POLYNOMIAL CONTROLLER FOR AC-DC CONVERTER WITH POWER FACTOR CORRECTION

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ABSTRACT
This paper deals with the control of a AC-DC converter with power factor correction (Boost PFC). The polynomial controller named RST by the three polynomials which constitute it, R(z), T(z) and S(z), is applied to the loop voltage and the loop current is controlled by hysteresis. This kind of controller generalizes the structure of the PID one. Simulation and experimental results show that modelling the open voltage loop by a first order system gives good results supported by a THD satisfying standard IEC even the system presents nonlinearities. Teaching and industrial applications are taken into account: it is the reason of using Labview with the peripheral NI 6009.

Keywords: Boost PFC, RST controller, hysteresis, total harmonic distortion (TDH), Labview

1. INTRODUCTION

Currently, there is apparition of the increased use of the apparatuses, primarily in the informatics fields and in the field of the electric household appliances, requiring supply provided with converter AC-DC using capacitor filters. Although of lower cost, this type of supply generates harmonics in the network. These current harmonics can generate problems for the energy distributor (Feld 2009):

- Increase of line losses
- accelerated ageing of the condensers of compensation because of their low impedance: their rated current may be exceeded
- over sizing of the transformers of distribution

The rate of re-injection of these current harmonics can be quantified by the harmonic rate of distortion TDH.
The power-factor fp is defined by:

$$f_p = \frac{P}{S} = \frac{V.I_1.\cos\varphi_1}{V.I} = \frac{I_1.\cos\varphi_1}{I} \quad (1)$$

With
S, P, indicating respectively, apparent power, active power
I, I_1,φ_1 : the effective value of the AC current, the effective value of fundamental of current, dephasing enters the tension and the fundamental current. The effective value of current is:

$$I = \sqrt{\left(\sum_{k=1} I_k^2\right)} = \sqrt{I_1^2 + \sum_{k=2} I_k^2} \quad (2)$$

I_k , harmonic of current of rank k
The expression of the THD is also defined as:

$$TDH = \sqrt{\left(\frac{I_2}{I_1}\right)^2 + \left(\frac{I_3}{I_1}\right)^2 ...} = \frac{1}{I_1}\sqrt{\sum_{k=2} I_k^2} \quad (3)$$

So, according to these three relations:

$$f_p = \frac{\cos\varphi_1}{\sqrt{1+TDH^2}} \quad (4)$$

The power-factor fp is thus related to the harmonic rate of distortion TDH. It means that this TDH may be an adapted parameter to quantify the harmonic degree of pollution on the network. In all that follows, it will be taken as index of comparison (in practice TDH expressed in % is used).
With a purely sinusoidal fundamental current and in phase with the voltage, a power-factor approaches the unit value (fp = 1).

Figure 1 and Figure 2 show respectively the current and voltage waveforms as well as the output voltage for a traditional rectifier (C = 470 [µF] and R = 328 [Ω]) and the resulting of current spectrum.

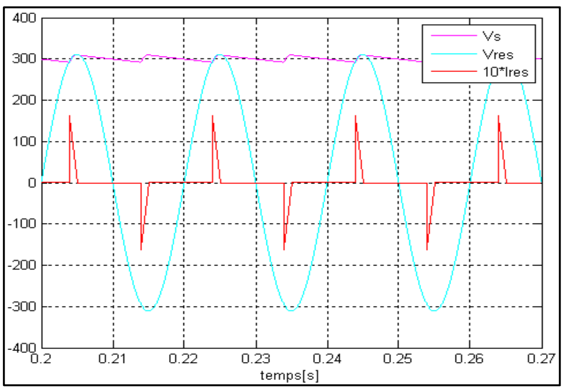

Figure1: Current and voltages waveforms

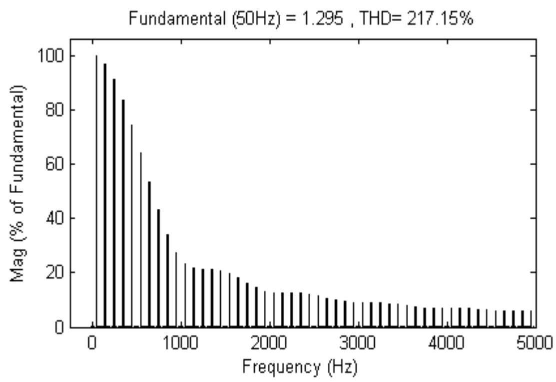

Figure 2: Current spectrum resulting

To bring solution of this problem, various strategies are proposed whose principal objectives are summarized as follows (Benaïssa 2006), (Razafinjaka 2008),(Tédjini 2008), (Singh 2003), (Keraï 2003):

