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Aggressive Control Design for Electric Power Generation Plants

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Abstract— **This article addresses the design problem of an aggressive load/frequency feedback controller against load disturbances for an electric power generation plant. The controller is comprised of two components. The primary aggressive component, whose design is based on LMI techniques, places the closed loop poles in a predefined region while providing fast attenuation and disturbance rejection. The resulting control action provides control commands with large amplitudes that trigger the plant's input saturator especially in case of large load disturbances. To account for this, an anti-windup compensator is provided assuring stability of the closed–lop system in all cases. The overall controller provides a fast response for small load disturbances and a rather conservative response owing to the anti-windup action for large loads. Simulation studies are offered to illustrate the efficiency of the control design.**

I. Introduction

This article suggests a framework of control design for the load frequency control (LFC) problem focusing on a single area power plant with input saturation. Although the linear version of this control loop has been extensively analyzed in the past [1–3], it is still an area of active research [4–8], mainly because the same control design objectives are now revisited from a slightly different perspective. Deregulation, distributed generation and decentralized control [9–12], along with security issues in cyber-physical systems [5–7, 13–15] and saturation induced instabilities [10, 14, 16] reveal the need for new approaches in control design.

The rest of the paper is divided in four sections. Section II presents the linearized dynamics of a single-area power system, whereas open-loop simulation studies delineate the control synthesis perplexities caused by the trade-off between the zero steady-state frequency deviation demand and the existence of the saturation hard constraints.

In Section III we briefly present the methodology for designing linear closed-loop regulators for the LFC problem by combining H_∞ concepts for disturbance attenuation and pole-clustering in LMI regions for performance. The input saturator is neglected in the design phase and ususlly it is only empirically taken care of by selecting "low gains" (non aggressive control). The dangers of instability is demonstrated when an aggressive control design addresses a power system with high load and an input saturator. In Section IV an anti-windup scheme is presented (abbreviated as AW henceforth) as a remedy to the above danger, while simulation results delineate the trade–off between controller's aggressiveness and stability ensured by the AW compensator at the expense of slow regulation of the frequency deviation to zero. Section V provides concluding remarks.

Regarding notations, I_n corresponds to the $n \times n$ identity matrix, $0_{n,p}$ is a zero matrix of appropriate dimensions, while the expression $M > 0$ (< 0) implies that M is a positive (negative) definite matrix.

The terms "Islanded Power Plant" and "single control area" will be used interchangeably while strictly speaking this is not always true. The same holds for the terms "Automatic Generation Control" and "Load Frequency Control".

II. Power Generation System Modelling and Control

We consider the linearized model of an islanded power plant [1, 2, 5–7] and its open-loop block diagram as shown in Figure 1. Inhere, the fast and stable speed governor dynamics

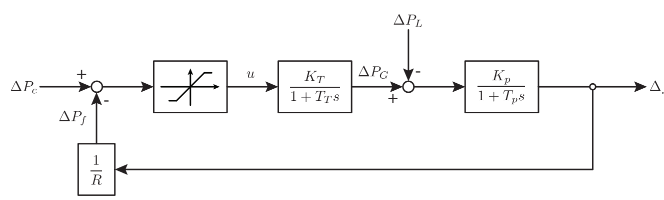

Fig. 1: Primary frequency control for a power plant [5]

are omitted, resulting in the plant's state vector $x(t)$

$$x(t) = [\Delta f(t) \qquad \Delta P_G(t)]^\top, \tag{1}$$

where $\Delta f(t)$ is the frequency deviation and $\Delta P_G(t)$ is the deviation from equilibrium value of the mechanical power produced in the output of the turbine. We assume that the mechanical power provided to the turbine rotor shaft is equal to the electrical power produced by the synchronous generator whose efficiency factor is considered to be $\eta = 1$.

An open–loop continuous-time state space linearized model can be formulated (by ignoring the input saturator) as [1, 5–7]

$$\begin{aligned} S_o \ : \ \dot{x}(t) &= A_o x(t) + B_u u(t) + B_w \Delta P_L(t) \\ z(t) &= C_z x(t) \end{aligned} \tag{2}$$

The performance variable $z(t) \in \Re$ corresponds to the first state variable $\Delta f(t)$, whereas the complete state vector can be used for feedback purposes. The disturbance corresponds to an unknown, piecewise constant and bounded power load

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deviation due to the demand of the consumers and its value range assigned in simulations is within the interval $|\Delta P_L| \leq \Delta P_L^{\max} = 150$ MW.

