Robust control of a UPFC system with H∞ control technique

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Article Info	ABSTRACT
  	FACTS (Flexible AC Transmission Systems) technology has now been accepted as a potential solution to the stability problem and load flow. The Unified Power Flow Controller (UPFC) is considered to be the most powerful and versatile among all FACTS devices. This paper presents the control of a UPFC system using H∞ robust control technique. A simulation study using Matlab/Simulink is presented to the performance of this control strategy and the robustness with respect to variations of the system parameters such as the inductance of the transmission line.

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1. INTRODUCTION

The Unified Power Flow Controller (UPFC), is among the FACTS devices that have attracted the attention of many researchers because it is capable of simultaneously and independently controlling the flow of active and reactive powers in a network. The UPFC combines a shunt compensation, (Static Compensator or STATCOM), and a series compensation (Static Synchronous Series Compensator or SSSC) and has the ability to control three parameters associated with the transit of powers namely the line voltage, the impedance of the line and the load angle. The UPFC is placed on the transmission line between the source and the load as shown in Figure 1 [1, 2].
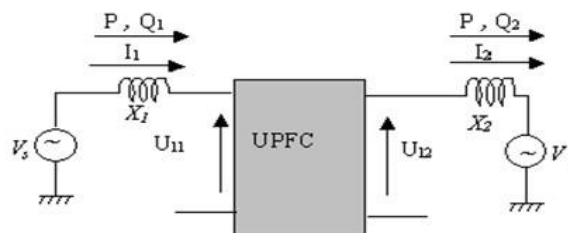

Figure 1. Electrical network with UPFC

It consists of two voltage source converters (VSC) connected through a common DC link. The first converter (A) is connected in series and the second (B) in parallel to the line (Figure 2). Converter A performs the main task of the UPFC by injecting an AC voltage adjustable via transformer T2. The role of converter B, is to supply or absorb the active power required by Converter A to the common DC circuit. It can also generate or absorb reactive power.
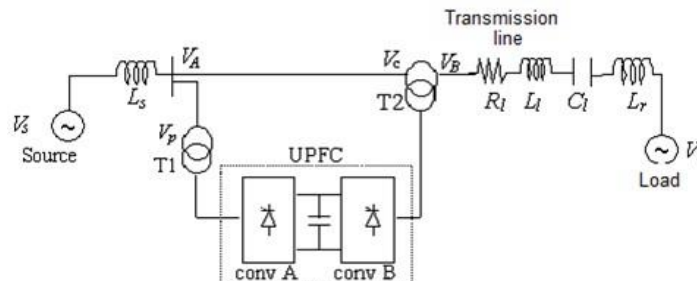

Figure 2. UPFC components and structure

This paper presents the control design approach based on control H∞ and a robust controller is formulated in the state space domain. H∞ robust control theory is probably the control theme which has led to the largest number of publications and greater efforts since the mid-80 s. The main reason for its popularity is because it represents a very natural way to formulate the problem of robustness.

It all started with an article by Zames [3], published in 1981 and followed by other articles [4, 5]. These articles did not concern the robustness problem, but rather the disturbance rejection. It is Kimura [4] who, in 1984, formulated the first robust control problem in terms of H∞. Although his position of the problem is hardly different from that proposed by Doyle and Stein [6, 7] (novelty residing in the explicit use of the H∞ framework that allowed Kimura to solve the synthesis problem). Thanks to the important concept of the standard problem that the work of Francis Doyle and [8] were unified.

The resolution of the standard problem grew very significantly in 1988 with Glover-Doyle algorithm [9], which uses state space representation. In the solutions of the problem, they introduced Ricatti equations [6, 8]. This approach is employed in this paper for solving the H∞ control problem. Robust stability is defined as the ability of a system to remain stable when subjected to perturbation such as modeling errors, measurement errors and external disturbances. Robust performance, on the other hand reflects the ability of the system to maintain the specified performance characteristics (stability, decoupling, time response...) when subjected to disturbances. Indeed, a physical system generally has non-linear characteristics that are not usually included in the model for simplification purposes. So an invariant model cannot accurately represent the reality and for this it is necessary to consider these errors in all control techniques. The H∞ control method is considered to be a very powerful design technique which has attracted many researchers from the electric power community.

