from the contact force of the 10 central spans, shaded with a gray box in Figures 3 and 4.

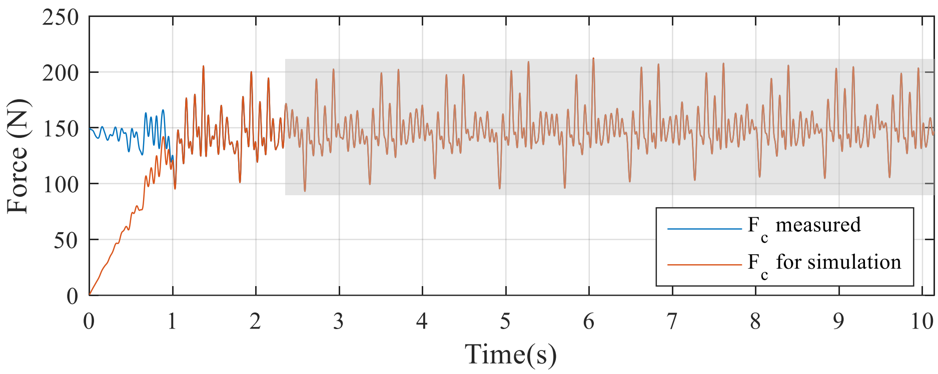

Figure 4: Contact force measured and input in simulation. Test without PID control.

The tests have been carried out with an initial contact force of 150 N. Table 1 shows the mean value, the standard deviation, the maximum, and the minimum values of the contact force.

Mean value (F_m) [N]	Standard deviation (σ)	Minimum (F_{min}) [N]	Maximum (F_{max}) [N]
149.34	18.22	93.19	212.44

Table 1: Force in a test without control.

Note that the average force and the standard deviation meet the range allowed by the standard for the train speed simulated ($v = 300km/h$) equations 2 and 3 provide:

$$F_{m,min} = 102.3\ N$$
$$F_{m,max} = 177.3\ N$$
$$\sigma_{max} = 44.8$$

Table 2 shows the results for the tests carried out with different values of K_P and controller response time (T_{res}). In all of them $F_{ref} = 140\ N$. The improvement has measured as a percentage of the dynamic behaviour achieved without the application of the PID control. In the case of the mean force, the improvement has referred to the desired decrease in mean force calculated with equation (5).

$$\%\ \Delta F_m \text{ improvement} = \frac{149.34 - F_m}{149.34 - F_{ref}} \cdot 100 \tag{5}$$

K_P	T_{res} [ms]	F_m [N]	ΔF_m improvement [%]	σ	σ improvement [%]	F_{min} [N]	F_{max} [N]
0.4	50	146.69	28.37	14.52	20.36	103.16	192.87
0.4	30	147.04	24.65	14.36	21.22	102.54	192.85
0.6	110	146.18	33.87	14.20	22.09	103.18	193.86
0.6	70	145.97	36.06	13.47	26.13	106.76	190.76
0.6	50	146.20	33.60	13.20	27.57	106.99	188.80
0.6	30	146.18	33.78	13.04	28.49	107.50	187.79
0.8	110	145.49	41.26	13.17	27.78	108.99	187.78
0.8	30	145.37	42.55	11.91	34.68	110.88	182.75
0.9	30	145.01	46.32	11.43	37.32	111.71	180.45
1.0	110	144.94	47.12	12.35	32.27	109.52	184.27
1.0	30	144.76	49.02	11.02	39.54	112.88	178.29
1.2	110	144.46	52.23	11.58	36.47	111.21	179.63
1.2	30	144.27	54.33	10.28	43.59	114.85	174.33

Table 2: Results with P control.

The best result corresponds to the highest value of K_P with the shortest response time of the actuator. Figures 5 represents i) the contact force measured with the load cells, ii) the force that is input into the simulation program and iii) the control force virtually apply. The results correspond to the test with the worst and the best improvement of the standard deviation. The ten spans analysed provides similar results, for the sake of clarity, the graphs only show the fifth.

For each value of K_P tested, the results improve when response time of the actuator decreases. The minimum value of the contact force is, in all cases, greater than 100 N, which would guarantee the absence of detachments. Furthermore, the maximum force in all cases is lower than the value obtained in the test without control. It is also observed that for each response time tested, the results improve when K_P increases. Figures 6 shows this trend for response times of 30 ms and 110 ms.

