# Project of a Fuzzy-PI Controller for a Pulsed Plasma Nitriding Power Source

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***Abstract* – The pulsed plasma nitriding process is widely used nowadays in the treatment and hardening of metallic components. But the voltage regulation on the nitriding chamber, although necessary, is hard to be done, because it depends on the components' dimensions, on pulse's width and on the unstable nature of plasma. Taking this in account, this work proposes the use of a Fuzzy-PI controller in the nitriding power source to provide a versatile control, allowing a good voltage regulation under different operation points, that means, for distinct chamber's conditions.**

## I. INTRODUCTION

Since many centuries before Christ, mankind has been using the iron as the main component of its tools and weapons. Today, the material and its uses remain basically the same, but the conditions of use demands much more from the materials, leading the treatment processes to pass through a great improvement during all this time. So, an entire area of study has arisen to research and develop new technologies for the treatment of iron and its most important sub-product: the steel.

During the XIX century, it was discovered that the metal's superficial characteristics define its mechanical and chemical properties. This allowed the development of many chemical treatment processes for hardening and increasing the resistance of metallic components, submitted to extreme operational conditions. In the early 1900's, when the thermal processes were the most employed in industries, the engineer Adolph Machlet studied the introduction of nitrogen in the steel surface, creating the nitriding process.

Since Machlet, the nitriding process has evaluated in three different ways: the gaseous nitriding, the liquid nitriding and the plasma nitriding processes. From these, the plasma nitriding rises over the others due to its lower treatment temperature, lesser process time and increased energetic economy; summing up, for its high efficiency. However, some problems, like the appearing of voltaic arcs and the over-heating of the pieces during the treatment, prejudiced a lot its use in industries. Only with the Power Electronics and Microelectronics development, these problems could be solved through the use of pulsed power sources, creating the pulse plasma nitriding process.

Nowadays, there are still many works about the pulsed plasma nitriding process, trying to achieve more efficiency and control over the process. In this context, this work tries to establish a more flexible control of the voltage applied to the nitriding chamber.

The maintenance of the chamber's characteristics are critical to the quality of the process and requires a precise and reliable control. So, this is an attempt to achieve a better control over the pulsed plasma nitriding process and assure the best product's quality.

## II. PLASMA NITRIDING

The plasma nitriding is a process of bombing metallic surfaces with Nitrogen ($N_2$) and Hydrogen ($H_2$) ions. To execute the process, it is necessary the creation of a plasma atmosphere from the $N_2$ and $H_2$ mixture that is injected in the nitriding chamber. The plasma's creation and maintenance requests the existence of a significant electrical potential difference, which is provided by a high power source near the chamber. So, a complete nitriding module is composed by a vacuum system, a power source and a nitriding chamber, this last one consisting of two parts electrically isolated (anode and cathode) that will be proven to a great electrical potential difference.

During the nitriding process, we should operate with voltages over 500V, pressures between 1 and 10mBar and temperatures near 500°C. However, due to the plasma's unstable nature, these parameters show great variations over the time and need to be rigorously controlled, to keep the gas mixture inside the chamber in the plasma state and assure the process efficacy. Due to this, the power source that provides voltage to the chamber usually controls the others parameters too, allowing their coordination to achieve the process' optimal conditions.

Unfortunately, the plant's behavior relation with these parameters is not well known and it is very difficult to be mathematically modeled. The causes are many: the unstable nature of plasma, the occurrence of voltaic arcs between the chamber's anode and cathode, the forms and dimensions of the pieces to be treatened, among others. So this is the reason for our proposal of implementing a Fuzzy-PI controller: to allow a intuitive control of the process, instead of the mathematically based control that we couldn't develop properly.

### *A. Available Equipments*

In this research, was used a pulsed plasma nitriding module composed by a vacuum system, a 350mm diameter and 400mm width nitriding chamber, a 2kW continuous power source and a 1kW pulsed power source (built as part of [2]).