- Obtaining a sinusoidal current network and in phase with the tension
- Or ensuring the smallest possible TDH in order to respect the standard normalizes: IEC-61000-3-2 for example for the systems of class D.
- Ensuring a voltage output constant

The generalized structure is shown in Figure 3.

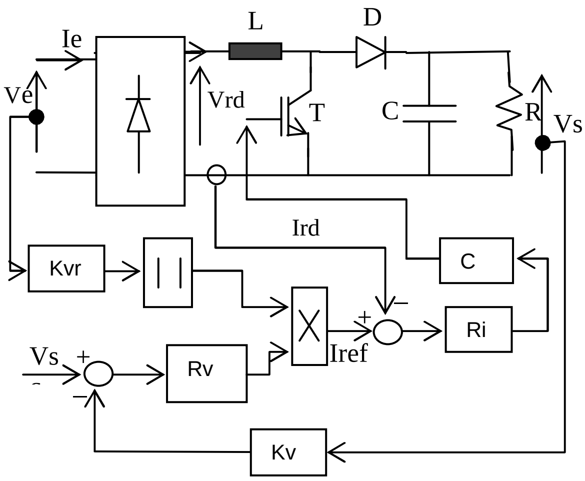

Figure 3: Structure for boost PFC

The existence of two loops is highlighted. The reference of the current Iref is obtained by multiplying the output voltage regulator by a party (K*Vrd) of rectified voltage. The output current regulator is treated in a shaping circuit CMF to obtain the command u(t) used to control the static inverter CS.

In this paper, the structure using polynomial RST for the loop tension and hysteresis control for the loop of current are used. First the loop of current is studied to obtain some conditions having a perfect loop in comparison with loop voltage. A structure using regulator PI is first used for the voltage loop to compare results. Modeling is then necessary for the synthesis of this kind of regulator. The model obtained is used when RST controller, primarily a numerical type, is applied.

2. STRUCTURE WITH PI CONTROLLER

In this case, voltage loop is controlled by a PI regulator and the current loop by a hysteresis (Figure 3).

2.1. Current loop

The control by hysteresis is selected for the current loop because the nonlinear model of the static inverter is. However, it is necessary to express the quench frequency in order to establish a dimensioning of inductance L.

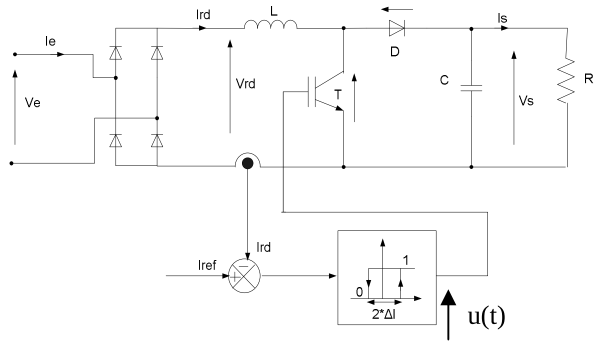

Figure 4: Control current scheme

The set value of current Iref (see Figure 4) must be in phase with the tension. It is also needed to ensure Iref ≈ Ird (Feld 2009): a fast variation of Ird around its reference Iref must be then satisfied which implies a high chopping frequency (Fd >10[kHz]). A value of inductance L according to the undulation of current ΔI must be so determined for this purpose. The value of the output voltage V_s and the effective value V_{rd} are considered as constant. When the variation of Ired around its reference Iref is supposed obtained, the output voltage Vs, and the effective value Vrd are considered as constants (Multon 2003), (Feld 2009). The expression is given by:

$$F_d = \frac{1}{T_d} = \frac{Vrd(Vs - Vrd)}{2.L.\Delta I.Vs} \tag{5}$$

The figure 5 shows curves giving Fd according to the inductance L for imposed ΔI. In this case, Vs = 400 [V], Vrd = 235 [V], ΔI = ± 0,1[A], ±0,2 [A], ± 0,3[A]

