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ROBUST DECENTRALIZED FEEDBACK CONTROLLERS FOR THE TURBOGENERATORS

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Abstract. Robust decentralized linear feedback controllers for the turbogenerators, using the structured singular value approach, are investigated. Different structures of decentralized controllers were applied and tested. The controllers were designed for structured and unstructured model uncertainty. The gain directionality compensation, due to a high condition number was considered.

1. Introduction

The single–machine infinite–bus system is a multivariable plant whose gain depends strongly on the direction of the input (control) signal. A parameter describing the gain directionality property is the condition number

$$cn = \frac{\overline{\sigma}(P)}{\underline{\sigma}(P)} \tag{1}$$

Here $\overline{\sigma}(P)$ and $\underline{\sigma}(P)$ denote the maximum and the minimum singular value of the plant

$$\begin{aligned} \overline{\sigma}(P) &= \max_{u\neq 0}\{||Pu||_2/||u||_2\} \\ \underline{\sigma}(P) &= \min_{u\neq 0}\{||Pu||_2/||u||_2\} \end{aligned} \tag{2}$$

where $||\cdot||_2$ is the Euclidean norm. The plants with a strong gain directionality property have a high condition number (ill–conditioned plants) [1-3].

The main problem in the control of ill–conditioned plants is the inherent presence of model uncertainty. The disagreement between plant P and model

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$\tilde{P}$ can, in the case of turbogenerator systems, successfully be described by a normalized multiplicative input perturbation argument Δ_u

$$P = \tilde{P}(I + l_u \Delta_u) \text{ and } \overline{\sigma}(\Delta_u) < 1 \tag{3}$$

where I and l_u denote the unity matrix and the uncertainty weighting operator respectively. The function l_u is also called the upper bound of model uncertainty [2,3]. The matrix Δ_u is an unknown unity norm bounded matrix $\overline{\sigma}(\Delta_u) < 1$. If Δ_u is a full matrix then the uncertainty is called unstructured. The structured model uncertainty assumes a block diagonal Δ_u.

2. The plant

The typical single–machine infinite–bus system consists of a generating unit connected to a constant voltage bus through two parallel transmission lines. An excitation system and automatic voltage regulator (AVR) are employed to maintain the terminal voltage profile. An associated governor monitors the shaft frequency and controls mechanical power and speed. The overall system is represented as a two–input, two–output system with the mechanical power and exciter–voltage settings as the two inputs and the measured incremental changes in load angle and terminal voltage as the outputs.

2.1 Linearized model

Neglecting the transients in stator circuit and the effect of rotor amortisseur, a simplified linear model for a synchronous machine connected to an infinite bus through a transmission line is given below in the form of Park's twoaxis machine representation [4]:

$$\dot{e}'_q = -\frac{1}{k_3 \tau'_{d0}} e'_q - \frac{k_4}{\tau'_{d0}} \delta + \frac{K_a}{\tau'_{d0}} v_s + \frac{K_a}{\tau'_{d0}} v_{ref} + \frac{K_a}{\tau - d0} v_1 \tag{4}$$

$$\dot{\omega} = -\frac{k_2}{2H} e'_q - \frac{k_1}{2H} \delta - \frac{D}{2H} \omega = \frac{1}{2H} t_m \tag{5}$$

$$\dot{\delta} = \omega_0 \omega \tag{6}$$

$$0 = v_d + r_d i_d - x_q i_q \tag{7}$$

$$e'_q = v_q + r_q i_q + x_d i_d \tag{8}$$

$$v_t^2 = v_d^2 + v_q^2 \tag{9}$$

where δ denotes machine load angle in radians, ω is machine rotor speed in pu (*per–unit*), e'_q represents quadrature axis transient voltage in pu, v_t is terminal feedback voltage in pu, τ'_{d0} is d–axis transient open circuit time constant in seconds, D is damping coefficient, H is inertia constant and K_a is exciter gain. The transmission network having an impedance of $r_e + jx_e$, which is connected to an infinite bus with voltage v_b, is given by the equations:

$$v_d = v_b \sin\delta + r_e i_d - x_e i_q \tag{10}$$

$$v_q = v_b \cos\delta + r_e i_q + x_e i_d \tag{11}$$

where v_d, v_q, i_d and i_q represent direct and quadrature axis voltages and currents respectively. A simplified AVR and exciter model is given in the form of the first order filter as:

$$\dot{v}_1 = -\frac{1}{\tau_r}v_1 - \frac{k_6}{\tau_r}e'_q - \frac{k_5}{\tau_r}\delta + \frac{1}{\tau_r}v_{ref} \tag{12}$$

where k_e is AVR gain, τ_e is AVR time constant and v_{ref} is reference input voltage. A power system stabilizer (PSS) is given in the form

$$\dot{v}_2 = -\frac{K_{stab}D}{2H}\omega - \frac{K_{stab}k_1}{2H}\delta - \frac{K_{stab}k_2}{2H}e'_q - \frac{1}{\tau_w}v_2 + \frac{K_{stab}}{2H}t_m \tag{13}$$

$$\dot{v}_s = -\frac{K_{stab}\tau_1}{\tau_2 2H}(D\omega - k_1\delta - k_2 e'_q) - \left(\frac{\tau_1}{\tau_2\tau_w} + \frac{1}{\tau_2}\right)v_2 - \frac{1}{\tau_2}v_s + \frac{\tau_1 K_{stab}}{\tau_2 2H}t_m \tag{14}$$

where K_{stab} is gain and τ_1, τ_2 and τ_w are PSS time constants and t_m is mechanical power.

