Pseudo-linear Anti-windup Controllers for a Single Machine/Infinite Bus Power System under Exciter and Steam Control Valve Saturation

V. A. TSACHOURIDIS , I. POSTLETHWAITE
Control Systems Research, Department of Engineering
University of Leicester
University Road, Leicester LE1 7RH
ENGLAND (UK)

Abstract: -This paper consider the design of pseudo-linear feedback controllers for a single machine/infinite bus power system in order to optimize the dynamic performance of the system, whether or not the system operates under actuator saturation. The stability of such a system should be guaranteed for any small disturbance to the system, and for any small deviations from normal operation. Two control inputs are available and not all of the states are measured. The overall control system design is based on a new anti-windup controller synthesis method, developed by the authors. The resulting control system can compensate exciter and turbine saturation in short time intervals and provides good system performance. The performance of the overall system is studied in simulation. *IMACS/IEEE CSCC'99 Proceedings,* Pages:1081-1087

Key-Words: - Electric Power System, Saturation, Anti-windup, LQR, H_2-Control, LTR *CSCC'99* Proc.pp..1081-1087

1 Introduction

The dynamic stability of a synchronous electric generator connected to an infinite bus through a transmission line has been investigated in great detail [1], [2], [3] (and their references).

In such a system, load disturbances, self excited oscillations and other phenomena, which perturb the system from its normal operation, can drive the system actuators into undesirable saturation. As will be shown, this is true, even when the system operates under relatively small variations of its dynamics.

So far the majority of controller designs aim to limit the feedback control action in such a way that saturation is unlikely to occur. For example, power system stabilizers put limits on voltage feedback signals in order to avoid exciter saturation [4]. In linear quadratic regulator (LQR) and H_2 designs, the weight selections are made in such a way that the control signal does not cause saturation. The above strategy may give reasonable designs in terms of saturation avoidance but in some cases it will limit the system performance.

This paper considers the design of an anti-windup control system, for a synchronous electric generator, connected to an infinite bus through a transmission line power system. A new design method [5] is used.

The structure of this paper is as follows. The system model and design specifications are described in section 2. The control system design method and its application are summarised in section 3. Simulations of the designed control system and a discussion of results are given in section 4 along with a comparison with an H_2 design. Conclusions are given in section 5.

2 Single Machine/Infinite Bus Power System

In this section, a description of the system under study is given together with numerical data and design specifications. For more detail see [1], [2], [3], [4], [6] and [7].

2.1 System Description and Modeling

Essentially, the control of the steady state normal operation of a synchronous electric generator connected to an infinite bus through a transmission line (see Fig.1) is implemented with two major control loops: an automatic voltage regulator (AVR) and an automatic load-frequency controller (ALFC) [2], [3]. A power system transfer function block diagram is shown with these two loops in Fig.2 and from now on it will be referred to as the open loop system. Useful nomenclature is given in Table 1 of section 2.2.

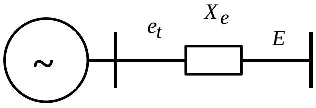

Fig.1 Single machine/infinite bus system.