2.   MODELING OF THE UPFC

The simplified phase circuit of the UPFC is shown in Figure 3. Using Kirchhoff's laws, we can write:

$$\begin{cases} V_{sa} - V_{ca} - V_{ra} = L_s \dfrac{d}{dt}\left(i_a + i_a'\right) + L \dfrac{di_a}{dt} + \dfrac{1}{C_L}\int i_a dt + Ri_a \\[3mm] V_{sb} - V_{cb} - V_{rb} = L_s \dfrac{d}{dt}\left(i_b + i_b'\right) + L \dfrac{di_b}{dt} + \dfrac{1}{C_L}\int i_b dt + Ri_b \\[3mm] V_{sc} - V_{cc} - V_{rc} = L_s \dfrac{d}{dt}\left(i_c + i_c'\right) + L \dfrac{di_c}{dt} + \dfrac{1}{C_L}\int i_c dt + Ri_c \end{cases} \qquad (1)$$
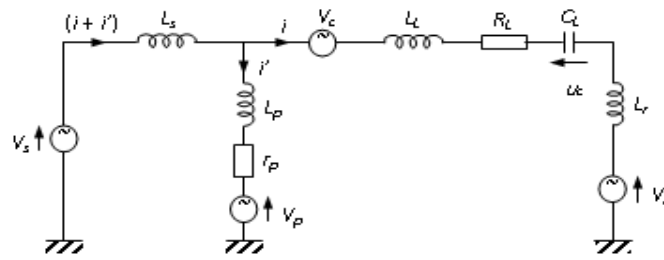
L is the total inductance of the line and the load.

Figure 3. Equivalent circuit of the UPFC

Using Park transformation, this system becomes:

$$\begin{cases} V_{sd} - V_{cd} - V_{rd} = L_s \dfrac{d}{dt}\left(i_d + i_d'\right) - \omega L_s\left(i_q + i_q'\right) + L\dfrac{di_d}{dt} - \omega L i_q + V_{cd} + R i_d \\[2mm] V_{sq} - V_{cq} - V_{rq} = L_s \dfrac{d}{dt}\left(i_q + i_q'\right) + \omega L_s\left(i_d + i_d'\right) + L\dfrac{di_q}{dt} + \omega L i_d + V_{cq} + R i_q \end{cases} \tag{2}$$

for the shunt compensator:

$$\begin{cases} V_{sd} - V_{pd} = L_s \dfrac{d}{dt}\left(i_d + i_d'\right) - \omega L_s\left(i_q + i_q'\right) + L_p\dfrac{di_d'}{dt} - \omega L_p\, i_q' + r_p i_d' \\[2mm] V_{sq} - V_{pq} = L_s \dfrac{d}{dt}\left(i_q + i_q'\right) + \omega L_s\left(i_d + i_d'\right) + L_p\dfrac{di_q'}{dt} + \omega L_p\, i_d' + r_p i_q' \end{cases} \tag{3}$$

for DC link:

$$\frac{1}{2} c \frac{dV_{dc}}{dt} = P_{ep} - P_e \tag{4}$$

$$P_{ep} = V_{pa}.i'_a + V_{pb}.\,i'_b + V_{pc}.\,i'_c$$

$$P_e = V_{ca}.i_a + V_{cb}.\,i_b + V_{cc}.\,i_c$$

P_{ep}: Active power consumption of the network through the parallel compensator and provided to the DC circuit and series compensator.

P_e: Power injected by the series compensator in the network.