Under normal operating conditions, applying small perturbation relations around a certain equilibrium point can derive a linear, time–invariant system. A linearized model [4] is shown in block diagram Fig. 1, where the parameter expressions of $k_1, \ldots, k_6$ are given in [5].

The following parameters were used in the derivation of the power system transfer function matrix (machine parameters in pu, time constants in seconds) [5]:
$P_n = 0.9$, $Q_n = 0.3$, $k_1 = 0.76$, $k_2 = 0.86$, $k_3 = 0.32$, $k_4 = 1.41$, $k_5 = -0.14$, $k_6 = 0.41$, $\tau'_{d0} = 7.3$, $D = 0.0$, $H = 3.5$, $K_a = 200$, $K_{stab} = 9.5$
where P_n is nominal real power and Q_n is nominal reactive power.

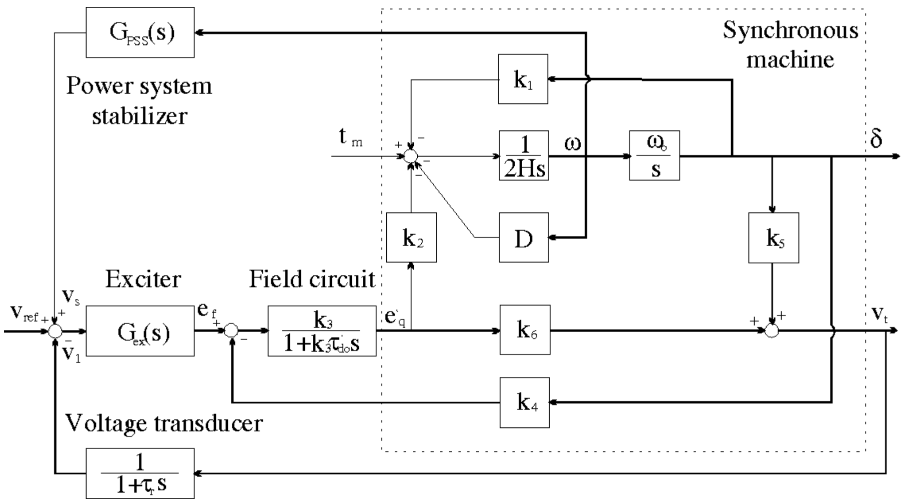

Figure 1. The block diagram of a system with a PSS and AVR

The resulting transfer function matrix (model)$\tilde{P}$, with system state variables

$$x = [\delta \ \omega \ e_q' \ v_1 \ v_2 \ v_s]^T \tag{15}$$

that maps the vector control signal

$$u = [t_m \ v_{ref}]^T \tag{16}$$

into the system output signal

$$y = [\delta \ v_t]^T \tag{17}$$

in matrix transfer function form, is

$$\tilde{P}(s) = \frac{1}{\tilde{D}(s)} \begin{bmatrix} \tilde{N}_{11}(s) & \tilde{N}_{12}(s) \\ \tilde{N}_{21}(s) & \tilde{N}_{22}(s) \end{bmatrix} \tag{18}$$

where

$$\tilde{N}_{11}(s) = [3769.9s^4 + 307021s^3 + 8767558s^2 + 105021172s + 231332389] \tag{19}$$

$$\tilde{N}_{12}(s) = [-551.5s^4 - 45221s^3 - 1201254s^2 - 17845247s - 94834565] \tag{20}$$

$$\tilde{N}_{21}(s) = [-465959s^3 - 37750791s^2 - 732726395s - 504294906] \tag{21}$$

$$\tilde{N}_{22}(s) = [4168s^5 + 337680s^4 + 6793978s^3 + 23935230s^2 + 377017608s + 259480292] \tag{22}$$

$$\tilde{D}(s) = [s^6 + 81s^5 + 2366s^4 + 312014s^3 + 159519s^2 + 1073268s + 717502] \tag{23}$$

The superscript T denotes transposition. The details concerning the modeling of power system can be found in [4,5].

2.2 Model uncertainty and the upper bound

The characteristics of the power system vary with system operating conditions because parameters $k_1, \ldots k_6$ are a function of power system configuration, loading condition etc. [5]. Such nonlinear behaviors can be modeled by the uncertainty model principle. The multiplicative model error is estimated by plotting the frequency responses of the system under various operating conditions, and a bound is chosen to represent the largest uncertainties, as

$$l_u(s) > \max \left| \frac{\tilde{P}_i(s) - \tilde{P}(s)}{\tilde{P}(s)} \right| \tag{24}$$

where $\tilde{P}_i$ is model of the plant under various operating points.

For each type of system configuration and/or operating condition variations, such l_u represents the worst case of the model uncertainties. An example of such case is shown in Fig. 2, showing model uncertainties under five operating conditions and the uncertainty bound.

Alternatively, l_u may be estimated from the frequency responses of nonlinear numerical or laboratory test benches at various operating points. It is not necessary to determine l_u with great accuracy, but only to estimate its essential features.