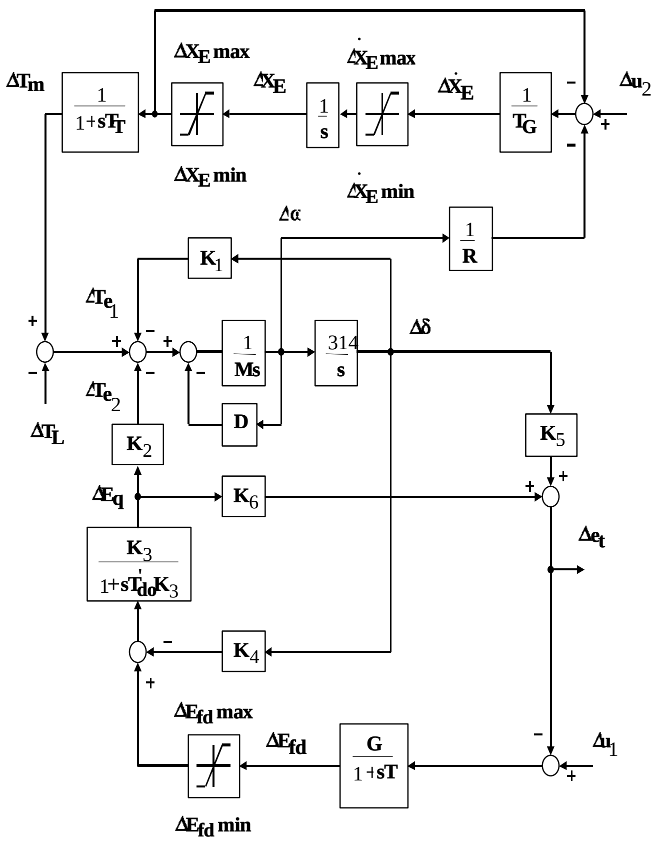

Fig.2 Power system block diagram.

To improve the dynamic performance of the system in Fig.2, the control inputs Δu_1 and Δu_2 are used. Δu_1 is an input to the exciter of the AVR loop, while Δu_2 is an input to the speed governor of the ALFC loop. Power system stabilizers are not included in our study.

We assume that the system operates under small dynamic variation. A linear mathematical model (in the time-domain) including saturation nonlinearities on the exciter [6] and turbine [7], can be obtained as:

$$\sigma(\Delta\dot{x}(t)) = A\,\sigma(\Delta x(t)) + B\Delta u(t) + \Gamma_1 \Delta T_L(t) \qquad (1)$$

$$\Delta y(t) = C\,\sigma(\Delta x(t)) + \Gamma_2 \Delta w_2(t) \qquad (2)$$

From now on, we will omit the time variable t for simplicity.

For the model (1), (2) we have

$$\sigma(\Delta x) = \begin{bmatrix}\Delta\delta & \Delta\omega & \Delta E_q & \Delta T_m & \sigma(\Delta X_E) & \sigma(\Delta E_{fd})\end{bmatrix}^T \qquad (3)$$

$$\sigma(\Delta\dot{x}) = \begin{bmatrix}\Delta\dot{\delta} & \Delta\dot{\omega} & \Delta\dot{E}_q & \Delta\dot{T}_m & \sigma(\Delta\dot{X}_E) & \Delta\dot{E}_{fd}\end{bmatrix}^T \qquad (4)$$

$$\Delta u = \begin{bmatrix}\Delta u_1 & \Delta u_2\end{bmatrix}^T,\ \Delta y = \begin{bmatrix}\Delta e_t & \Delta\omega & \Delta E_{fd}\end{bmatrix}^T,$$
$$\Delta w_2 = \begin{bmatrix}\Delta w_{21} & \Delta w_{22} & \Delta w_{23}\end{bmatrix}^T \qquad (5)$$

$$A = \begin{bmatrix} 0 & 314 & 0 & 0 & 0 & 0 \\ \frac{-K_1}{M} & \frac{-D}{M} & \frac{-K_2}{M} & \frac{1}{M} & 0 & 0 \\ \frac{-K_4}{T'_{do}} & 0 & \frac{-1}{T'_{do}K_3} & 0 & 0 & \frac{1}{T'_{do}} \\ 0 & 0 & 0 & \frac{-1}{T_T} & \frac{1}{T_T} & 0 \\ 0 & \frac{-1}{RT_G} & 0 & 0 & \frac{-1}{T_G} & 0 \\ \frac{-GK_5}{T} & 0 & \frac{-GK_6}{T} & 0 & 0 & \frac{-1}{T} \end{bmatrix} \qquad (6)$$

$$B = \begin{bmatrix} 0 & 0 & 0 & 0 & \frac{1}{T_G} & \\ 0 & 0 & 0 & 0 & 0 & \frac{G}{T} \end{bmatrix}^T \qquad (7)$$

$$\Gamma_1 = \begin{bmatrix} 0 & \frac{-1}{M} & 0 & 0 & 0 & 0 \end{bmatrix}^T \qquad (8)$$

$$C = \begin{bmatrix} K_5 & 0 & K_6 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix} \qquad (9)$$

$$\Gamma_2 = \begin{bmatrix}\gamma_1 & \gamma_2 & \gamma_3\end{bmatrix}^T \qquad (10)$$

The constants K_1 to K_6 can be calculated from formulas in terms of the system numerical data and normal point of operation [1].