Using Park transformation:

$$\frac{dV_{dc}}{dt} = \frac{3}{2C.V_{dc}}\left(V_{pd}.i'_{\ d} + V_{pq}.i'_{\ q} - V_{cd}.i_d - V_{cq}.i_{\ q} \right) \tag{5}$$

Let δ and θ be the phase shifts between the reference and the converter output voltages V_c and V_p, respectively. The d-q components can be expressed as follows [6]:

$$V_{cd} = \mathrm{k}_1.\, V_{dc}.\mathrm{Cos}(\delta);\ V_{cq} = \mathrm{k}_2.\, V_{dc}.\sin(\delta) \tag{6}$$

$$V_{pd} = \mathrm{k}_2.\, V_{dc}.\, \mathrm{Cos}(\theta);\ V_{pq} = \mathrm{k}_2.V_{dc}.\sin(\theta) \tag{7}$$

Assuming that the voltages at the source and receiving end are equal and the influence of the output shunt is neglected, the previous equations become:

$$\begin{cases} L_s \dfrac{di_d}{dt} + L\dfrac{di_d}{dt} - \omega L_s i_q - \omega L i_q + u_{cd} + U_{cd} + R i_d = 0 \\ L_s \dfrac{di_q}{dt} + L\dfrac{di_q}{dt} + \omega L_s i_d + \omega L i_d + u_{cq} + U_{cq} + R i_q = 0 \end{cases} \qquad (8)$$

$$\begin{cases} i_d - C_L \dfrac{du_{cd}}{dt} + \omega C_L u_{cq} = 0 \\ i_q - C_L \dfrac{du_{cq}}{dt} - \omega C_L u_{cd} = 0 \end{cases} \qquad (9)$$

Rearranging (8) and (9):

$$\begin{cases} \dfrac{di_d}{dt} = -\dfrac{R}{L_T} i_d + \omega i_q - \dfrac{1}{L_T}\left(u_{cd} + U_{cd}\right) \\ \dfrac{di_q}{dt} = -\dfrac{R}{L_T} i_q - \omega i_d - \dfrac{1}{L_T}\left(u_{cq} + U_{cq}\right) \\ C_L \dfrac{du_{cd}}{dt} = i_d + \omega C_L u_{cq} \Rightarrow \dfrac{du_{cd}}{dt} = \dfrac{1}{C_L} i_d + \omega u_{cq} \\ C_L \dfrac{du_{cq}}{dt} = i_q - \omega C_L u_{cd} \Rightarrow \dfrac{du_{cq}}{dt} = \dfrac{1}{C_L} i_q - \omega u_{cd} \end{cases} \qquad (10)$$

with: $L_T = L + L_s$.

This system can be written in the state space form as follows:

$$\begin{cases} \dot{X} = AX + BU \\ Y = CX + DU \end{cases} \quad A = \begin{bmatrix} -\dfrac{R}{L_T} & \omega & -\dfrac{1}{L_T} & 0 \\ -\omega & -\dfrac{R}{L_T} & 0 & -\dfrac{1}{L_T} \\ \dfrac{1}{C_L} & 0 & 0 & \omega \\ 0 & \dfrac{1}{C_L} & -\omega & 0 \end{bmatrix} \quad B = \begin{bmatrix} 0 & -\dfrac{1}{L_T} \\ -\dfrac{1}{L_T} & 0 \\ 0 & 0 \\ 0 & 0 \end{bmatrix}$$

$$C = \begin{bmatrix} u_{rdo} & u_{rqo} \\ u_{rqo} & -u_{rdo} \\ 0 & 0 \\ 0 & 0 \end{bmatrix}^T ; \quad D = \begin{bmatrix} 0 & 0 \\ 0 & 0 \end{bmatrix} ; \quad U = \begin{bmatrix} V_{cq} \\ V_{cd} \end{bmatrix} ; \quad Y = \begin{bmatrix} P \\ Q \end{bmatrix} ;$$

and the system transfer functions can be easily obtained from the state space equations:

$$\begin{bmatrix} P \\ Q \end{bmatrix} = \begin{bmatrix} G_{11}(s) & G_{12}(s) \\ G_{21}(s) & G_{22}(s) \end{bmatrix} \begin{bmatrix} V_{cq} \\ V_{cd} \end{bmatrix}$$

with:

$$G_{11}(s) = \dfrac{P}{V_{cq}} \quad G_{12}(s) = \dfrac{P}{V_{cd}} \quad G_{21}(s) = \dfrac{Q}{V_{cq}} \qquad G_{22}(s) = \dfrac{Q}{V_{cd}}$$