The following upper bound of model uncertainty was obtained

$$l_u = 0.25 \frac{\frac{s}{0.1} + 1}{\frac{s}{20} + 1} I \tag{25}$$

2.3 Singular values

Fig. 3 shows the frequency response of the singular values and the condition number of the model $\tilde{P}$. At low frequencies the condition number is better $cn(s = 0) \approx 29$. The singular value decomposition at $s = 0$

$$\tilde{P} = U \Sigma V^T \tag{26}$$

where U and V are left and right singular vector matrix and Σ represent diagonal matrix of the singular values

$$U = (\overline{u}, \underline{u}) = \begin{bmatrix} 0.89 & -0.44 \\ -0.44 & -0.89 \end{bmatrix}$$
$$V = (\overline{v}, \underline{v}) = \begin{bmatrix} 0.4 & -0.91 \\ -0.91 & -0.4 \end{bmatrix} \tag{27}$$

where $(\overline{u}, \underline{u})$ and $(\overline{v}, \underline{v})$ are left and right singular vectors associated with $\overline{\sigma}, \underline{\sigma}$:

$$\Sigma = \mathrm{diag}(\overline{\sigma}, \underline{\sigma}) = (86.34, 2.75)$$
$$\tilde{P}\overline{v} = \overline{\sigma u} \tag{28}$$
$$\tilde{P}\underline{v} = \underline{\sigma u}$$

reveals that the input direction with the largest gain is $\overline{v} = (0.4, -0.91)^T$ and the output direction associated with this input direction is $\overline{u} = (0.89, -0.44)^T$. The input direction with the smallest gain is $\underline{v} = (-0.91, -0.4)^T$ and its output direction is $\underline{u} = (-0.44, -0.89)^T$.

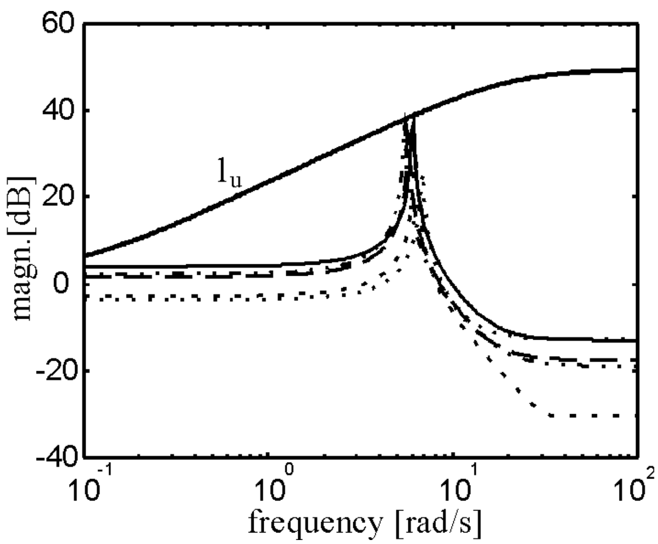

Figure 2. Model uncertainties and the upper bound

The condition number increase with frequency. At high frequency ($s = j100$ rad/s ($j = \sqrt{-1}$)) the condition number is $cn \approx 116$. The singular value decomposition at $s = j100$ rad/s

$$\tilde{P} = U\Sigma V^T \tag{29}$$

$$U = (\overline{u}, \underline{u}) = \begin{bmatrix} 0.01 & 0.99 \\ -0.99 & 0.01 \end{bmatrix}$$
$$V = (\overline{v}, \underline{v}) = \begin{bmatrix} 0.0015 & 1 \\ -1 & -0.0015 \end{bmatrix} \tag{30}$$

$$\Sigma = \mathrm{diag}(\overline{\sigma}, \underline{\sigma}) = (3.96, 0.04)$$
$$\tilde{P}\overline{v} = \overline{\sigma u} \tag{31}$$
$$\tilde{P}\underline{v} = \underline{\sigma u}$$

reveals that the input direction with the largest gain is $\overline{v} \approx (0, -1)^T$ and the output direction associated with this input direction is $\overline{u} \approx (0, -1)^T$. The input direction with the smallest gain is $\underline{v} \approx (1, 0)^T$ and its output direction is $\underline{u} \approx (1, 0)^T$.

The consequence of this gain directionality is that setpoint changes collinear with require large control actions. Similarly it is expected that disturbances collinear with u are more difficult to reject.

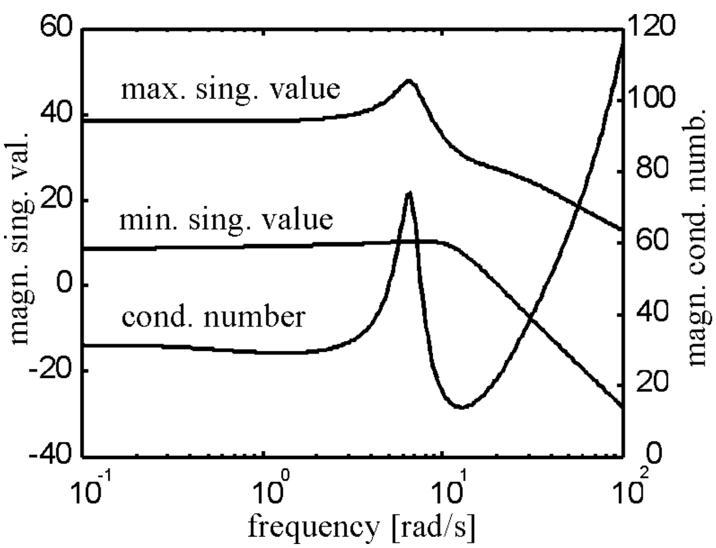

Figure 3. The singular value and the condition number frequency response

3. The μ–optimality framework

Figure 4 shows the block diagram of a feedback system with input multiplicative model uncertainty and with setpoints as external inputs. The operator W_p is the sensitivity weighting filter. W_p is used by the designer to give a specified shape to the sensitivity operator E:

$$E(r \to e) = (I + PK)^{-1} \tag{32}$$

The robust performance means that the weighted multiplicative norm (or seminorm) of the sensitivity operator is unity bounded for any perturbation Δ_u of the plant

$$||W_p E||_m < 1 \tag{33}$$

where the operator $||\cdot||_m$ denotes a multiplicative norm (or seminorm). The sensitivity weight are chosen as in [6]:

$$W_p = \frac{0.02(s + 0.2)}{s + 0.002} I \tag{34}$$

This sensitivity weighting filter indicates that at low frequency, the closed–loop system should reject disturbances at the output by a factor of 20–to–1. In other words, the steady–state tracking error due to reference step- input should be on the order of 0.05 or smaller. This performance specification gets less emphasis at higher frequency.

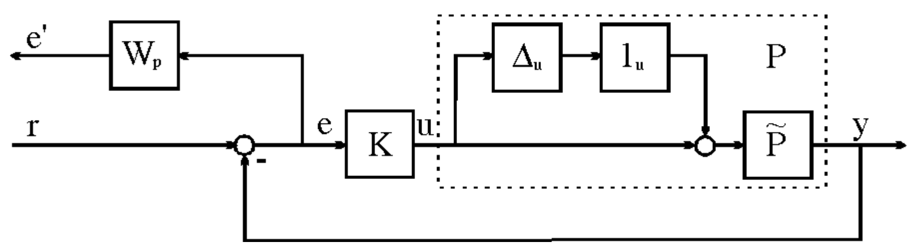

Figure 4. The block diagram of the feedback system with setpoint changes as external inputs

When Fig. 4 is rearranged to match Fig. 5 the interconnection matrix G is obtained as follows:

$$G = \begin{bmatrix} M & G_{12} \\ G_{21} & G_{22} \end{bmatrix} = \begin{bmatrix} -K\tilde{E}\tilde{P}l_u & K\tilde{E} \\ -W_p\tilde{E}\tilde{P}l_u & W_p\tilde{E} \end{bmatrix} \tag{35}$$

$$\tilde{E} = (I + \tilde{P}K)^{-1} \tag{36}$$

Simple manipulations give:

$$E = G_{22} + G_{21}\Delta_u(I - M\Delta_u)^{-1}G_{12} \tag{37}$$

The μ–optimality framework gives the following conditions [7-11]:

1° nominal stability $\Rightarrow G$ is (internally) stable

2° nominal performance $\Rightarrow NP = \sup_\omega\{np(\omega)\} < 1,\ np(\omega) = \overline{\sigma}(G_{22})$

3° robust stability $\Rightarrow RS = \sup_\omega\{rs(\omega)\} < 1,\ rs(\omega) = \mu_{\Delta_u}(M)$

4° robust performance $\Rightarrow RP = \sup_\omega\{(rp(\omega)\} < 1,\ rp(\omega) = \mu_\Delta(G)$

where $\Delta = \text{diag}(\Delta_u, \Delta_p)$ and Δ_p is a full unity norm bounded matrix $(\overline{\sigma}(\Delta_p) < 1)$. The operator $\mu_\Delta(\rightarrow)$ denotes the structured singular value of the operand $\rightarrow$ computed according to the block–diagonal structure of Δ [9]. The functions NP, RS and RP are a measure of the nominal performance (NP), robust stability (RS) and robust performance (RP) respectively.

Considering that the transfer function Δ is unknown (e.g. the argument and the magnitude of this function is unknown), all that is known about Δ is that its magnitude is unity bounded $(\overline{\sigma}(\Delta_p) < 1)$, conditions 2–4 ensure that the closed–loop system from Fig. 5 cannot be destabilized by any such Δ. Intuitively, the concept of the NP, RS and RP measure (conditions 2–4) can be understood as a demand that the loop gain of the feedback system from Fig. 5 be kept less than 1 at any frequency. In other words, the smaller is the NP, RS and RP measure the better is the performance and the robustness of the closed–loop system from Fig. 4.

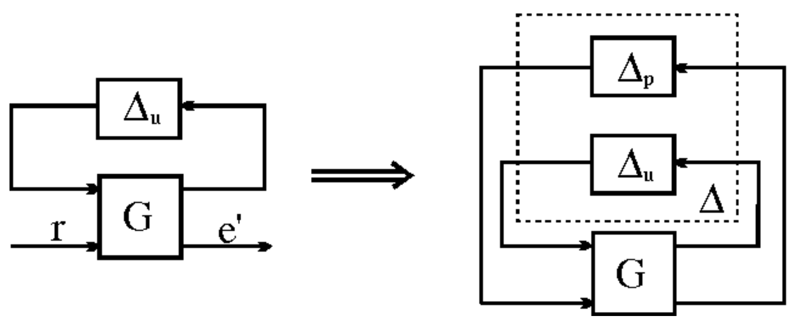

Figure 5. The $G - \Delta$ form

4. The decentralized (diagonal) controller design

The basic idea in decentralized control is to generate the i–th control signal only with respect to the i–th output signal, and the influence of other control signal is neglected. This approach is a natural consequence if the plant P is diagonal or, in other words, if the interaction between the inputs does not exist [3,10,11].