In general $\Delta\alpha := \alpha - \alpha^o$ denotes the deviation of α from its normal value of operation α^o, and $\sigma(\Delta\alpha)$ denotes the radial ellipsoidal saturation function of $\Delta\alpha$ given by (11):

$$\sigma(\Delta\alpha) := \begin{cases} \Delta\alpha\, max, & \Delta\alpha \geq \Delta\alpha\, max \\ \Delta\alpha, & \Delta\alpha\, min < \Delta\alpha < \Delta\alpha\, max \\ \Delta\alpha\, min, & \Delta\alpha \leq \Delta\alpha\, min \end{cases} \qquad (11)$$

Since (11) is a nonlinear function, it may be argued that system (1)-(2) is also nonlinear despite its linear structure. For this reason, systems of this type will be referred to as ‘pseudo-linear’.

From (5) it is apparent that full state information of the system is not available in our study. Hence this work may be useful for cases where some of the system states are difficult to be measured for various reasons. Furthermore, the presence of a load disturbance ΔT_L and a measurement disturbance Δw_2 are taken account into the system formulation.

2.2 System Data and Specifications

The system data is taken from [8]:

$X_d = 1.03$ pu $X_d' = 0.247$ pu $X_q = 0.612$ pu

$T_{do}' = 6.05$ sec $X_e = 0.3$ pu $G = 100$

$T = 0.05$ sec $T_T = 1$ sec $T_G = 0.1$ sec

$R = 0.04$ pu $D = 3$ $M = 10$ sec

The nomenclature is given in Table 1 below.

NOMENCLATURE	
e_t Terminal Voltage	R Regulation Droop
E Infinite Bus voltage	G Exciter Gain
X_e Series Transmission Line Reactance	P Real Power
X_d d-axis Synchronous Reactance	Q Reactive Power
X_d' d-axis Transient Reactance	T_e Electromagnetic Torque
X_q q-axis Synchronous Reactance	δ Rotor Angle
T_G Speed Governor Time Constant	ω Rotor Speed
T_T Turbine Time Constant	E_q Generated Field Voltage
T_{do}' Generator Field Time Constant	T_m Prime Mover Torque
M Inertia Coefficient	X_E Steam Control Valve
D Damping Coefficient	E_{fd} Excitation Voltage
T_L Load Disturbance	w_2 Measurement Disturbance

Table 1. System Nomenclature.

The normal steady state operating point is subject to a lagging power factor $P + Qj = 1.2 + 0.4j$ pu and a terminal voltage 1 pu. With respect to the previous values, K_1 to K_6 are computed as [1]:

$K_1 = 1.0571$ $K_2 = 1.3843$ $K_3 = 0.5997$

$K_4 = 1.0839$ $K_5 = -0.1573$ $K_6 = 0.4723$

Saturation of the exciter and the turbine steam control valve can be expressed with functions similar to (11). More specifically, we have the following limits:

Exciter

$$\Delta E_{fd}\ max = 1 \text{ pu},\ \Delta E_{fd}\ min = -1 \text{ pu} \qquad (12)$$

Turbine steam control valve

$$\Delta X_E\ max = 0.01 \text{ pu},\ \Delta X_E\ min = -0.01 \text{ pu} \qquad (13)$$

$$\Delta \dot{X}_E\ max = 0.1 \text{ pu},\ \Delta \dot{X}_E\ min = -0.1 \text{ pu} \qquad (14)$$

Finally, the measurement disturbance matrix is

$$\Gamma_2 = 0.01 I_3 . \qquad (15)$$

The above data specifies the numerical values of the state space data (6)-(9). Hence the model (1)-(2) is determined. Furthermore, the eigenvalues of the open loop system are -10.7724 ±8.0265j, 0.5390 ±6.5391j, -0.9461, -10.1626. Obviously, the open loop system at the above operating condition is unstable.