The total control signal $u(t)$ from Figure 1, consists of two components, namely the primary frequency control action $\Delta P_f(t)$ and the secondary "Automatic Generation Control (AGC)" law $\Delta P_c(t)$.

$$u(t) = \Delta P_c(t) + \Delta P_f(t) \tag{3}$$

and is subject to a saturation hard constraint of the form

$$-u_{\max} \leq u(t) \leq u_{\max}, \quad \forall t \geq 0, \tag{4}$$

where the control bound $u_{\max} \in \Re_+^*$ is (in this study) 33% higher than $\Delta P_L^{\max}$, or $|u_{\max}| = 200$ $[MW]$.

We remark that the 'symmetric' saturator limits were necessarily assumed to be larger than the maximum expected load (otherwise a zero frequency deviation would be simply unreachable) while allowing the handling of negative values for ΔP_L in case of load reduction.

The open–loop system matrix A_o in (2) is given as [5–7]

$$A_o = \begin{bmatrix} -\frac{1}{T_p} & \frac{K_p}{T_p} \\ 0 & -\frac{1}{T_T} \end{bmatrix}, \text{ where} \tag{5}$$

$$B_u = \left[0, \frac{K_T}{T_T}\right]^\top, B_w = \left[-\frac{K_p}{T_p}, 0\right]^\top, C_z = [1, 0] \ . \tag{6}$$

.

It is well known that any power load change causes the electrical frequency to deviate from its nominal value. The primary frequency control action, performed by the speed governor, is a "coarse" regulator attached on the prime mover, implementing a proportional linear control law, i.e.

$$\Delta P_f(t) = -\frac{1}{R}\Delta f(t). \tag{7}$$

The steady-state frequency deviations are eliminated by the automatic generation control signal $\Delta P_c(t)$ which was initially a pure integrator or PI control law [1–3], while recently more advanced control schemes were developed and tested [4, 8].

Taking into account the expression for ΔP_f in (7), while still neglecting the input saturator, the state-space description is

$$\begin{aligned} S_c \ : \ \dot{x}(t) &= A_c x(t) + B_u u(t) + B_w \Delta P_L(t)) \\ z(t) &= C_z x(t), \text{ where} \end{aligned} \tag{8}$$

$$A_c = A_o + \begin{bmatrix} 0 & 0 \\ -\frac{K_T}{RT_T} & 0 \end{bmatrix} . \tag{9}$$

A detailed explanation of all individual parameters involved in the equations 5-6 along with their corresponding values and measurement units is provided in Table I. For completeness, we also provide the formulas associated with the gain K_p and the time constant T_p as

$$K_p = \frac{1}{D}, \quad T_p = \frac{2HP_B}{f^\circ D}. \tag{10}$$

TABLE I: Parameter values for the islanded control area of Figure 1 (*Source:* [1].)

Parameter	Symbol	Value	Units
Nominal Frequency	f°	50	Hz
Power Base	P_B	2000	MW
Load Dependency Factor	D	16.66	MW/Hz
Speed Droop	R	1.2×10^{-3}	Hz/MW
Generator Inertia Constant	H	5	s
Turbine Static Gain	K_T	1	MW/MW
Turbine Time Constant	T_T	0.3	s
Area Static Gain	K_p	0.06	Hz/MW
Area Time Constant	T_p	24	s
Controller Static Gain	K_I	5000	MW/Hz

For the parameter values provided in Table I, the system (8) is stable and the eigenvalues of the matrix A_c are $\lambda_{1,2} = -1.687 \pm j2.058$, while the matrix pair (A_c, B_u) is controllable. Notice that the system representation in 8 is already in the standard formulation encountered in optimal and robust control theory [17, 18].

III. Closed Loop Load Frequency Controller Synthesis

Usually each control area has its own AGC unit which, as known from standard control engineering, must necessarily incorporate integral action. It is well known that the easiest way to enforce integral action is to "artificially" augment the system dynamics with an extra state variable being equal to the time integral of the signal to be regulated. Such an approached guarantees asymptotic regulation (set–point tracking) in the presence of piecewise constant disturbances (reference signals) [18–21]. This idea was also followed for the LFC/AGC problem by the power community even in the early days when purely integral controllers were designed. The system's state vector was augmented with the integral of the so called "Area Control Error" (ACE) as exemplified in the relevant literature [1, 2].