The instantaneous active and reactive powers generated and absorbed are defined as follows:

$$P_{source} = \frac{3}{2}(V_{sd}\,i_{sd} + V_{sq}\,i_{sq}) \; ; \; Q_{source} = \frac{3}{2}(V_{sq}\,i_{sd} - V_{sd}\,i_{sq}) \tag{11}$$

and the active and reactive powers absorbed by the load are:

$$P_r = \frac{3}{2}(V_{rd}\,i'_d + V_{rq}\,i'_q) \; ; \; Q_r = \frac{3}{2}(V_{rq}\,i'_d - V_{rd}\,i'_q) \tag{12}$$

with:

$$i_{sd} = i_d + i'_d \quad \text{and} \quad i_{sq} = i_q + i'_q$$

3. CONTROL OF THE UPFC

The combination of both parallel and serial converters with a DC link provides four quadrants control. Figure 4 show the block diagram of overall control scheme of the UPFC [10-12].
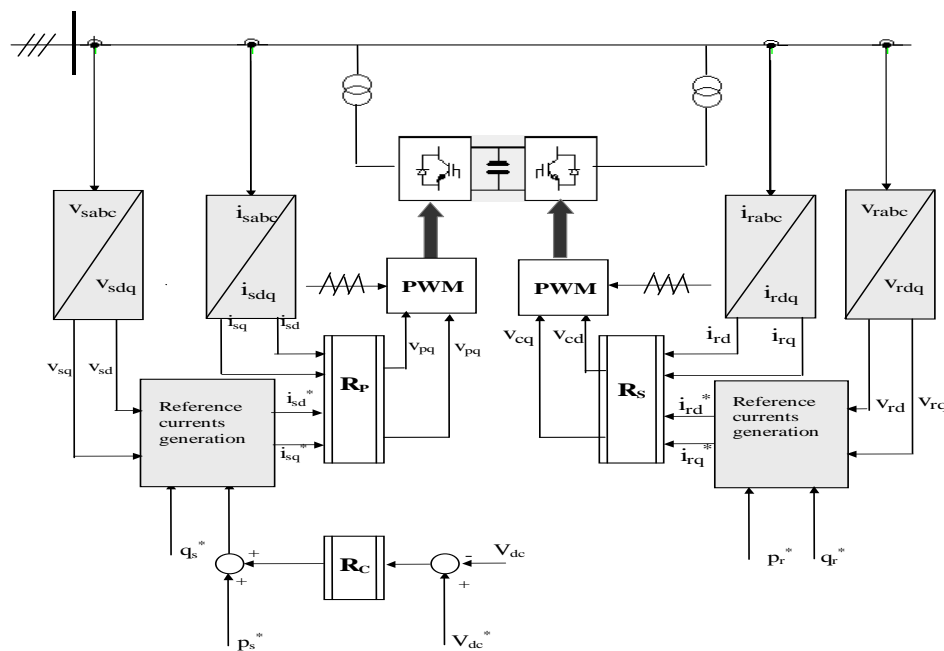

Figure 4. Full control of the UPFC

3.1. H∞ Control Approach
3.1.1. The H∞ Optimal Control Synthesis

Our system is represented by a transfer matrix $G(s)$ with a number of disturbance elements associated with the environment of the physical system (interference signals, etc.) and modeling errors (reduced order model, idealization actuators, parametric uncertainties, etc.) as shown in Figure 5 [7].

The aim of compensation $K(s)$ is to ensure the stability of the closed loop system and a nominal satisfactory behavior. All controller qualities should be preserved as much as possible in the presence of external perturbations (w) and modeling uncertainties $\Delta(s)$, the latter being translated using interference signals v'. At this level, weighting matrices can be introduced on the signals (v') and (w) to perform a frequency and distribution of their structural effects. Assume first that these weights have been addressed in the $P(s)$ model as shown in Figure 6.
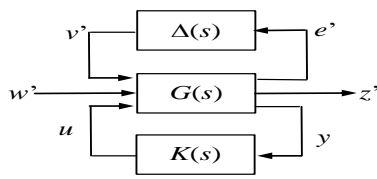
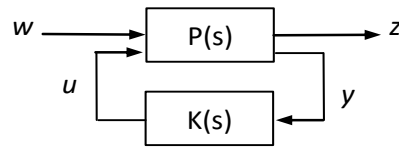Figure 5. The canonical robust control problem