In the present study, the control problem is the design of a control system to stabilize and optimize the dynamic response of the open loop system, under relatively small deviations of its normal operation and under the action of small load disturbances. The control system should be able to handle saturation of the system exciter and turbine, subject to (12)-(14), and to provide settling times of 1 to 2 sec approximately [3]. For the validity of (1), (2), the system steady state and dynamic deviation from its normal operation should always be relatively small.

3 Control System Design

In this section, the design of an anti-windup control system for the power system in the previous section is considered. A new design method developed by the authors is used. This method can be applied to various systems with saturation constraints on the actuator dynamical model. The method is summarised without proofs because of the limited space. A detailed presentation of the design method will be the subject of another paper [5].

3.1 Pseudo-linear Anti-windup Controllers

Let the controllable and observable plant be

$$\sigma(\dot{x}) = A\sigma(x) + B\sigma(u) + \Gamma_1 w_1 \qquad (16)$$

$$y = C\sigma(x) + \Gamma_2 w_2 \qquad (17)$$

where $x \in \Re^n$, $u \in \Re^m$, $y \in \Re^p$, $w_1 \in \Re^{k_1}$, $w_2 \in \Re^{k_2}$ are the state, control input, output, state disturbance and output disturbance time variables of the system, and A, B, C, Γ_1, Γ_2 are the associated state space data respectively.

$\sigma(\cdot)$ denotes a saturation function similar to (11). The upper and lower saturation limits are denoted as $\dot{x}^+$, $\dot{x}^-$ for $\dot{x}$, x^+, x^- for x and u^+, u^- for u. For an unconstrained component, say v, of $\dot{x}$, or x, or u, it is $\dot{x}_{v1}^+ = \varepsilon$ and $\dot{x}_{v1}^- = -\varepsilon$, or $x_{v1}^+ = \varepsilon$ and $x_{v1}^- = -\varepsilon$, or $u_{v1}^+ = \varepsilon$ and $u_{v1}^- = -\varepsilon$, respectively. ε is an adaptive parameter satisfying

$$k\varepsilon := \begin{cases} sign(k)\infty, k \neq 0 \\ 0, k = 0 \end{cases} \text{ and } \tau + k\varepsilon := \begin{cases} \tau, \tau \neq 0 \\ k\varepsilon, \tau = 0 \end{cases}.$$

Furthermore, let the performance vector $\xi := E_1 x + E_2 u$, where $E_1 \in \Re^{r \times n}$, $E_2 \in \Re^{r \times m}$ are design matrices such that $E_1^T E_2 = 0$. For the rest of the analysis the following assumptions should hold.

Assumption 1: B is full rank and $\Gamma_1 \in Ker\left(B^l\right)$, where B^l is the left inverse of B.

Assumption 2: Saturation constraints are defined with functions similar to (11), and only for:

a) The actuators' outputs, states, and rate of states.
b) Any state (not actuator state), which is present in an actuator state space equation (i.e. it is present in a differential equation (16), where a control input component is present as well).

Our objective is to design a feedback controller, for the plant (16), (17) such that the closed loop system is:

(i) Asymptotically stable.
(ii) Optimal in an H_2 sense.

A solution to the above problem can be obtained with theorem 1, which constitutes the control design problem.

Before we state theorem 1, the following definitions are made.

$$R_1 := E_1^T E_1,\ R_2 := E_2^T E_2 \quad (18)$$

$$V_1 := \Gamma_1 \Gamma_1^T,\ V_2 := \Gamma_2 \Gamma_2^T \quad (19)$$

$$\overline{R}_1 := \begin{bmatrix} R_1 & 0 \\ 0 & 0 \end{bmatrix} \quad (20)$$

Note that R_1, V_1 are positive semi-definite matrices and R_2, V_2 are positive definite matrices. Moreover R_1, R_2 can be viewed as weighting matrices on the state and control input respectively.