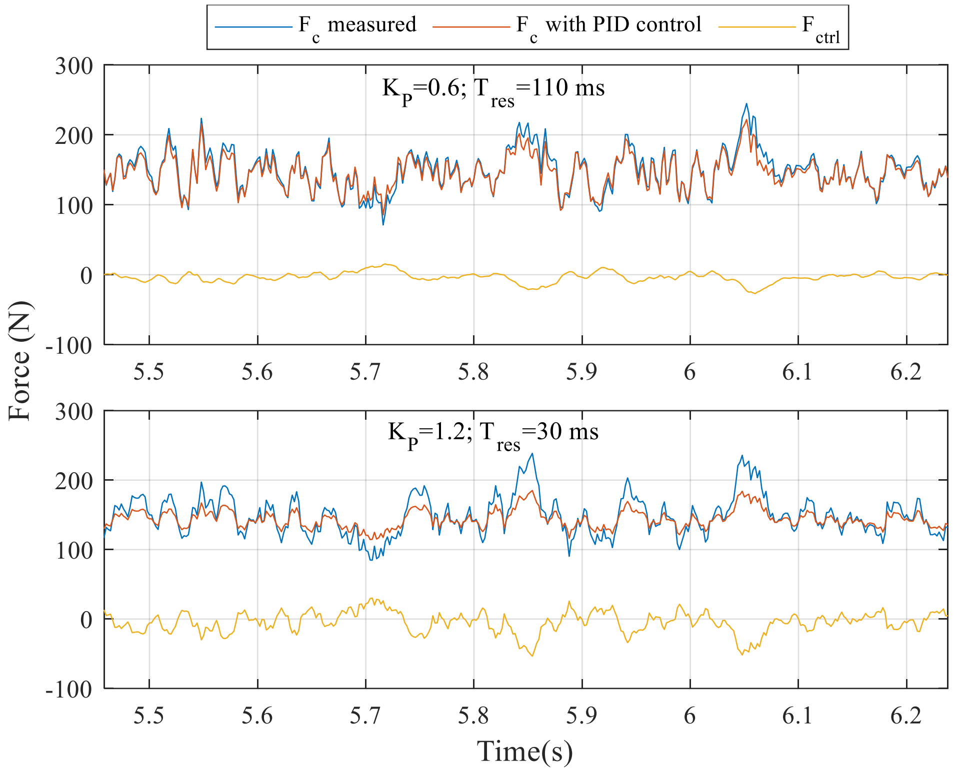

Figure 5: Effect of the PID control on the contact force.

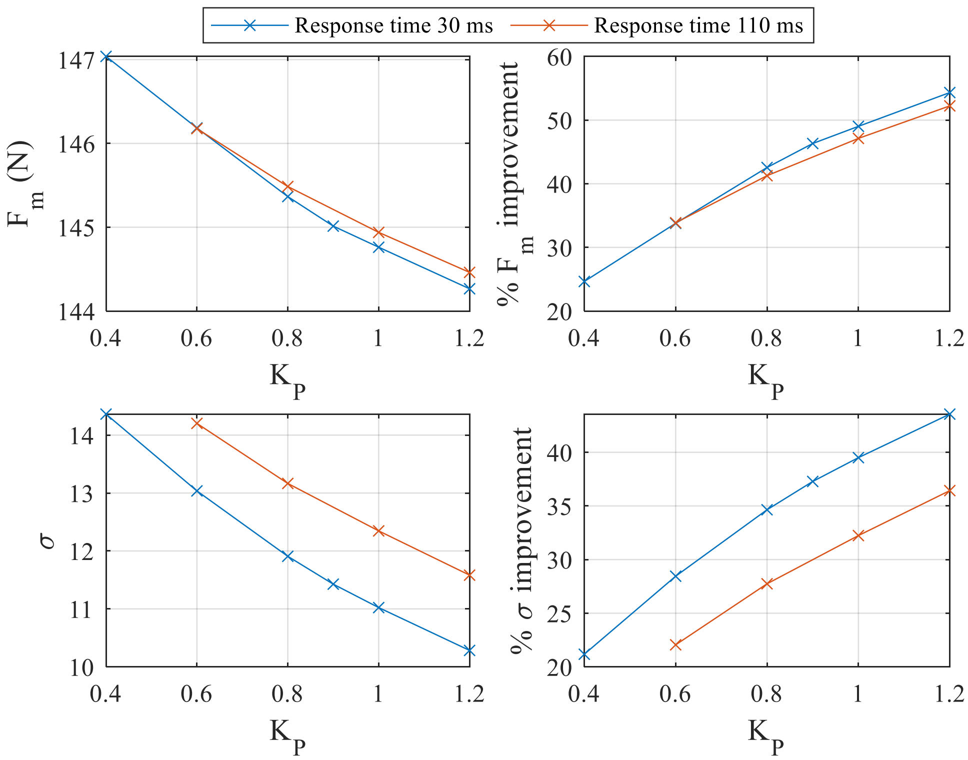

Figure 6: Mean value and standard deviation of the contact force with PID control.

The tests with a complete PID control have been carried out with $K_P = 1.2$, $K_D = 0.0025$ and different values of K_I. The dynamic response is assumed to be a first-order system with time constant, $110/3\,ms$, and unit gain. Table 3 shows the results.

K_I	F_m [N]	σ	F_{min} [N]	F_{max} [N]
0.2	142.71	11.61	110.34	180.19
0.3	142.22	11.54	110.27	179.12
0.4	141.84	11.51	109.56	177.58
0.5	141.58	11.47	109.28	176.76
0.6	141.39	11.50	108.76	176.30

Table 3: Results with PID control.

Compared to the results obtained without PID, both the mean force and the standard deviation show better behaviour. However, the comparison with the test carried out with only proportional control ($K_P = 1.2$), the improvements are not as significant. As expected, increasing the value of K_I decreases the value of the mean force, but does not necessarily decrease the standard deviation of the contact force.

4 Conclusions and Contributions

In this work, a PID control has been implemented to improve the contact force between a pantograph and a railway catenary. The implementation has been carried out on a HIL test bench with a real pantograph and a virtual catenary. In the tests, the control force is applied by a simulated actuator.

The control action seeks to achieve an average force that is as constant as possible. To accomplish this objective, a constant reference force has been imposed in the PID control.

To measure the current collection quality, the average contact force and its standard deviation have been obtained from both the test without control and those from the tests with a PID control. The effectiveness of the control has also been measured as a percentage of improvement compared to the test without control. During the conducted tests, railway standards have been taken into consideration.

In all the tests with PID control, the contact force demonstrated enhancement in comparison to simulations conducted without control. Specifically, both the mean force and the standard deviation of the contact force have decreased without reaching detachment.

As expected, the best results were obtained with higher values of K_P and shorter actuator response times. The influence of K_I and K_D with respect to the use of K_P only is not significant, although it may be necessary to perform a larger battery of tests to find an optimal combination of all the PID parameters.

The next step is to achieve more realistic simulations based on commercial actuators. These devices should be able to provide a control force with a value and response time that significantly improve current collection quality. The possibility of implementing a real device in the test bench available to the authors will also be explored.

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