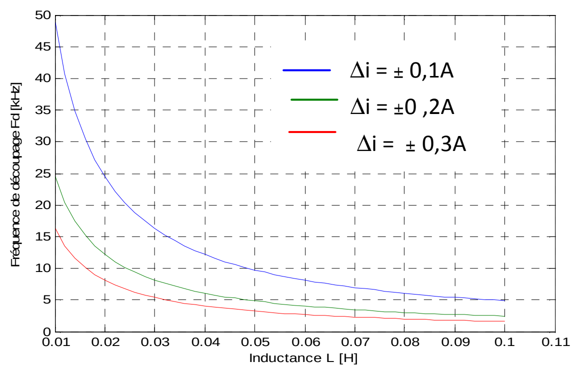

Figure 5: Curves giving Fd according L

2.2. Voltage loop

The voltage loop gives the signal which will act to the reference current Iref. This current must have an sinusoidal form conformed with the network voltage.

It is assumed that current loop is faster than the voltage one and every time Ired = Iref. It is there possible to adopt the following approximation obtained by modelling by assessment of power (Feld 2009):

$$\frac{V_s(p)}{I_{red}(p)} \simeq \frac{V_s(p)}{I_{ref}(p)} \quad (6)$$

So

$$\frac{V_s(p)}{I_{red}(p)} = \frac{V_M}{4.V_S} \times \frac{R}{1+\frac{RC}{2}p} \quad (7)$$

Where, VM is the peak value of the network voltage, Vs the value of the output voltage, R represents the load resistance and C the capacitor.

The opened loop is defined by a first order t function. (8)

$$G(p) = \frac{K}{1+pT}$$

With $K = \frac{V_M . R}{4 . V_S}$ and $T = \frac{RC}{2}$ (9)

A PI regulator is sufficient to control such system. Its function transfer may be expressed like followed:

$$G_R(p) = \frac{1+p.AT_i}{pT_i} \quad (10)$$

The gain A and the constant time Ti can be determined by imposing a frequency Fc for the closed loop. Assuming that the transfer function for opened loop Go(p) is:

$$Go(p) = G_R(p).G(p) = \frac{1+pAT_i}{pT_i} . \frac{K}{1+pT} \quad (11)$$

It is possible to pose by method compensation:

$$A.Ti = T \quad (12)$$

The transfer function for closed loop is:

$$H(p) = \frac{Go(p)}{1+Go(p)} = \frac{1}{1+p\frac{T_i}{K}} \quad (13)$$

Imposing frequency Fc according the relation (13) gives Ti and then the gain A by relation (12).

Figure 6 shows the simulation results when frequency at closed loop is Fc= 5 [Hz] and FC=15[Hz]. Current waveform at steady state and the spectrum analysis at the frequency Fc = 5 [Hz] are presented respectively in Figures 7 and 8.

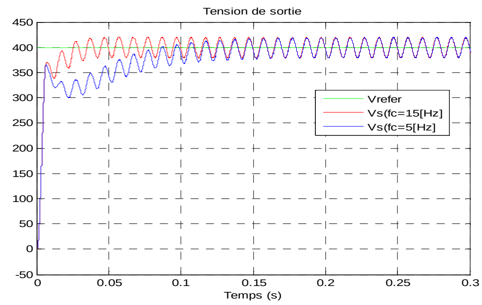

Figure 6: Step responses of Vs at Fc=5[Hz] and Fc=15[Hz]

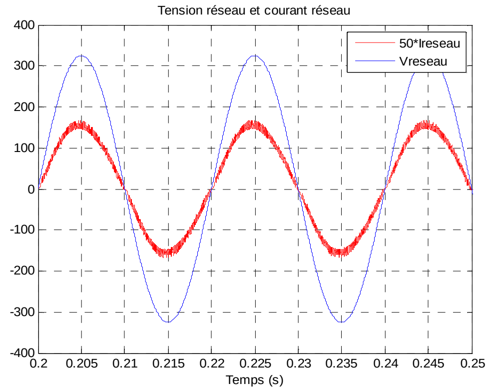

Figure 7: Current network waveform (Fc = 5[Hz])