We approximate P with $\tilde{P}$, where

$$P = \begin{bmatrix} P_{11} & P_{12} & \dots & P_{1n} \\ P_{21} & P_{22} & \dots & P_{2n} \\ \vdots & \vdots & & \vdots \\ P_{n1} & P_{n2} & \dots & P_{nn} \end{bmatrix} \tag{38}$$

and

$$\tilde{P} = \mathrm{diag}(P_{11}, P_{22}, \dots, P_{nn}) \tag{39}$$

Consequently, the optimal controller $K = \hat{K}$ will be diagonal:

$$\hat{K} = \mathrm{diag}(K_1, K_2, \dots, K_n) \tag{40}$$

The sensitivity and complementary sensitivity operators with $\tilde{P}$ instead of P are $\hat{E}$ and $\hat{H}$ respectively:

$$\hat{E} = \mathrm{diag}(\hat{E}_1, \hat{E}_2, \dots, \hat{E}_n) = (I + \hat{P}\hat{K})^{-1} \tag{41}$$

$$\hat{H} = \mathrm{diag}(\hat{H}_1, \hat{H}_2, \dots, \hat{H}_n) = \hat{P}\hat{K}(I + \hat{P}\hat{K})^{-1} \tag{42}$$

In this study the following parameterizations of the diagonal controller was used:

$$\begin{aligned} \hat{K}_1 &= \frac{k_d}{s}\,\mathrm{diag}\left(\frac{1}{\tilde{P}_{11}}, \frac{1}{\tilde{P}_{22}}\right) \\ \hat{K}_2 &= \frac{1}{s}\,\mathrm{diag}\left(\frac{k_{d1}}{\tilde{P}_{11}}, \frac{k_{d2}}{\tilde{P}_{22}}\right) \end{aligned} \tag{43}$$

5. The optimization

The goal is to select the adjustable parameters in order to derive the best RP measure. First shall be assume that $\hat{K} = \hat{K}_1$ and that the uncertainty is not structured (Δ_u =full matrix). Fig. 6 shows the nominal performance, robust stability and robust performance measure as a function of the adjustable parameter $k_d(NP(k_d), RS(k_d), RP(k_d))$. As can be seen with such a parameterization the robust performance demand can be reached $\Rightarrow RP(k_d) < 1$ for any $k_d < 0.055$.

The reason for such a relatively high RP measure is that the controller $\hat{K}$ is basically an inversion based controller with respect to $\tilde{P}$. Such a controller completely compensates the gain directionality of the nominal diagonal plant $(\tilde{P})$ and a good NP measure can be expected. Unfortunately, even slight perturbations of the plant can modify the gain directions causing that the closed–loop performance and stability measure deteriorates.

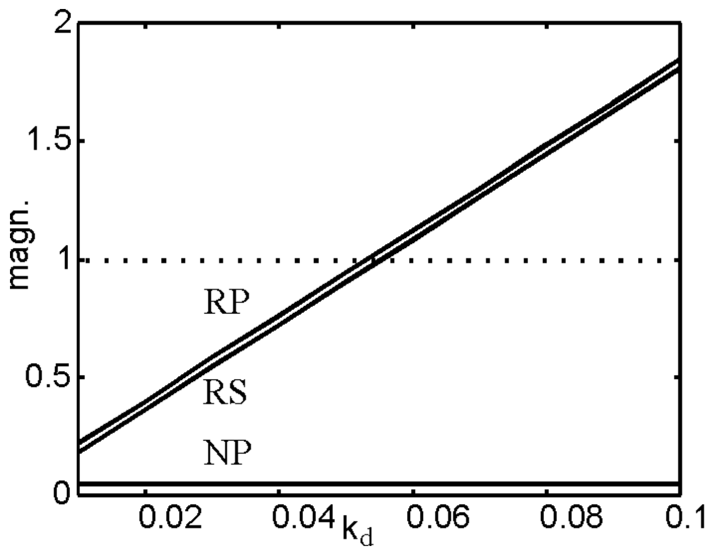

Figure 6. Decentralised controller design for unstructured model uncertainty. NP,RS and RP measure are shown as a function of the adjustable parameter k_d : $NP(k_d), RS(k_d)$ and $RP(k_d)$

In Fig.7 the frequency response of $rp(\tilde{k}_d, \omega) = \mu_\Delta[G(\tilde{k}_d, \omega)]$, $rs(\tilde{k}_d, \omega) = \mu_\Delta[M(\tilde{k}_d, \omega)]$ and $np(\tilde{k}_d, \omega) = \overline{\sigma}[W_p \tilde{E}(\tilde{k}_d, \omega)]$, for $k_d = \tilde{k}_d = 0.055$, is shown. The maximum of the rp measure is $RP(\tilde{k}_d) = 0.99$.