The pulsed power source shows three significant advantages over the continuous power source:

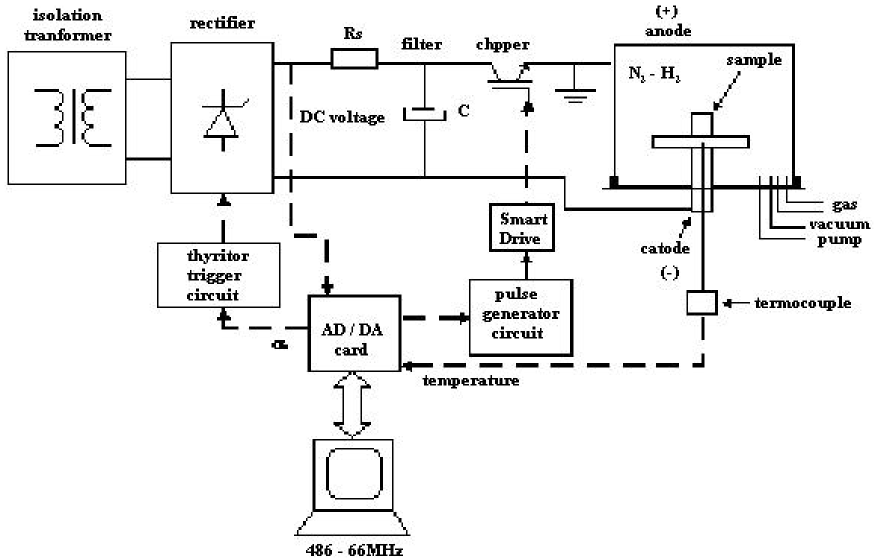

Fig. 1. Pulsed plasma nitriding power source diagram.

The first one is the power economy, because the duty cycle is variable and the average power applied to the chamber is always lesser or at least equal to the power applied by the continuous source.

Second is that, by means of the duty cycle, we can control the power applied to the chamber and then avoid the over-heating of the components treated.

The third advantage is that the use of voltage pulses with frequencies between 1kHz and 10kHz eliminates the occurrence of voltaic arcs during the process, because the pulse's width is not long enough to allow the accumulation of ions that can generate an arc.

Unfortunately, the use of a pulsed power source inserts one more parameter to be considered in the process control. The width of the applied pulses modifies the chamber's characteristics and interferes significantly in the behavior of the plasma placed in there. Once again, the use of a simpler and intuitive control for the process becomes necessary to provide a better adaptability to new operations points.

For the controller's implementation, we will work only with the pulsed power source, which is the most used in industries and it is more interesting to us. The complete power source's diagram can be seen in Fig. 1 and it is composed basically by an hybrid bridge rectifier in series with an IGBT acting as a chopper. Completing the system, we have an RC filter in the rectifier's output, a thyristor trigger circuit based on a TCA 780, a pulse generator circuit and a smart-drive for the IGBT's control, a galvanic isolation transformer and a 66MHz PC 486 equipped with a data acquisition card to execute the process' control.

*B. Plant's Modeling*

The nitriding process control loop is showed in Fig. 2. The controller receives the error signal as its input and outputs a voltage correspondent to the thyristors' triggering α angle. By controlling the α angle, the controller can establish the desired voltage in the rectifier's output, that will be filtered by a RC filter to decrease the ripple significantly and then will be applied to the nitriding chamber. The voltage supplied by the rectifier depends on α angle and it is given below:

$$V_a = \frac{V(1+\cos a)}{p} + \sum_{n=1}^{\infty} [a_n \cos(nwt) + b_n \,\mathrm{sen}(nwt)] \quad (1)$$

It is a typical non-linear function that is also limited to some α values, due to the following RC filter (the thyritors cannot conduce when the voltage stored at the capacitor is greater than the voltage supplied by the net). So, the rectifier itself is a non-linear system.

The chamber, on the other hand, can show resistive, inductive and/or capacitive behavior, changing its values greatly during the process. For this reason, it is represent by a variable impedance Z. The IGBT works at high frequencies (nearly 10kHz) and does not interfere significantly in the filter dynamics. However, its duty cycle changes the equivalent impedance of the chamber, mainly its reactance, in a very difficult way to be modeled. So, we preferred to ignore the IGBT in the scheme and consider its effects as some of the many variations the chamber suffers during the time.

The controller's objective is to keep the voltage on the chamber equal to the reference voltage, defined by the user in the computer that commands the process. The controller will do this by monitoring the output voltage and adjusting the α angle of thyristor triggering to control the hybrid rectifier's output voltage. So, we will use just one variable control (α angle) defined from the difference between the reference voltage and the voltage in the chamber (error).