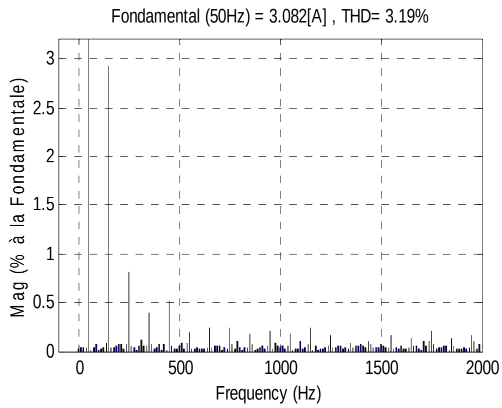

Figure 8: Current spectrum (Fc = 5[Hz])

Following conclusions can be expressed:

- The current is sinusoidal and in phase with the voltage
- More the frequency loop is higher more the regulation is faster but the harmonic rate distortion of the current is higher
- F_c= 5 [Hz] TDH = 3,19%
  F_c = 15 [Hz] TDH = 7,62 %

3. STRUCTURE WITH RST CONTROLLER

In this case, numerical regulation is applied for the loop voltage because RST controller is primarily numerical. The current loop is always controlled by hysteresis command. Using RST controller, the functional scheme is given by Figure 9. The basic idea is to search the three polynomials R(z), S(z) and T(z) to have correspondence. The closed transfer function $H_m(z)$ is given: it represents the desired model.

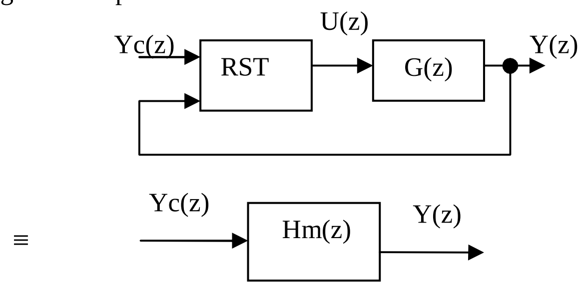

Figure 9: Basic schemes for RST calculation

The RST controller generalizes the law of command obtained by a classic one.

$$R(z).U(z) = T(z).Yc(z) - S(z).Y(z) \qquad (14)$$

Where R(z) , T(z) and S(z) are polynomials and R(z) is selected as a normalized polynomial.
Having G(p), the discrete transfer function G(z) can be calculated with a sampling period h :

$$G(z) = (1 - z^{-1})Z\left\{L^{-1}[\frac{G(p)}{p}]\right\} \qquad (15)$$

Where Z denotes the discretization operation and L^{-1} the inverse operation of Laplace's transformation.
Using the relation (8), G(z) is as followed:

$$G(z) = K\frac{1 - e^{-h/T}}{z - e^{-h/T}} \qquad (16)$$

It is more practical to use the following form for G(z):

$$G(z) = \frac{b_o}{z - z_o} = \frac{B(z)}{A(z)} \qquad (17)$$

Where bo and zo are related to K, h and T. The polynomials B(z) and A(z) have no common factor.

According Figure 9, Y(z) = G(z).U(z) (18)

Using relations (14) and (17), the closed loop function transfer is given as:

$$\frac{Y(z)}{Yc(z)} = \frac{B(z).T(z)}{A(z).R(z) + B(z).S(z)} \qquad (19)$$

Assume that the desired closed loop is:

$$H_m(z) = \frac{B_m(z)}{A_m(z)} \qquad (20)$$

Relations (19) and (20) give:

$$\frac{B(z).T(z)}{A(z).R(z) + B(z).S(z)} = \frac{B_m(z)}{A_m(z)} \qquad (21)$$

To obtain relation (21), it can be posed:

$$B(z).T(z) = Ao(z).Bm(z) \qquad (22)$$

$$A(z).R(z) + B(z).S(z) = Ao(z).Am(z) \qquad (23)$$

Where Ao(z) is defined as the observant polynomial.

The polynomial B(z) is defined as follow:

$$B(z) = B^+(z).\ B^-(z) \qquad (24)$$

There are several methods to calculate the polynomials RST: with zero cancellation or without zero cancellation. Both methods can be completed by compensation of disturbance. All these methods lead in the resolution of Diophantine equation:

$$A_1(z).R_1(z) + B_1(z).S_1(z) = C(z) \qquad (25)$$

Where the unknown polynomials are $R_1(z)$ and $S_1(z)$.