Figure 6. A simplified representation of the control structure

The goal is to find a dynamic compensator such that the stability of the system stability is ensured and that some transfer norm from w to z denoted $F_l(P, K)$ characterizing the performance criteria and/or robustness will be minimized. The problem is then:

$$\min \left\| F_l\,(P,K) \right\| \tag{13}$$

Let $\begin{pmatrix} P_{11} & P_{12} \\ P_{21} & P_{22} \end{pmatrix}$ be a partition of matrix P, the dimensions of each sub-matrix matches with the number of inputs and outputs. Then $F_l(P, K)$ is expressed as:

$$z = Fl(P,K).w = (P11 + P12\ K(I - P22\ K)\text{-}1\ P21).w \tag{14}$$

The problem formulated in (35) is therefore re-written as:

$$\min \left\| P11 + P12\ K(I - P22\ K)\text{-}1\ P21 \right\| \tag{15}$$

The stabilization of the system P by the compensator K is one of the objectives of the compensation. However, P is a multivariable system (multiple inputs and multiple outputs) then, the concept of stability must be specified.

Based on Figure 7, the standard problem is as follows: find the compensator $K(s)$ stabilizes $P(s)$ and minimizes $\left\| Tzw \right\| \infty$.

Tzw: represents the transfer matrix between w and z.

$P(s)$: is the augmented system that allows us to generate z, corresponding to the objectives of the command and can be represented in state space form by:

$$\begin{bmatrix} x \\ y \\ z \end{bmatrix} = \left[\begin{array}{c|cc} A & B_1 & B_2 \\ \hline C_1 & D_{11} & D_{12} \\ C_2 & D_{21} & D_{22} \end{array} \right] \begin{bmatrix} x \\ w \\ u \end{bmatrix} \tag{16}$$

or by its transfer matrix.

$$P = \begin{bmatrix} P_{11}(s) & P_{12}(s) \\ P_{21}(s) & P_{22}(s) \end{bmatrix}, \begin{bmatrix} z \\ y \end{bmatrix} = \begin{bmatrix} P_{11}(s) & P_{12}(s) \\ P_{21}(s) & P_{22}(s) \end{bmatrix} \tag{17}$$

To achieve these results, our control problem should be transformed into the standard form according to the principle illustrated in Figure 7.

The objectives of the control are defined as follows:
a) Disturbance rejection and tracking error:
   Minimize $\left\| W_T(s).T(s) \right\| \infty$.
b) Noise attenuation $m(s)$, return to maximizing margin multiplicative stability (multiplicative uncertainty output)
   Minimize $\left\| W_S(s).T(s) \right\| \infty$.
c) Maximize the margin of stability additive, i.e. limiting the amplitude of the control signal.
   Minimize $\left\| Wu(s).K(s).\ S(s) \right\| \infty$.

This implies the minimization of:

$$\left\| \begin{array}{c} W_S(s).S(s) \\ W_T(s).T(s) \\ W_u(s).K(s).S(s) \end{array} \right\|_\infty \tag{18}$$

The standard problem can be represented by the equivalent diagram shown in Figure 8.
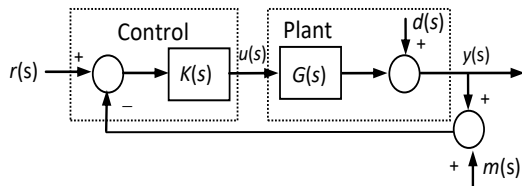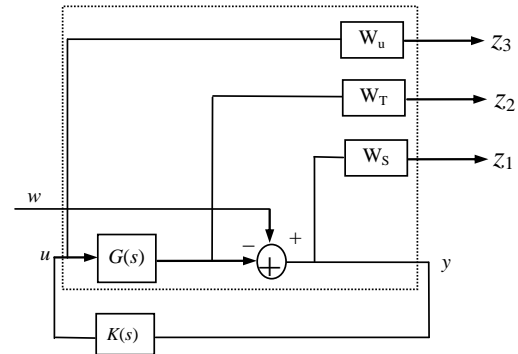
Figure 7. Classical feedback control system   Figure 8. Closed-loop system with modeling error