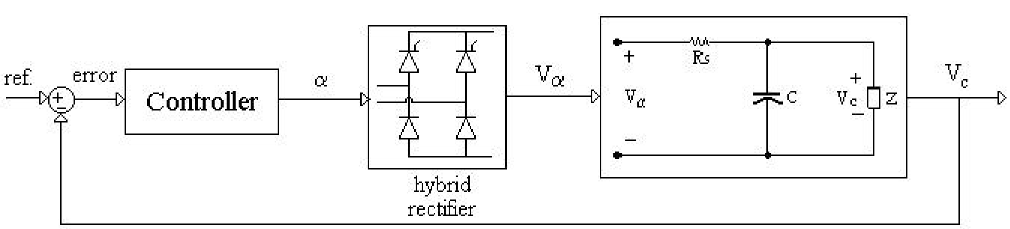

Fig.2. Nitriding Process Control Loop

$$\frac{\Delta V_C}{\Delta V_\alpha} = \frac{a}{s + \frac{1}{Z(s).C} + a}$$

$$\frac{a}{s + \frac{1}{RC} + a} \quad \textit{Resistive Behavior}$$

$$\frac{(\frac{R}{L} + s)a}{s^2 + \left(\frac{R}{L} + a\right)s + \frac{1}{LC} + \frac{R}{L}a} \quad \textit{RL Behavior (similar to RC)}$$

$$\frac{(\frac{1}{LC_v} + \frac{R}{L}s + s^2)a}{s^3 + \left(\frac{R}{L} + a\right)s^2 + \left(\frac{1}{LC} + \frac{1}{LC_v} + \frac{R}{L}a\right)s + 1} \quad \textit{RLC}_v \textit{ Behavior}$$

$$\textit{with } a = \frac{1}{R_S C}$$

Fig.3. Possible transfer functions for the RC filter and nitriding chamber association.

The transfer function of the association between the RC filter and the nitriding chamber, relating the rectifier's output voltage $V_\alpha$ with the voltage applied to the chamber $V_C$ and presented in Fig. 2, is very easy to be found, but depending on the electrical characteristics the chamber presents during the time, it can evaluate to three very different situations, according to Fig 3:

As can be seen, depending on the chamber's characteristics, we may have a simple one pole plant, a two pole and one zero plant or a three pole and two zero plant. So, it is evident that a simple PI controller cannot handle these three very distinct situations properly. The solution is the implementation of a flexible controller that, although does not achieve a better performance than a PI controller designed for one plant only, maintains a good performance for that and many others different plants. This capability is well achieve with Fuzzy Logic, so this is one reason for our choice.

The other reason is a consequence of the hybrid rectifier used to provide the voltage to the chamber. It is a non-linear device, so it is more adequate to be controlled by a non-linear controller that could compensate its particularities. Putting these two reasons together, and adding the fact that a PI approach would be easier to implement and to evaluate its results, we got to the idea of the Fuzzy-PI controller.

The Fuzzy-PI's main advantages over conventional PI control are that the Fuzzy-PI does not have a specific operation point, allowing it to maintain a good performance under different operation points; and that we can, also, implement non-linear control strategies, to improve its efficiency under specific circumstances. These two benefits are explored in our controller so we can achieve its best performance.

## III. Fuzzy-PI Control

The idea of implementing a Fuzzy-PI controller appeared to compensate the deficiencies of the already implemented PI controller [2]. The PI approach will be maintained, but in spite of the mathematical formulation previously developed, it will be used an empiric knowledge base for adjusting more efficiently the voltage applied to the chamber.

For the Fuzzy-PI implementation, it was taken in account the error (difference about the reference voltage and the sampled voltage) and the error variation. From theses variables, it will be deducted the control signal's variation. This approach derives from the PI controller's definition:

$$u = K_P.e + K_{i.}\int e.dt \qquad (2)$$

Deriving both sides, we get an equation that relates the variation of the control signal $\Delta u$ with the error $e$ and the variation of the error $\Delta e$, through two gains defined as $K_p$ e $K_i$:

$$\Delta u = K_P.\Delta e + K_i.e \qquad (3)$$

We want to replace this function, where $K_p$ e $K_i$ are constants and must be defined, mathematically or empirically, for a group of simple and intuitive rules that are more efficient on controlling such a complex plant.