Theorem (Longchamp 1991)

There is a causal RST when these conditions are verified:

$$\deg(A_m) - \deg(B_m) \geq \deg(A) - \deg(B) \qquad (26)$$

$$\deg(Ao) \geq 2.\deg(A) - \deg(A_m) - \deg(B^+) -1 \qquad (27)$$

In several cases, $H_m(z)$ is selected as followed:

$$H_m(z) = \frac{B^-(z)\frac{P(1)}{B^-(1)}}{z^d.P(z)} \qquad (28)$$

Where z^d is chosen to respect (23).

The polynomial P(z) is generally as followed:

$$P(z) = z + c \qquad (29)$$

$$P(z) = z^2 + c_1 z + c_2 \qquad (30)$$

In these expressions, the different coefficients c, c_1, c_2 are selected to ensure the absolute and relative conditions of damping.
To ensure permanent error e_p equal to zero, $H_m(z)$ must verify:

$$H_m(1) = 1 \qquad (31)$$

This condition is obtained by using the relation (28). Even integrating effects are introduced this error cannot be cancelled if this condition is not checked.

3.1. Algorithm

According the form of G(z), there is no zero to be cancelled here. So,

$B^{+}(z) = 1$ and $B^{-}(z) = B(z)$ (32)

The Diophantine equation gives R(z) and S(z). The relations (24), (28) and (32) imply that:

$B_m(z) = B(z).B'_m(z)$ (33)

With

$$B'_m(z) = \frac{P(1)}{B^{-}(1)} \quad (34)$$

The polynomial T(z) is calculated as followed:

$T(z) = B'_m(z).Ao(z)$ (35)

3.2. Application for the loop voltage

It already said that there is no zero to be cancelled. In this study, the case with no perturbation compensation is used. A first degree polynomial P(z) degree can be selected: it ensure the absolute condition of damping.
In this case, the observant polynomial Ao(z) is defined like followed:
deg(Ao) = 0 and Ao(z) = 1 (36)

By solving equation (26) and using relation (27), the polynomials RST verify:

deg(R) = deg(S) = deg (T) = 0 (37)

$R(z) = 1$ $S(z) = s_1$ $T(z)= t_1$ (38)

The relation (14) gives the implemented law:

$u(k) = t_1.yc(k) - s_1.y(k)$ (39)

For the practical test, an autotransformer which can deliver variable voltage is used. To ensure a boost function, Vrd < Vs. First, the conditions are:

$$V_{rd} = 60\sqrt{2} \text{ [V]} \qquad Vs = 90 \text{ [V]} \quad (40)$$

The figure 10 shows the front panel. The teaching applications are taken into account for this purpose.

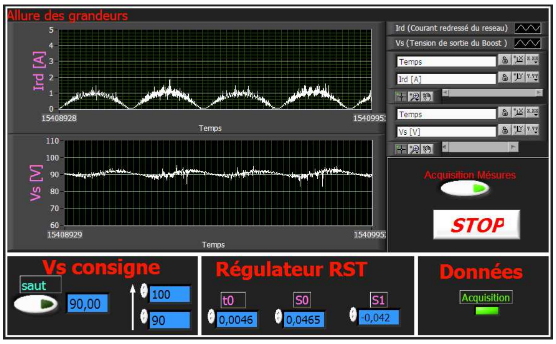

Figure 10: Front panel window

The complete stand is presented by Figure 11.

Figure 11: Complete stand for boost PFC

3.3. Results

The results obtained by simulation using Matlab and Simulink are given by Figure 12 and Figure 13. The set value of Vs is here: Vsc= 90[V]. These comments can be notified:

- The current is sinusoidal and in phase with the voltage (Figure 12).
- The THD is 3,74 %. It is more than the THD obtained by regulator PI (3,19% - Fc= 5[Hz]) but the regulation is more faster.