With the controller $\tilde{K}_2$ better RP measure was obtained for $k_{d1} = \tilde{k}_{d1} = 65$ and $k_{d2} = \tilde{k}_{d2} = 0.05$, and $RP(\tilde{k}_{d1}, \tilde{k}_{d2}) = 0.99$. Obviously this parameterization gives a better results than the previous. The nominal performance NP, robust stability RS and robust performance RP measure as a function of two adjustable parameter k_{d1} and k_{d2} are shown in Fig.8a, 8b and 8c.

Now shall be assume that the uncertainty is structured. This means that Δ_u is a diagonal matrix. In the case of turbogenerators this assumption is more realistic than the assumption that Δ_u is a full matrix.

If $\hat{K} = \hat{K}_1$ in Fig.9 the NP, RS and RP measure are shown as a function of the adjustable parameter k_d. Comparing this figure with Fig.6, an improvement can be observed. The RP, RS and NP demand can be satisfied for $k_d <$ 2.1. Figure 10 contains the frequency responses of $rp(\tilde{k}_d, \omega) = \mu_\Delta[G(\tilde{k}_d, \omega)]$, $rs(\tilde{k}_d, \omega) = \mu_{\Delta_u}[M(\tilde{k}_d, \omega)]$ and $np(\tilde{k}_d, \omega) = \overline{\sigma}(W_p \tilde{E}(\tilde{k}_d, \omega),\ k_d = \tilde{k}_d = 2.1$.

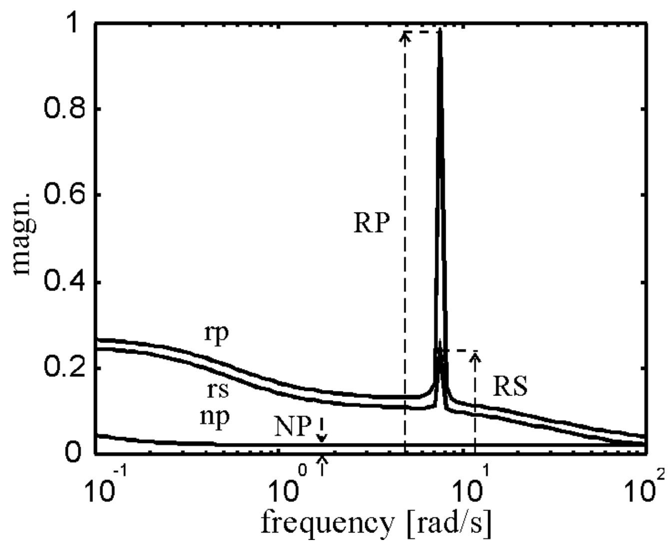

Figure 7. Unstructured model uncertainty, $k_d = 0.05$.
The frequency responses of: $np(\omega), rs(\omega)$ and $rp(\omega)$.

The lower RP measure is obviously the consequence of the structure of the uncertainty. Namely, a diagonal perturbation argument Δ_u does not alter the direction of the control signal u (see Fig.4) significantly. In other words, the nominal and the perturbed gain directions of the plant are similar; this has a positive impact on the closed–loop behavior of the inversion based controller.

For $\hat{K} = \hat{K}_2$ the optimum parameters are $\tilde{k}_{d1} = 69$ and $\tilde{k}_{d2} = 2$, and $RP(\tilde{k}_{d1}, \tilde{k}_{d2}) = 0.99$ and this controller yields an robust closed–loop performance. The robust stability RS and robust performance RP measure as a function of two adjustable parameter k_{d1} and k_{d2} are shown in Fig.11a, 11b and 11c.

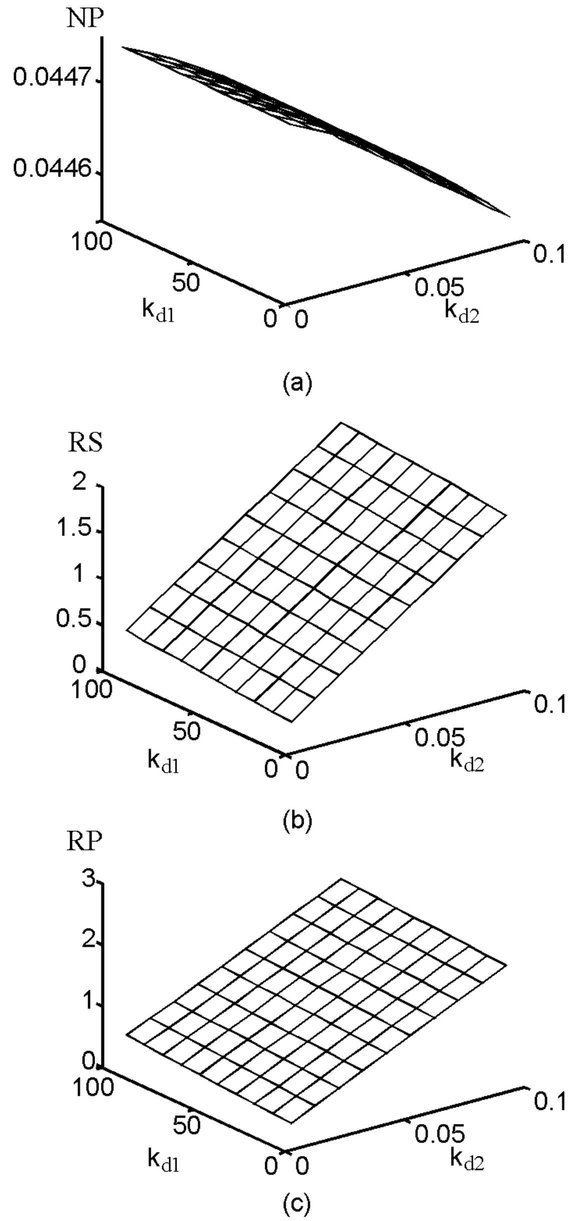

Figure 8. *Unstructured case: NP, RS and RP measure are shown as a function of the two adjustable parameters* k_{d1} *and* k_{d2}*: (a)* $NP(k_{d1}, k_{d2})$*, (b)* $RS(k_{d1}, k_{d2})$ *and (c)* $RP(k_{d1}, k_{d2})$*.*