Furthermore, define $\alpha, \overline{\alpha} \in \Re^{n \times n}$ as

$$\alpha_{ij} := 0, \text{ if } (x_{i1} \text{ and } \dot{x}_{i1}: \text{unconstrained}) \text{ or } (i \neq j) \quad (21)$$

$$\alpha_{ij} := 1, \text{ if } (x_{i1} \text{ or } \dot{x}_{i1}: \text{constrained}) \text{ and } (i = j) \quad (22)$$

$$\overline{\alpha}_{ij} := 1, \text{ if } (x_{i1} \text{ and } \dot{x}_{i1}: \text{unconstrained}) \text{ or } (i = j) \quad (23)$$

$$\overline{\alpha}_{ij} := 0, \text{ if } (x_{i1} \text{ or } \dot{x}_{i1}: \text{constrained}) \text{ or } (i \neq j) \quad (24)$$

Also, $\tilde{A} := A - BB^l A \overline{\alpha}$.

Finally, let $\tilde{u} \in \Re^m$, with saturation function similar to (11) and upper and lower limits

$$\tilde{u}^- := max\left(\left| -B^l A\alpha \right| x^-, \left| B^l \alpha \right| \dot{x}^-, u^-\right) \quad (25)$$

$$\tilde{u}^+ := min\left(\left| -B^l A\alpha \right| x^+, \left| B^l \alpha \right| \dot{x}^+, u^+\right) \quad (26)$$

The saturation function of $\tilde{u}$ apart from the structure (11), can also be expressed as

$$\sigma(\tilde{u}) = \begin{cases} \tilde{u}, \tilde{u}^T R \tilde{u} \leq 1 \\ \left(\tilde{u}^T R \tilde{u}\right)^{\frac{-1}{2}} \tilde{u}, \tilde{u}^T R \tilde{u} > 1 \end{cases} \quad (27)$$

where $R \in \Re^{m \times m}$, is positive-definite.

Theorem 1 ([5]): Let assumptions 1, 2 hold and suppose that there exist semi-positive definite matrices $X, Y, Z \in \Re^{n \times n}$ satisfying

$$\tilde{A}^T X + X\tilde{A} - XBR_2^{-1}BX + R_1 = 0 \quad (28)$$

$$\tilde{A}Y + Y\tilde{A}^T - YC^T V_2^{-1} CY + V_1 = 0 \quad (29)$$

$$\left(\tilde{A} - YC^T V_2^{-1} C\right)^T Z + Z\left(\tilde{A} - YC^T V_2^{-1} C\right) + XBR_2^{-1}BX = 0 \quad (30)$$

Define

$$\Omega := \begin{bmatrix} X + Z & -Z \\ -Z & Z \end{bmatrix},\ E_c := B,\ C_c := -R_2^{-1} B^T X,$$

$$B_c := -YC^T V_2^{-1},\ A_c := \tilde{A} + BC_c - B_c C,$$

$$\overline{A} := \begin{bmatrix} A & BC_c \\ B_c C & A_c \end{bmatrix},\ \overline{B} := \begin{bmatrix} B \\ E_c \end{bmatrix},\ \overline{C} := \begin{bmatrix} 0 & C_c \end{bmatrix}.$$

Suppose that $\left(\bar{A}, \bar{R}_1 + \bar{C}^T R_2 \bar{C}\right)$ is observable, and let the dynamic feedback controller structure be given

$$\dot{x}_c = A_c x_c + B_c y + E_c\left(\sigma(\tilde{u}) - \tilde{u}\right) \qquad (31)$$

$$\tilde{u} = C_c x_c \qquad (32)$$

$$u = \sigma(\tilde{u}) - B^l A \bar{\sigma}\sigma(x_c), \qquad (33)$$

where $\sigma(x_c)$ has the same constraints as $\sigma(x)$.