which gives:

$$\begin{bmatrix} z \\ y \end{bmatrix} = \begin{bmatrix} W_S & -W_S.G \\ 0 & W_T.G \\ 0 & W_u \\ I & -G \end{bmatrix} \begin{bmatrix} w \\ u \end{bmatrix} \tag{19}$$

replacing u by Ky:

$$T_{Zw} = \begin{bmatrix} W_S.S \\ W_T.T \\ W_u.K.S \end{bmatrix} \tag{20}$$

The solution of this problem is obtained using the function H_{inf} or $H_{inf\text{-}opt}$ from the Matlab Robust Control Toolbox called Mixed Sensitivity Problem. Other representations of the augmented system to several inputs (w_1, w_2, w_3), and one output z can be addressed.

The synthesis of H_∞ control may be summarized by:
a) Translate the objectives $\|\ \|_\infty$.
b) Select the weighting functions in terms of their frequency response.
c) Set up the matrix $P(s)$ of the equivalent standard problem.
d) Solve the optimization problem.
e) Test the performance of the closed-loop system.

3.1.2. Solution of the Standard Problem and Selection of the Weighting Functions
Doyle and others [7, 13-17] have solved this problem by performing standard programs to give the controller status of state space from the system and weighting functions. The assumptions used in the resolution of this problem are:
1) (A, B_2) stabilizable and (A, C_2) detectable.
2) Rank $(D_{12}) = m_2 = \dim (u)$ and rank $(D_{21}) = P_2 = \dim(y)$.

3) $D_{12} = \begin{bmatrix} 0 \\ I \end{bmatrix}, D_{21} = [0, I]$

4) $\text{Rank} \begin{bmatrix} A - j\omega\omega & B_2 \\ C_1 & D_{22} \end{bmatrix} = n + m_2, \forall \omega \in [0, \infty[$

5) $\text{Rank} \begin{bmatrix} A - j\omega\omega & B_1 \\ C2 & D_{21} \end{bmatrix} = n + P2, \forall \omega \in [0, \infty[$

   a)   Assumption (I) is necessary and sufficient for the existence of a solution.
   b)   Assumptions (II), (IV) and (V) ensure that the problem is well posed, in other words, the compensator is appropriate.
   c)   Assumptions (IV) and (V) indicate that P_{12} (s) and P_{21}(s) have no zeroes on the imaginary axis, they can be avoided [7].
   d)   Assumption (III) simplifies the solution.
   e)   If assumption (II) is satisfied, it can used to check system (III). This operation is performed by the H_{inf} program Matlab.
   f)   The only problem that may arise is that of the validation of assumption (II).

3.2. Validation of the Assumption (II)
        If, by executing the instruction Hinf (Robust Control Toolbox of Matlab), the error signal «matrix D_{12} is not in full column rank», this means that the hypothesis (II) is not verified, and therefore the transfer functions P_{12}(s) and P_{21}(s) have zeros at infinity [9].
        In order to ensure the closed loop stability and simultaneously achieve the desired control performance under process variations or in the presence of other disturbances weighting functions dependent of the frequency in the process are introduced as shown in Figure 9.
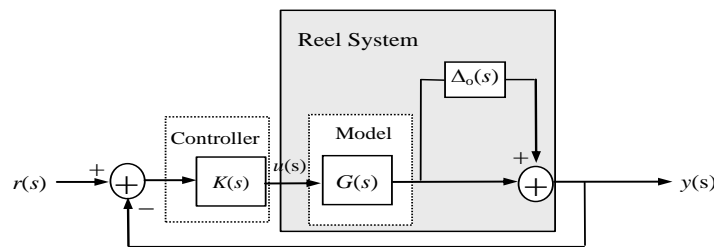