In our case the extra state variable x_I needed is

$$\dot{x}_I(t) = z(t) = C_z x(t) = \Delta f(t) \Rightarrow x_I(t) = \int_0^t z(\tau)d\tau \tag{11}$$

and the augmented dynamics S_a can be expressed as

$$x_a(t) \triangleq \begin{bmatrix} \Delta f(t) & \Delta P_G(t) & \int_0^t \Delta f(\tau)d\tau \end{bmatrix}^\top, \tag{12}$$

$$\begin{aligned} S_a \ : \ \dot{x}_a(t) &= A_a x_a(t) + B_{u,a} u(t) + B_{w,a} \Delta P_L(t), \\ z(t) &= C_{z,a} x_a(t), \end{aligned} \tag{13}$$

where the extra subscript "a" signifies the augmented version of each vector or matrix; in our case,

$$A_a \triangleq \begin{bmatrix} A_c & 0_{2,1} \\ C_z & 0 \end{bmatrix}, \quad B_{u,a} = \begin{bmatrix} B_u \\ 0 \end{bmatrix}$$

It is now clear that designing of a static state–feedback regulator for (13) will provide a controller consisting of two parts: the desired integral action, assuring a zero steady state output error despite the presence of the unknown piecewise constant disturbance, and a regulating state feedback term which focuses on the performance criteria.

$$u(t) \quad = \quad -K_a x_a(t) = -K_x x(t) - K_I \int_0^t \Delta f(\tau) d\tau \quad (14)$$

In this work the robust regulator for the augmented single–area dynamics (13) is designed by combining H_∞ methodologies for disturbance attenuation, enhanced with closed–loop pole clustering for performance. Since both synthesis objectives are formulated as LMI feasibility problems, combining them into a single LMI allows the combined satisfaction of both design criteria as presented next.

A. LFC Controller Synthesis based on a Combination of H_∞ and Pole Clustering Methodologies

The design methodology for Static State Feedback (SSF) H_∞ and pole clustering control synthesis has been extensively described elsewhere [8] and only a brief description will be given here along with some simulation results.

Given the system from (8) the search for a stabilizing static state–feedback $u(t) = Kx(t)$ guaranteeing an optimum H_∞ norm γ, corresponding to a minimum level of disturbance attenuation $\|z\|_2/\|\Delta P_L\|_2 < \gamma$, is equivalent (if and only if) with the existence of a symmetric positive definite matrix X and a matrix Y such that the following matrix inequality holds [17]

$$X \quad > \quad 0,$$

$$\begin{bmatrix} \Lambda+\Lambda^T & B_w & XC_z^T \\ B_w^T & -\gamma I_1 & 0 \\ C_z X & 0 & -\gamma I_1 \end{bmatrix} \quad < \quad 0 \qquad (15)$$

where (for brevity of notation) $\Lambda(X,Y) = AX + B_u Y$. If LMI (15) has a feasible solution (in terms of X, Y, γ), the SSF control gain $K = YX^{-1}$ stabilizes the closed loop system while minimizing the disturbance effect on the performance channel in the sense of "γ-attenuation" explained before.

Since the optimization procedure does not place any restriction on the gain matrix K and its norm, the ensuing gain elements can become unacceptably large (hence not implementable). In order to prevent $\|K\|$ from becoming unacceptably large, and also enhance the controller with performance specifications, two approaches were further investigated: 1) add constraints on the norm of the gain, expressed as additional LMIs [22]. 2) pole clustering again expressed again as LMI constraints, with the latter being our choice for this work. The motivation behind "Pole Clustering within an LMI region" along with its LMI formulation, can be traced in [21, 23–25] whereas applications to the LFC problem have been presented in [8, 12].