The result closed loop system is given by

$$\sigma(\dot{\bar{x}}) = \bar{A}\sigma(\bar{x}) + \bar{B}(\sigma(u) - u) + \begin{bmatrix}\Gamma_1^T & 0\end{bmatrix}^T w_1 \qquad (33)$$

$$y = \begin{bmatrix}C & 0\end{bmatrix}\sigma(\bar{x}) + \begin{bmatrix}\Gamma_2^T & 0\end{bmatrix}^T w_2, \ \bar{x} := \begin{bmatrix}x & x_c\end{bmatrix}^T. \ (34)$$

If the initial conditions $\bar{x}_o := \begin{bmatrix}x_o & x_{co}\end{bmatrix}^T$, of the closed loop system (33), (34) satisfy

$$\bar{x}_o^T \Omega \bar{x}_o < \lambda_{max}^{-1}\left(\bar{C}^T R \bar{C}\Omega^{-1}\right)$$

($\lambda_{max}(\cdot)$ denotes the maximum eigenvalue of a matrix), then the closed loop system is asymptotically stable. Furthermore, the H_2-type cost functional

$$J(\bar{x}_o) := \int_0^\infty \left[\bar{x}^T \bar{R}_1 \bar{x} + u^T R_2 u + 2\bar{x}^T \Omega \bar{B}\left(\tilde{u} - \sigma(\tilde{u})\right)\right] dt$$

is minimized, with a minimum equal to $\bar{x}_o^T \Omega \bar{x}_o$.

Remark 3.1.1: The controller (31)-(33) has a pseudo-linear structure and hence the term ‘pseudo-linear anti-windup controller’. A block diagram of the controller is shown in Fig.3.

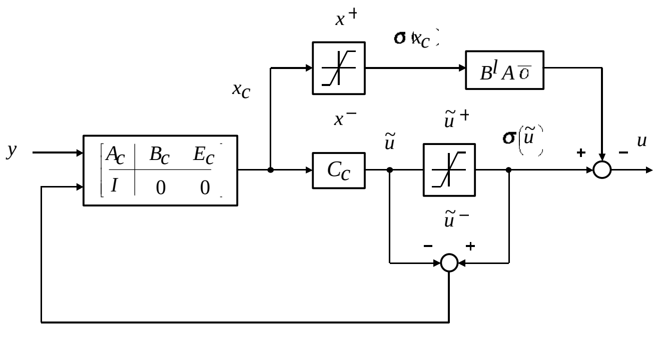

Fig.3 Pseudo-linear anti-windup controller block diagram.

Remark 3.1.2: The set

$$\Psi := \left\{\bar{x}_o \in \Re^{2n} : \bar{x}_o^T \Omega \bar{x}_o < \lambda_{max}^{-1}\left(\bar{C}^T R \bar{C}\Omega^{-1}\right)\right\}$$

defines a subset of the domain of attraction of the closed loop system. Since the theorem 1 provides sufficient conditions for asymptotic stability, it is possible that for initial conditions that do not belong in Ψ, the closed loop system can be asymptotically stable.

Remark 3.1.3: Equations (28)-(30) are identical with those associated with the H_2 control problem. Hence, an loop transfer recovery (LTR) process [9], [10] can be posed in order to obtain certain performance specifications, with the aid of state-feedback design laws, such as LQR pole-placement [11] and others. In this situation, the closed loop system will in general not be optimal in an H_2 sense, since $V_1 := \Gamma_1 \Gamma_1^T + q^2 BB^T$ ($q \geq 0$), is used instead of V_1 in (19). Full-state LTR is possible for minimum phase systems [9], which is the case in this work. By selecting q we actually compromise between stability margins and disturbance attenuation.

3.2 Proposed Design Method

In order to meet the design specifications of section 2.2, we make use of theorem 1 of the previous section, with R_1 and R_2 as shown next.