Figure 9. Control system with modeling error

        The controller optimization is defined by the following equation:

$$\| W_T(s).T(s) \|_\infty < \gamma \ \forall \omega \in [0, \infty] \tag{21}$$

        These weighting functions define the frequency characteristics of the signals of the system as well as their amplitudes. Putting $|W_T(j\omega)| \geq 1$ for a certain frequency range, the gain reduction of the complementary sensitivity function $T(j\omega)$ can be achieved beyond this range.
        It is now assumed that also seeks a good performance (characterized by $S(j\omega)$) residing in the disturbance rejection. This performance can be achieved by finding the controller K(s) by solving the following equation:

$$\| W_S(j\omega).S(j\omega) \|_\infty \ \forall \omega \in [0, \infty] \tag{22}$$

        This equation is equivalent to:

$$\| WS(j\omega).S(j\omega) \|_\infty < \gamma const \ \forall \omega \in [0, \infty[\tag{23}$$

γ_{const} is an arbitrary constant which is not necessarily equal to γ (22).

Performance objectives and the robust stability can be simultaneously achieved by seeking a controller K(s) satisfying the following inequality:

$$\left\| \begin{matrix} W_S(j\omega).S(j\omega) \\ W_T(j\omega).T(j\omega) \end{matrix} \right\| < \gamma \tag{24}$$

The choice of the weighting functions is as follows: Depending on the required performance, $W_S(j\omega)$ is large at low frequency and smaller at high frequency, representing a low pass filter.

In our case, it is a diagonal matrix $W_S(j\omega) = w_S.I$, where wS represents the weighting function selected such that:

$$\left| S(j\omega) \right| \langle \frac{1}{\left| w_s(j\omega) \right|} \qquad \text{or} \qquad \overline{\sigma}(S(j\omega)) \langle \frac{1}{\left| W_S(j\omega) \right|}$$

for multivariable systems.

Generally, the uncertainties and dynamics are neglected high frequencies, $W_T(j\omega)$ must be represented by a high pass filter to ensure robustness for high frequencies ($\omega > \omega 0$) and acceptable performance for low frequencies ($\omega < \omega 0$).

Our choice of weighting coefficients is completely connected to the parameter γ as explained above (following the objectives set such that the bandwidth in this case equal 70rd/s [6]), after trial and error, a value of $\gamma = 1.92$ was selected and the transfers functions of the weighting coefficients are:

$$W_S = \frac{10s+1}{10(1/70s+1)} \qquad \text{and} \qquad W_{T=} \frac{278}{0.01s+0.01}$$

These weighting coefficients WS and WT define the controller K(s). The responses of the active and reactive powers are illustrated in Figure 10. From these results, it can be noted that the powers track their respective references perfectly, reflecting the right choice of parameters of our K(s). In addition, through the weights W_T and W_S defined, the interaction between the powers is completely eliminated and hence the controller was able to decouple the system and ensure good performance and achieve the control objective [18-26].
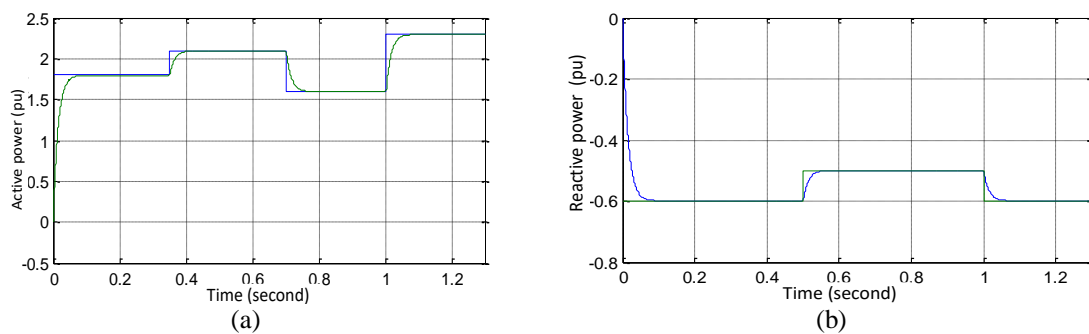

Figure 10. Response of the active power (a) and reactive power (b) with K(s) control