For a generic Linear Time Invariant system (A, B_u), the synthesis LMIs for a state feedback controller $u = Kx$ placing the closed poles inside a prespecified LMI region $D(\alpha, r, \theta)$, are given below in terms of a symmetric positive definite matrix X and a matrix Y satisfying the three separate LMIs for D_α, D_r, D_θ [8, 21, 24]

$$\begin{aligned} X \; &= \; X^T > 0 \\ D_\alpha(X,Y) \; &: \; 2\alpha X + \Lambda + \Lambda^T < 0 \\ D_r(X,Y) \; &: \; \begin{bmatrix} -rX & \Lambda^T \\ \Lambda & rX \end{bmatrix} < 0 \\ D_\theta(X,Y) \; &: \; \begin{bmatrix} \sin\theta[\Lambda+\Lambda^T] & \cos\theta[-(\Lambda)+\Lambda^T] \\ (*)^T & \sin\theta[\Lambda+\Lambda^T] \end{bmatrix} < 0 \quad (16) \end{aligned}$$

where again $\Lambda(X,Y) = AX + B_u Y$ and the controller gain is computed as $K = YX^{-1}$.

Since "multiple LMIs combine into one LMI" , the two sets of LMIs (15) and (16), reflecting respectively disturbance attenuation and transient performance control objectives, are combined by demanding that the decision variables X, Y appearing there are common.

Applying this generic control synthesis methodology to the augmented islanded power system dynamics in (13) provides a family of "baseline" robust linear frequency regulators. (Robustness signifies the capability of regulating to zero despite the presence of the unknown piecewise constant disturbances).

It should be noted that even if the set of LMIs (15) and (16) is feasible, there is a crucial remaining issue of whether the resulting controller generates a control signal that respects the saturation limits. An aggressive controller can theoretically achieve faster regulation of the frequency deviation to zero, but there is a great chance that the saturator limits are violated with whatever adverse effect this may cause [10].

One way to handle this trade–off between performance and respect of the saturation limits is via an appropriate ("ad hoc") selection of the LMI region (mainly its α-parameter) so that the saturator work close to its limits (especially during the first seconds of the load variation) but without hitting the upper/lower bounds max or min.

Even with a constant and known value on the expected load change $\Delta P_L(t)$, this implies a tedious exhaustive search on the set of candidate LMI regions so that the saturated responses are only slightly overshooting when compared with their unsaturated versions [8].

1) Simulation Results with non–aggressive design : For the specific system under investigation, a "non–aggressive" choice for the LMI region $D(\alpha, r, \theta)$ with $\alpha = 0.25$, $r = 6$, $\theta = 25°$, was found to give a trade–off between performance, attenuation and saturation limits, and the synthesis LMIs (15),(16) for the augmented system yielded an augmented state feedback gain $K_a = [K_x \;\; K_I]$ of

$$K_a = 1000 \times \begin{bmatrix} -3.6328 & -0.0023 & -1.0891 \end{bmatrix}$$

and a guaranteed disturbance attenuation of $\gamma = 8.7187 \times 10^{-4}$, whereas the closed–loop poles were placed at $\lambda_{1,2} = -5.456 \pm j2.251$, $\lambda_3 = -0.260$.

Figure 2 presents the unsaturated and the saturated system response $\Delta f(t)$, for a step load of $\Delta P_L = 150$ *MW* ($\Delta P_G(t)$ and $u(t) = \Delta P_c(t) + \Delta P_f(t)$ are not shown due to space limitations). Due to the integral action, both the unsaturated and saturated responses of $\Delta f(t)$ return slowly and steadily to zero, with a settling time of approximately 25 seconds, while the smooth control action never triggers the saturator.

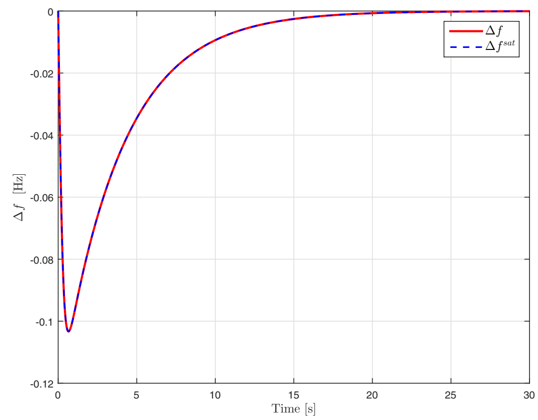

Fig. 2: $\Delta f(t)$ with non aggressive design ($\alpha = 0.25,\ r = 6,\ \theta = 25°$) and $\Delta P_L = 150\ MW$