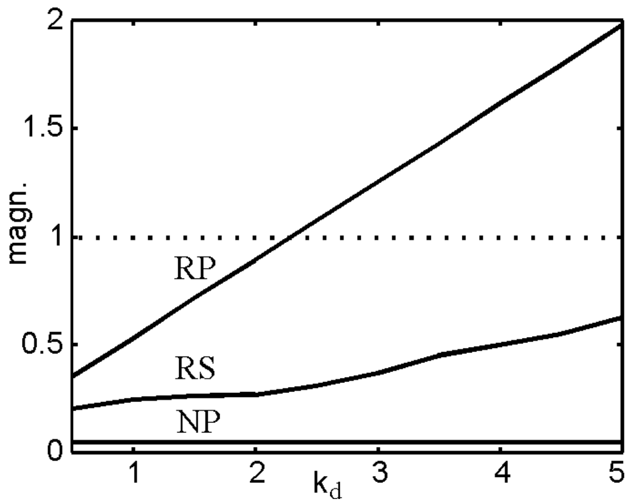

Figure 9. *Decentralized controller design for structured modeluncertainty. NP,RS and RP measure are shown as a function of the adjustable parameter k_d: $NP(k_d), RS(k_d)$ and $RP(k_d)$.*

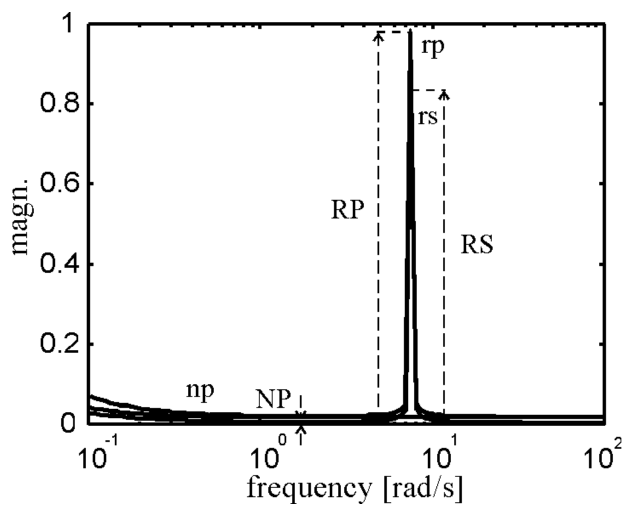

Figure 10. *Structured model uncertainty, $k_d = 2.0$. The frequency responses of: $np(\omega), rs(\omega)$ and $rp(\omega)$.*

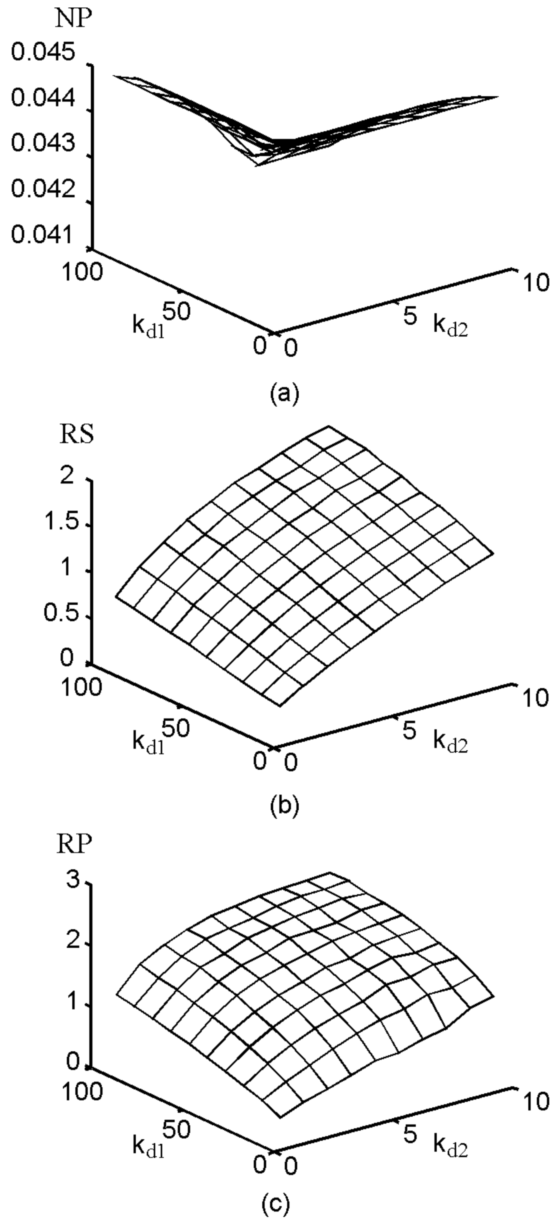

Figure 11. Structured case: NP, RS and RP measure are shown as a function of the two adjustable parameters k_{d1} and k_{d2}
(a) $NP(k_{d1}, k_{d2})$, (b) $RS(k_{d1}, k_{d2})$ and (c) $RP(k_{d1}, k_{d2})$.