It is obvious that (28) is associated with a state-feedback LQR problem, in which the static feedback controller gain is equal to C_c. Therefore we choose the LQR optimal pole-placement method of [11], in order to achieve the settling time of 1-2 sec, to achieve reasonable damping in the dynamic system response and reasonable stability margins. The algorithm of [11], is used with respect to the system $\left(\tilde{A}, B\right)$ and with respect to a relative degree of stability $h = 3$, which corresponds approximately to a settling time of 1 sec. Hence, the weighting matrix R_1 can be evaluated and $R_2 = I$.

After calculating R_1, R_2, as above, we can apply within theorem 1 a full-state LTR process, such as in [9] and [10], in order to recover the state-feedback performance and stability margins. As was stated in remark 3.1.3, because our system is minimum phase, full recovery may be feasible [9]. Because of this, the closed loop system (33)-(34) will approximate the dynamics of the static state-feedback closed loop system. Therefore we expect the poles of the state-feedback closed loop system, designed via the algorithm in [11], to belong approximately to the set of the eigenvalues of $\bar{A}$.

Also, because of theorem 1 the overall control system will be able to compensate actuator saturation events and disturbances effects.

4 Controller Computation and System Simulation

With respect to the system data in section 2.2, we apply the proposed design method of section 3.2.
We assume the initial conditions

$$\bar{x}(0) = [0.1 \quad 0 \quad -0.05 \quad 0 \quad 0.005 \quad 0_{7\times 1}]^T \qquad (35)$$

and the disturbances

$$\Delta T_L(t) = step(0.01), \; \Delta w_2(t) = 0_{3\times 1}. \qquad (36)$$

Using the method of [11] with a degree of relative stability $h = 3$, we found that

$$R_1 = \begin{bmatrix} 0.4370 & -24.2502 & 0.5567 & -0.3522 & -0.0066 & 0.0029 \\ -24.2502 & 1834.247 & -37.9986 & 46.2783 & 2.9216 & -0.1979 \\ 0.5567 & -37.9986 & 1.3129 & -0.9066 & -0.0530 & 0.0084 \\ -0.3522 & 46.2783 & -0.9066 & 13.0149 & 1.3970 & -0.0047 \\ -0.0066 & 2.9216 & -0.0530 & 1.3970 & 0.1525 & -0.0002 \\ 0.0029 & -0.1979 & 0.0084 & -0.0047 & -0.0002 & 0.00005 \end{bmatrix}$$

$R_2 = I_2$. Moreover, selecting $q = 0$, we have that $V_2 = 0.0001 I_3$ and $V_1 = diag(0, 0.01, 0, 0, 0, 0)$.
Applying theorem 1, the overall control system is calculated.

The time simulation of the computed closed loop system (33), (34), with respect to (35) and (36), is shown in Fig.4. In the same figure, an H_2 design is shown with the same design parameters as in theorem 1.

It is apparent that under saturation, the H_2 design gives an unstable system. Whereas, the new controller based on theorem 1 manages to stabilize the system well and eliminates the saturation effect very quickly. The proposed method provides a dynamic response with a settling time about 2 sec. For the unsaturated components Δe_t and α, the response of the system with saturation is almost identical with the response assuming no saturation. This is also true for the saturated components, after the termination of the saturation event. This is clearly not the case in the H_2 design. From the above, we conclude that the new controller is able to satisfy the specifications.

5 Conclusions

The design of a pseudo-linear anti-windup control system has been presented for the power system in Fig.1, under saturation of its actuators. It was shown via simulations of the closed loop system that, the proposed method satisfies the system specifications. The designed control system appears to perform very well in situations where saturation occurs. In cases without saturation, the performance is better than the cases with saturation. The proofs of the theoretical results were omitted but they will reported in more detail in another paper [5].