3.3. Robustness Test
3.3.1. Increase of the Inductance of the Line by 20%:

We have introduced changes to one of the line parameters (inductance) to analyze the robustness of our controller. Note that the increase of 20% of this parameter, does not affect the characteristic as shown in Figure 11 (a), because the active power follows perfectly the set point which explains the qualities of our controller K (s) H∞.
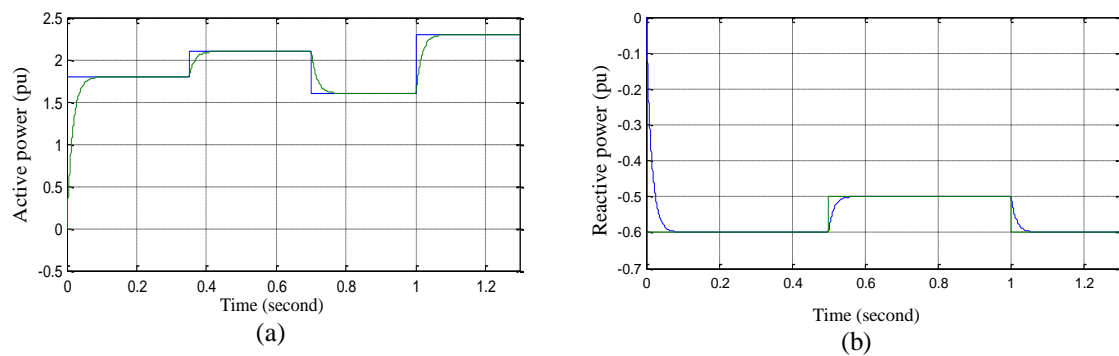
Figure 11. Active power (a) and reactive power (b) corrected by the regulator H∞ for the inductor of the line increased by 20%

Figure 11 (b) shows the curve of the corrected reactive power after reduction of the inductance of the line by 20%, it is found that our characteristic is similar to that of Figure 10 (b), that is to say that it has not undergone any variation, which explains the robustness of our corrector $K(s)$.

3.3.2. Reduction of the Inductance of the Line by 20%:
Figures 12 (a) and (b) represent respectively the curves of the active and reactive powers corrected after the reduction of the inductance of the line of 20%, these characteristics prove once more that our regulator retains its qualities, in particular its robustness.
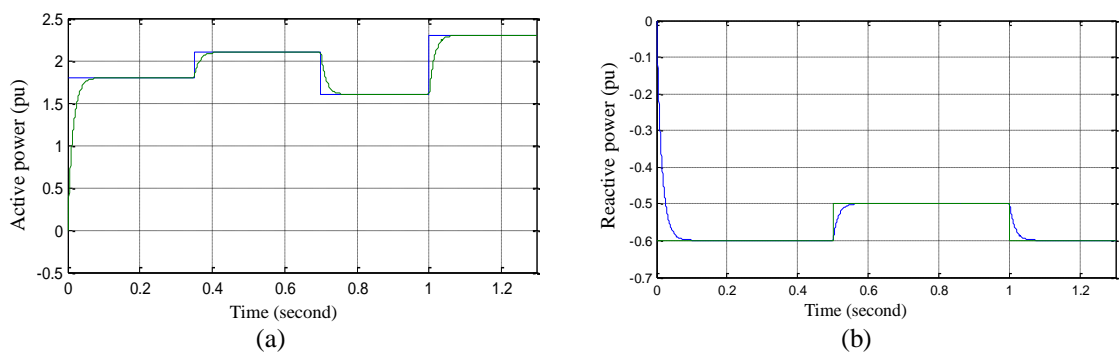

Figure 12. Active power (a) and reactive power (b) corrected by the regulator H∞ for the inductance of the reduced line by 20%

We can then conclude that the various changes made did not affect the qualities of the controller, which implies that the controller K(s) defined by the H∞ approach is perfect for our system.

4.   CONCLUSION
In this work, we focused to show the control of the UPFC by the H∞ control. The control H∞ could ensure the desired performance, this implies that the control H∞ is robust and also implies a good synthesis of coefficients and weighting functions thereof. We can therefore probably say that the H∞ approach is, in the field of robust control, the theme that continues to give rise to a large number of publications following very great efforts. All this is not due to chance, because it represents a very natural way of formulating the problem of robustness.

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