So, following a procedure similar to that one adopted in [4], we defined five fuzzy sets to classify our input variables: PM (positive medium), PS (positive small), ZE (zero), NS (negative small) and NM (negative medium). For each variable taken in account, we have a different membership function to classify the sample into a concept (fuzzification). The determination of each one of these membership functions is completely empirical and implied in many tests to find out the optimal values and ranges for the nitriding process (controller's tuning).

After the correct transformation of the controller's numerical inputs in concepts like PM, ZE, etc, through the minimum weight rule (fuzzification), we defined the fuzzy control rules adopted to estimate the output value, shown in table I:

Table I
Rules Table for the Control Signal Variation

| | | Error | | | | |
|---|---|---|---|---|---|---|
| | | **NM** | **NS** | **ZE** | **PS** | **PM** |
| Error Variation | **NM** | PM | PM | PM | PS | ZE |
| | **NS** | PM | PS | PS | ZE | NS |
| | **ZE** | PM | PS | ZE | NS | NM |
| | **PS** | PS | ZE | NS | NS | NM |
| | **PM** | ZE | NS | NM | NM | NM |

In Table I, we submit our error and error variation concepts and obtain a concept for the control signal variation, without defining any constants $K_p$ or $K_i$ that would be necessary in (3). With the result obtained from this table, we go to the process of defuzzification, where we transform our result concept in the variation of the control signal that will be applied to the plant, according to the center-of-area method.

Then it is necessary to sum the control signal variation obtained from the Fuzzy-PI with the control signal previously applied, through an integrator in the controller's output. Doing this, we obtain the control signal that will define the trigger angle of the thyristor in the hybrid rectifier.

Before outputting this signal from the computer, it needs to be multiplied by a constant that will condition the signal according to the limitations of the computer's output and the TCA 780's input. This constant will be defined according to the values adopted by the TCA 780 for each trigger angle.

## IV. EXPERIMENTS AND RESULTS

To test the controller, a new rectifier was built following the same scheme of the nitriding plasma source. Instead of the chamber, two circuits were used, one with pure resistive behavior and the other one with resistive-capacitive behavior, which could be commuted using a simple switch. This possibility was included in order to allow us to simulate the transitories in the chamber's electrical characteristics.

The resistive plant, associated with the RC filter in the rectifier's output, have the following transfer function:

$$G(s) = \frac{40}{s + 43.33} \tag{4}$$

Considering that this is the chamber's predominant behavior, it was considered the default situation and both controllers were tuned to achieve its optimal performance with this plant.

The transfer function for the resistive-capacitive plant is:

$$G(s) = \frac{300(s+10)}{30s^2 + 304s + 100} \tag{5}$$

With these two plants, we did some experiments to determinate if the Fuzzy-PI was really a best option for the process control.

The first step was to compare the two controllers' reaction to a increase in the voltage applied to the purely resistive plant. The PI controller went from 10V to 90V in 115ms (fig. 4), while the Fuzzy-PI did the same in 250ms (fig.5). This was already expected, because the PI controller was tuned for this situation and it is still the best choice for static or low-varying plants.

Then, we experimented a fast transition between the resistive plant and the resistive-capacitive plant, to see which of the two controllers would react best. The PI suffered a variation of nearly 10V and stabilized in 280ms (Fig. 6). The Fuzzy-PI also had a variation of nearly 10V, but stabilized in 250ms.

Although their reactions looked very alike, the Fuzzy-PI's behavior is smoother compared with the PI controller. This happened because the PI controller was not tuned for the new situation, and it reacts very abruptly as if the reference voltage level were changed.

## V. CONCLUSIONS

These results have shown that the Fuzzy-PI controller acts as well as the PI controller. The PI is faster to achieve the desired voltage with a resistive plant, but shows more variations to compensate transitories.