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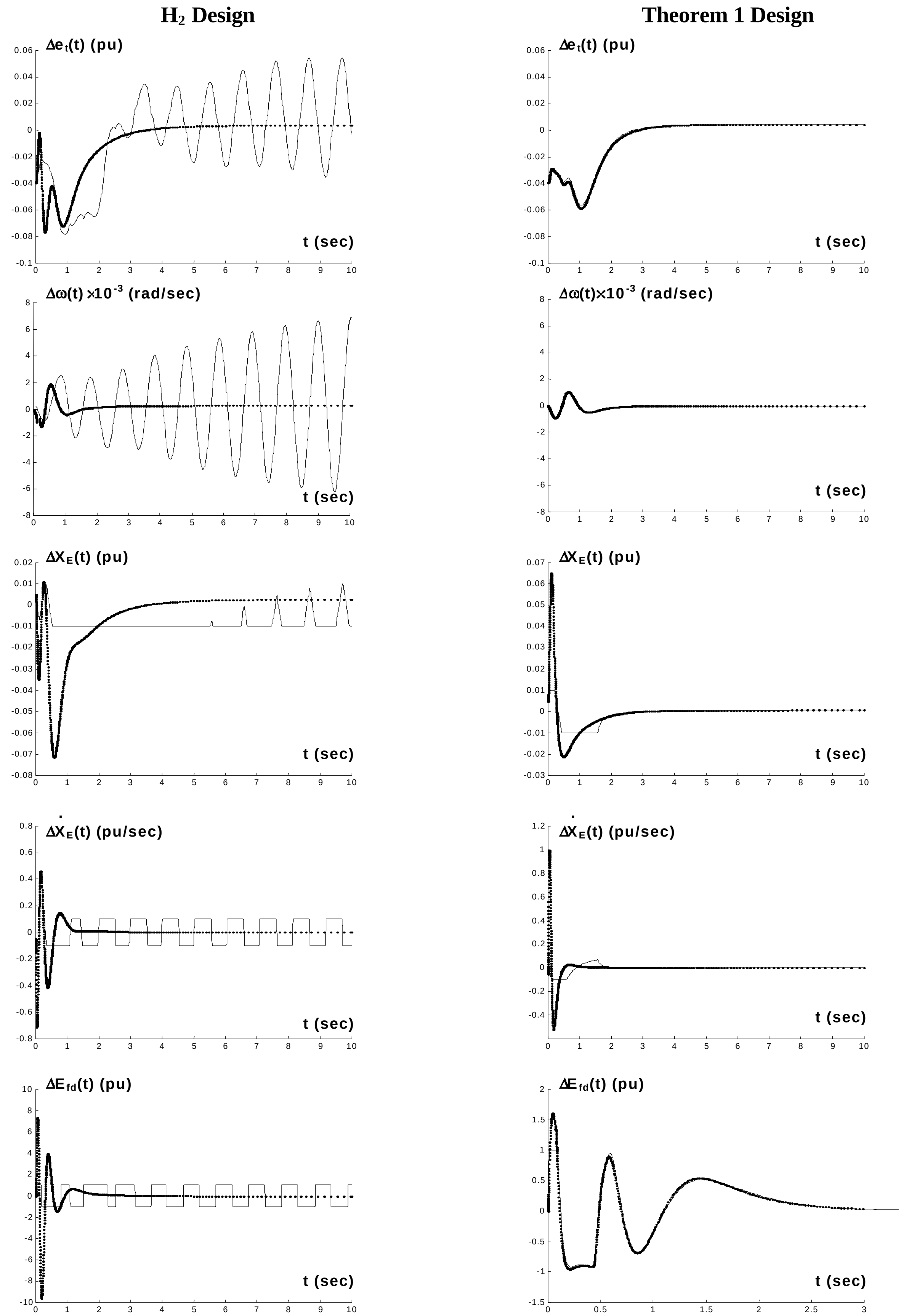

Fig.4 closed loop system simulation (solid line: with saturation, dote line: without saturation).

$$\bar{x}(0)=\begin{bmatrix}0.1 & 0 & -0.05 & 0 & 0.005 & 0_{7\times 1}\end{bmatrix}^T,\ \Delta T_L(t)=step(0.01),\ \Delta w_2(t)=0_{3\times 1}.$$