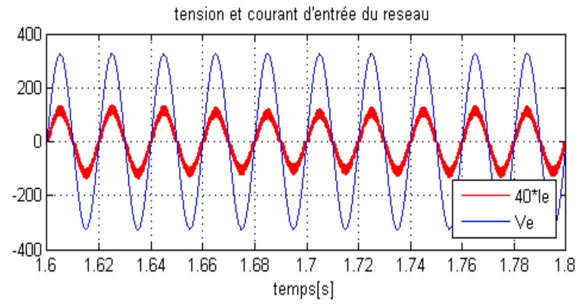

Figure 12: Voltage and current waveforms

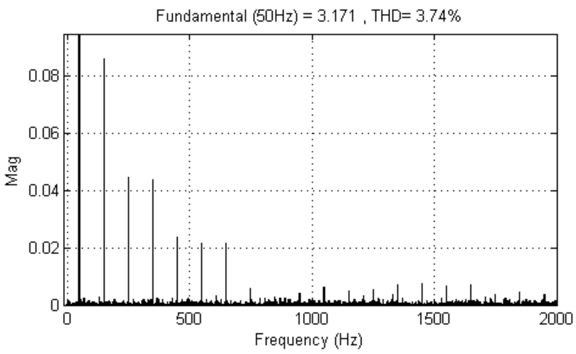

Figure 13: Current spectrum (THD=3,74%)

In Figure 14 and Figure 15, the simulations and the experimental results are given in steady states. The corresponding must be notified.

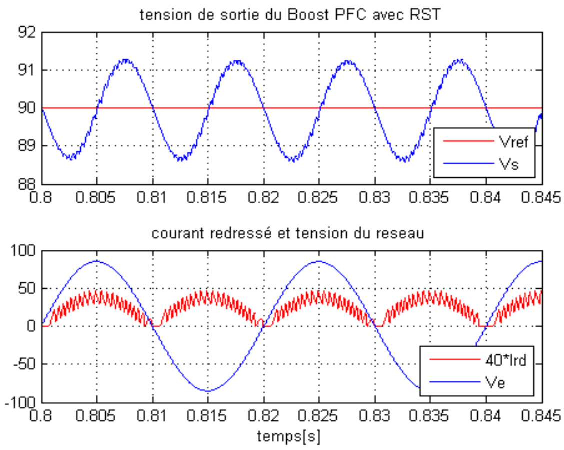

Figure 13: Steady state by simulation

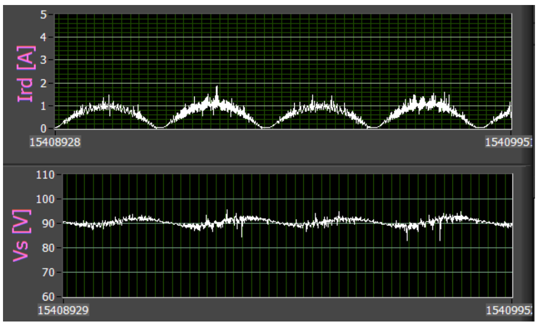

Figure 14: Experimental result (Vsc = 90 V)

Figure 15 show the result when the set value of voltage is Vsc= 100 V.

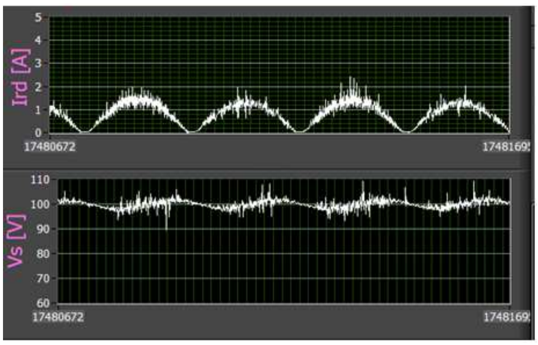

Figure 15 Experimental result (Vsc = 100 V)

In all these applications, the undulation at a frequency 100 [Hz] is present around Vs. His amplitude depends on the value of C. From the principle of the power factor correction, it cannot be eliminated. It is necessary to note that more the value of C is higher more this amplitude of Vs decreases but more the effects of harmonics current increase.

CONCLUSION

In this paper, polynomial RST controller is used for a boost PFC. Modeling the loop voltage as a first order system is sufficient even there is nonlinearity created by the static inverter. The RST controller gives good results in comparison with the classic PI one. The same TDH is obtained but the great difference is located especially at the velocity of the regulation. It must be noted that if the regulation with corrector PI is wanted to be faster, the distortion of the current waveform increases.

Labview with the peripheral NI 6009 is used for the applications. Teaching and industrial applications are aimed at same time. The implementation with Labview gives possibility to visualize the effects by varying the different coefficients of the RST controller. Applying nonlinear control like fuzzy command is also possible by using Labview.

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