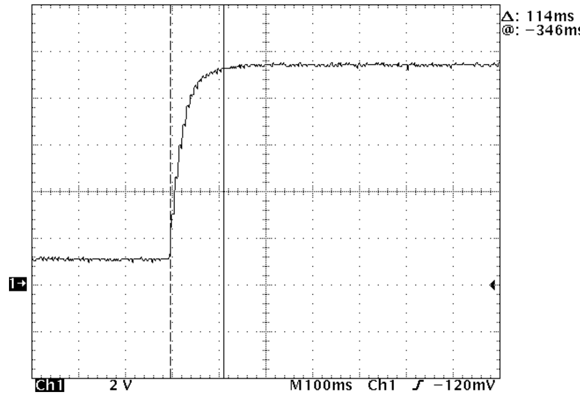

Fig.4. Voltage step from 10V to 90V with a PI controller.

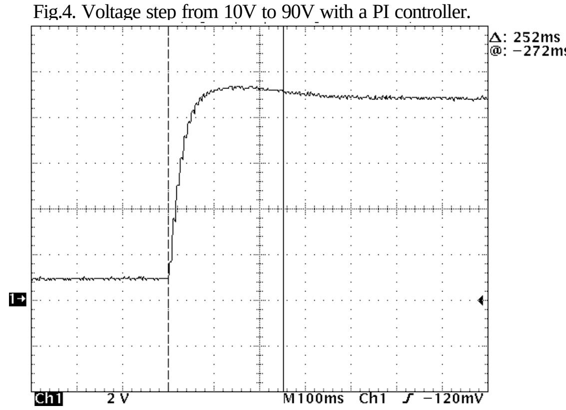

Fig.5. Voltage step from 10V to 90V with a Fuzzy-PI controller.

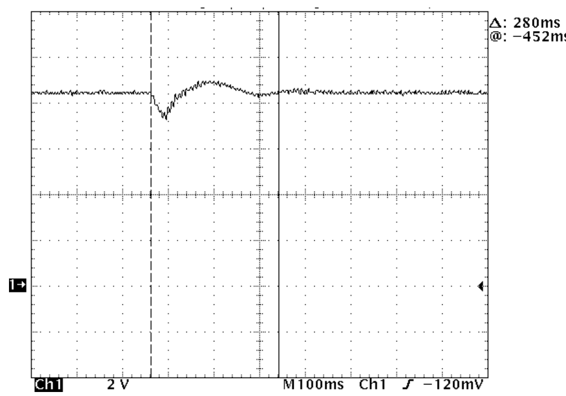

Fig.6. Transition to an RC plant with a PI controller.

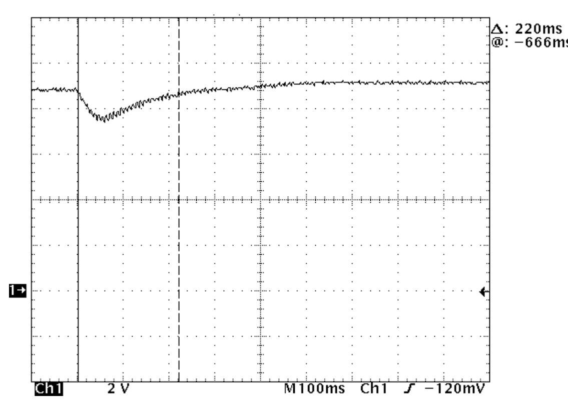

Fig.7. Transition to an RC plant with a Fuzzy-PI controller.

This does not happen with the Fuzzy-PI, which shows softer and shorter variations, because it does not have a specific operational point. If we keep in mind that the real chamber shows great variations all over the time (during just a few milliseconds), the Fuzzy-PI seems to be the best solution, because it will allow a smoother voltage regulation.

Unfortunately, we could not test the Fuzzy-PI controller in the nitriding chamber, because it has been repaired to fix some problems. But as soon as the nitriding chamber works properly, we'll test and compare the two controllers again in the real process.

What we expect is that in those critical conditions (with the chamber's parameters varying greatly all the time) the differences between the PI controller and the Fuzzy-PI controller become more evident and that they justify the use of a Fuzzy Logic based controller to assure the best voltage regulation on the chamber.

After all, like any industrial process, the pulsed plasma nitriding needs to be reliable and efficient under different operation conditions, and the Fuzzy-PI controller can certainly attend to these requirements.

## VI. References


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