2) Simulation Results with aggressive design: Being unsatisfied with the slow response (settling time of 25 s), the designer is tempted to "make response faster" by trying more aggressive ("high–gain") control laws which possibly interact in a damaging way with the input saturator, a danger delineated in the following simulation experiment showing the results of employing increasingly aggressive controllers, generated by increasing values of the area parameter α i.e. by forcing the decay–rate of the closed–loop system to become faster. Figure 3 presents the saturated $\Delta f(t)$ system responses with a step load ΔP_L =150MW, $r = 20,\ \theta = 25°$ and increasing values of the area parameter α.

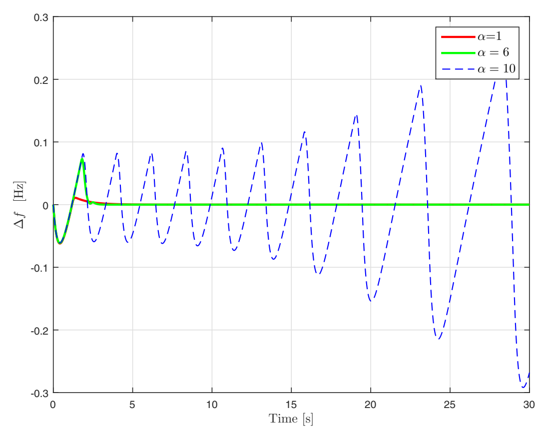

Fig. 3: $\Delta f(t)$ with integral action and combined H_∞/pole clustering, for $\alpha \in \{1,\ 6,\ 10\}$

For ($r = 20,\ \theta = 25°$) kept constant in all following simulations, and $\alpha = 10$, the augmented state feedback gain is $K_a = 10000 \times \begin{bmatrix} -0.9144 & -0.0001 & -4.9429 \end{bmatrix}$, placing the closed–loop poles of the "saturation–free" linear system at $\lambda_{1,2} = -18.032 \pm j7.676,\ \lambda_3 = -10.723$ The interaction of the aggressive controller with the input saturator clearly induces instability in $\Delta f(t)$ (as can be seen in Figure 3) but also to all signals involved in the LFC loop i.e., $\Delta P_G(t)$ and ΔU_{tot} as well (not shown).

The dangerous interplay between aggressive control with integral action and saturation, has recently become an important issue, since it has been shown that saturation induced instabilities can occur during the transient response in large–scale power networks [10, 13, 16].

IV. AGC/LFC Controller Anti–Windup Enhancement

It is evident from the previous section that even in the case of a simple electric power plant instability can occur when input amplitude saturation co-exists with aggressive control designs. In order to improve the LFC controller capabilities and overcome saturation issues, an anti-windup (AW) compensator will be designed and tuned in the current section.

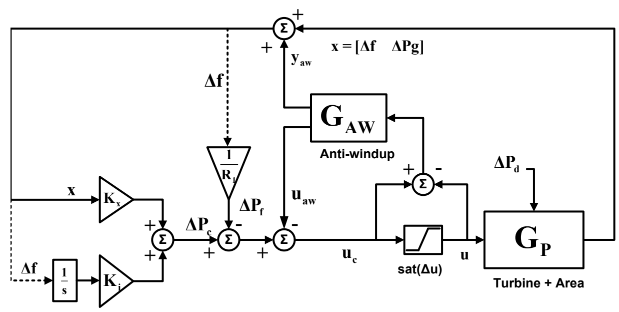

Fig. 4: Block-diagram of the anti–windup scheme (inspired from [26])

Instead of the usual LMI approach found in anti-windup synthesis [27], a Riccatti equation based approach presented in [26] was adopted not only due to its numerical advantage, but also because it provides the capability of tuning the dynamics of the AW compensator using a weighting matrix while preserving the L_2 performance. No rate constraints were taken into account although this could be a source of further complications [16, 28].

For the special case of strictly proper plants ($D_p = 0$) with $C_p = I$, like the current linearized model of an islanded power plant, the anti-windup compensator of [26] can be cast in the following state space form:

$$G_{AW}: \begin{cases} \dot{x}_{aw}(t) = A_w x_{aw}(t) + B_p \Delta u(t) \\ u_{aw}(t) = F_w x_{aw}(t) \\ y_{aw}(t) = x_{aw}(t) \end{cases} \tag{17}$$

The matrix $A_w = A_p + B_p F_w$ is Hurwitz while u_{aw} and y_{aw} are the two outputs of the AW compensator, that are applied to the system according to Figure 4 which delineates the structure of the AW compensator to be designed. The role of y_{aw} is to modify the measured output of the plant and u_{aw} is responsible for the immediate modification of the control signal. The saturation has the form

$$u(t) = \text{sat}(u_c(t)) = \begin{cases} u_c(t) & \text{if } |u_c(t)| \le u_{\max} \\ u_{\max}\text{sign}(u_c(t)) & \text{elsewhere} \end{cases} \tag{18}$$

and the term $\Delta u(t) = u_c(t) - u(t)$ is activated when saturation takes place.

The F_w is a tunable parameter that can be obtained if there exist matrices $X = X^T$, $W = \mathrm{diag}(k_1, \ldots, k_m) > 0$ and a real positive scalar γ such that the following continuous-time algebraic Riccati equation is satisfied

$$A_p^T X + X A_p - \gamma^{-2} X B_p B_p^T X + I = 0, \text{ while} \tag{19}$$

$$Z = 2I - \gamma^{-2} W > 0, \text{ resulting in} \tag{20}$$
$$F_w = (\gamma^{-2} I - W^{-1}) B^T X \tag{21}$$

1) Tuning the Anti–Windup : Following the remarks of [26] the γ is fixed to the $\gamma_{opt} = \|G_p(s)\|_\infty$ and the only parameter that is left for tuning is the W which in the current case is a scalar. Using (20) the interval for the W is calculated as $W \in (0.0, 2.0]$. In Figure 5 the interval of W was uniformly sampled and the relevant responses for ΔP_G and ΔU_{tot} were plotted verifying that increasing or decreasing the values of W provides slower or faster dynamic responses respectively. The values of the AW tuning parameters finally used in the

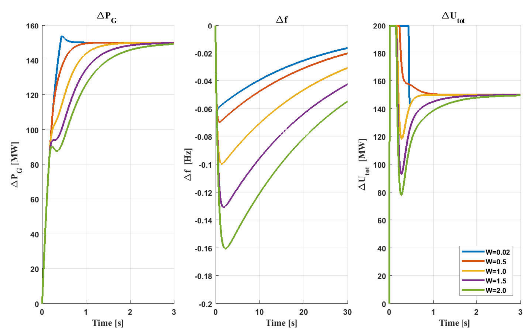

Fig. 5: Anti–Windup Tuning using the W-parameter.

simulations below are $W = 0.02$ and $\gamma = 1.018$.

2) Simulation Results with aggressive design and Anti–Windup : The importance of using AW compensators when dealing with aggressive control laws interacting with the input saturators, is demonstrated next, by computing the response of the electric power plant used in the previous simulations employing a controller designed with the presented methodology (i.e. with integral action and combined H_∞/pole clustering methodologies) with the $D(\alpha, r, \theta)$ area selected as $\alpha = 10,\ r = 20,\ \theta = 25^\circ$. In Figure 6 the blue curves are the "saturated" responses for $\Delta P_L = 150\ MW$ when no AW compensation is provided. The unstable behavior of all signals involved is clear and AW is not a luxury but a real need. The "bang–bang" behavior of the total control signal varying between the upper and lower saturation limits is also worth noting.

Following the "Riccatti–based" algorithm presented in the previous section for AW design, the same system/controller/load triplet that yielded the unstable response, now responds as shown by the green curves in Figure 6. The stability is regained even in these extreme situation, at the expense of slow regulation of $\Delta f(t)$ to zero.

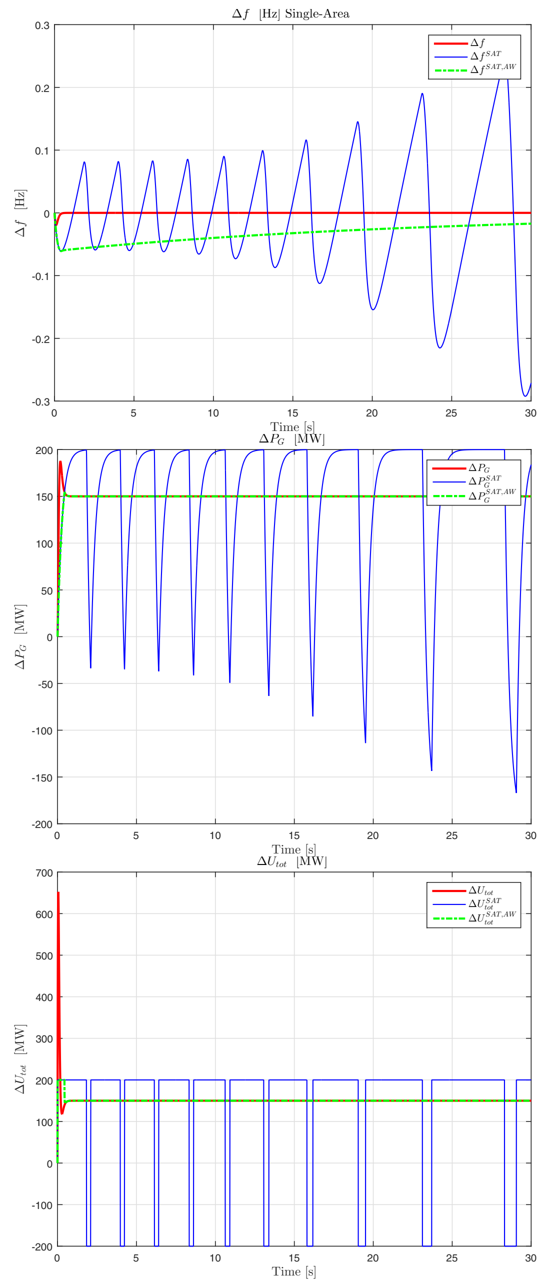

Fig. 6: $\Delta f(t)$, $\Delta P_G(t)$ and ΔU_{tot} responses without and with AW compensator with aggressive design ($\alpha = 10,\ r = 20,\ \theta = 25^\circ$) and $\Delta P_L = 150\ MW$

The same aggressive controller of the previous section ($D(\alpha, r, \theta)$ area with $\alpha = 10,\ r = 20,\ \theta = 25^\circ$)is now tested against different loads increasing as $\Delta P_L = 10,\ 50,\ 100,\ 145\ MW$. In Figure 7 one can clearly see a rather generic result confirmed after many simulations: that for a given aggressive controller and "low loads"($\Delta P_L =$

10, 50), the responses converge as fast to the desired value as the unsaturated ones. As the load ΔP_L increases towards its critical value of $\Delta P_L = 150\ MW$ the saturator is triggered and so does the AW stabilizing mechanism, making the regulation to zero slower but stable.

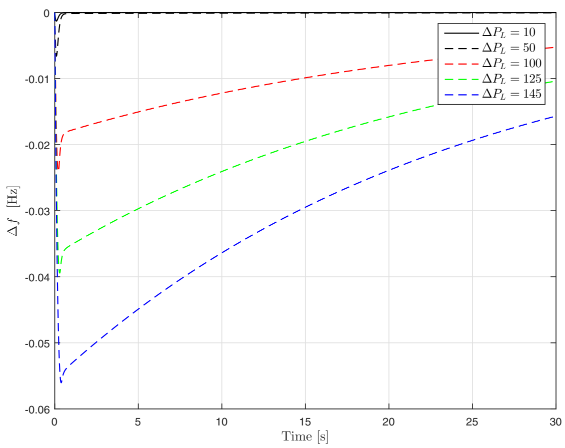

Fig. 7: $\Delta f(t)$ responses with anti–windup, aggressive design ($\alpha = 10, r = 20, \theta = 25°$) and increasing Load ΔP_L

V. Conclusions

The focus of this article was to offer a methodology that avoids the danger of saturation–induced instabilities in electric power plants when aggressive control laws are employed. The synthesis of linear state feedback regulators satisfying a combination of disturbance rejection with transient performance criteria is straightforward using concepts from H_∞ control ad using LMIs as a optimization tool. The danger of instability is shown even in the simplest of cases by combining an aggressive control tuning with a "large" load variation. A anti–windup compensator is then designed and it is shown that in all cases it can diminish the adversarial effect of the saturators.

VI. Acknowledgments

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