6. The transient analysis

To see how the system reacts to external disturbances or setpoint changes some closed–loop simulations have been performed. The input signals were chosen to correspond to the most critical directions ⇒ low gain directions. Fig. 12a contains the response to a set point change of the input t_m. As expected the best response is obtained with $\hat{K}_2$ designed for structured uncertainty and the worst with the $\hat{K}_1$ designed for unstructured uncertainty. From this figure it is evident that the controllers designed for structured uncertainty have a better response. Fig. 12b shows the same response as Fig.12a, but with a different load condition (perturbed plant): $(0.8P_n, 0.8Q_n)$.

The difference between the responses observed in Fig.12 is more expressive in Fig.13 (a) case ($P = \tilde{P}$) and (b) for the case of perturbed plant ($P \neq \tilde{P}$). Fig. 14-15 shows the other response of the nominal and perturbed system to a step change in reference voltage setpoint v_{ref} and step change in mechanical power t_m.

Obviously, the best step response was obtained with a controller:

$$K = \hat{K}_2 = \begin{bmatrix} \frac{k_{d1} d(s)}{n_{11}(s)} & 0 \\ 0 & \frac{k_{d2} d(s)}{n_{22}(s)} \end{bmatrix} \tag{44}$$

where

$$k_{d1} = 69, \qquad k_{d2} = 2 \tag{45}$$

$$n_{11}(s) = [1130s^4 + 92106s^3 + 2630267s^2 + 31506351s + 69399716] \tag{46}$$

$$n_{22}(s) = [2092s^4 + 88695s^3 + 182772s^2 + 5101174s + 3583611] \tag{47}$$

$$d(s) = [s^5 + 43s^4 + 785s^3 + 3568s^2 + 29040s + 19824] \tag{48}$$

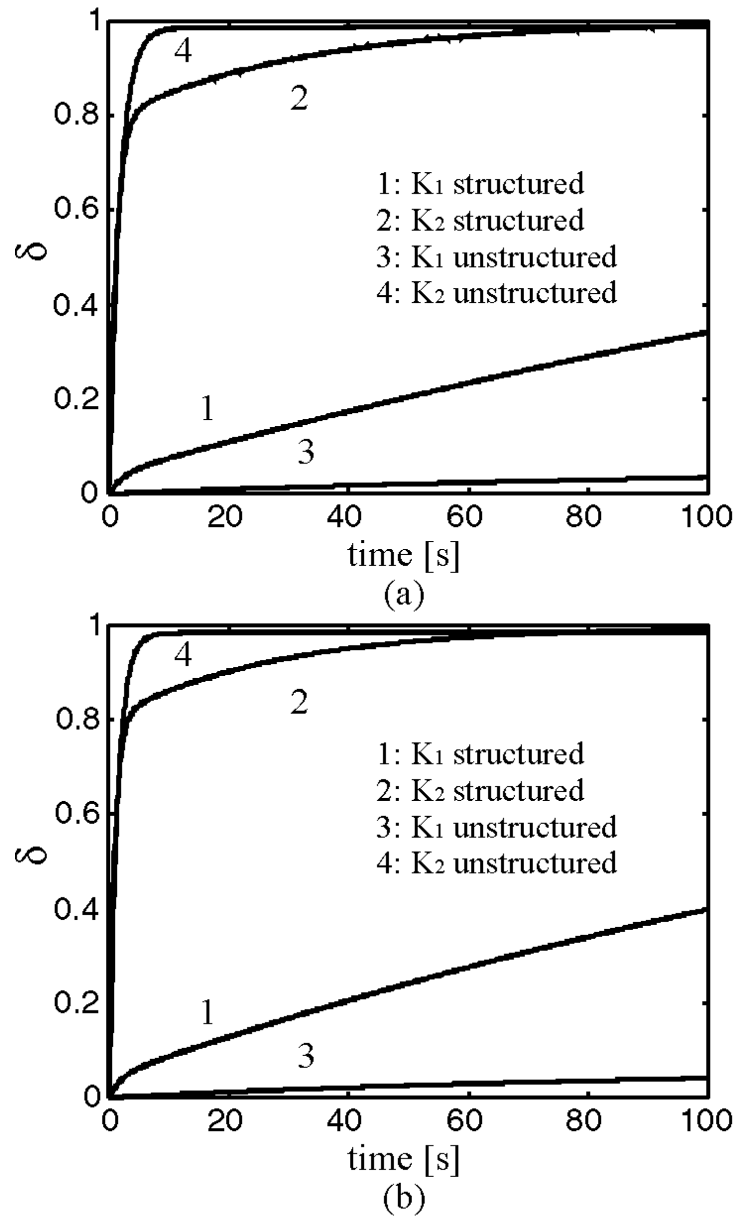

Figure 12. Response of the load angle to a step setpoint change acting on t_m (mechanical power), (a) case ($\tilde{P} = P$), (b) case ($\tilde{P} \neq P$).

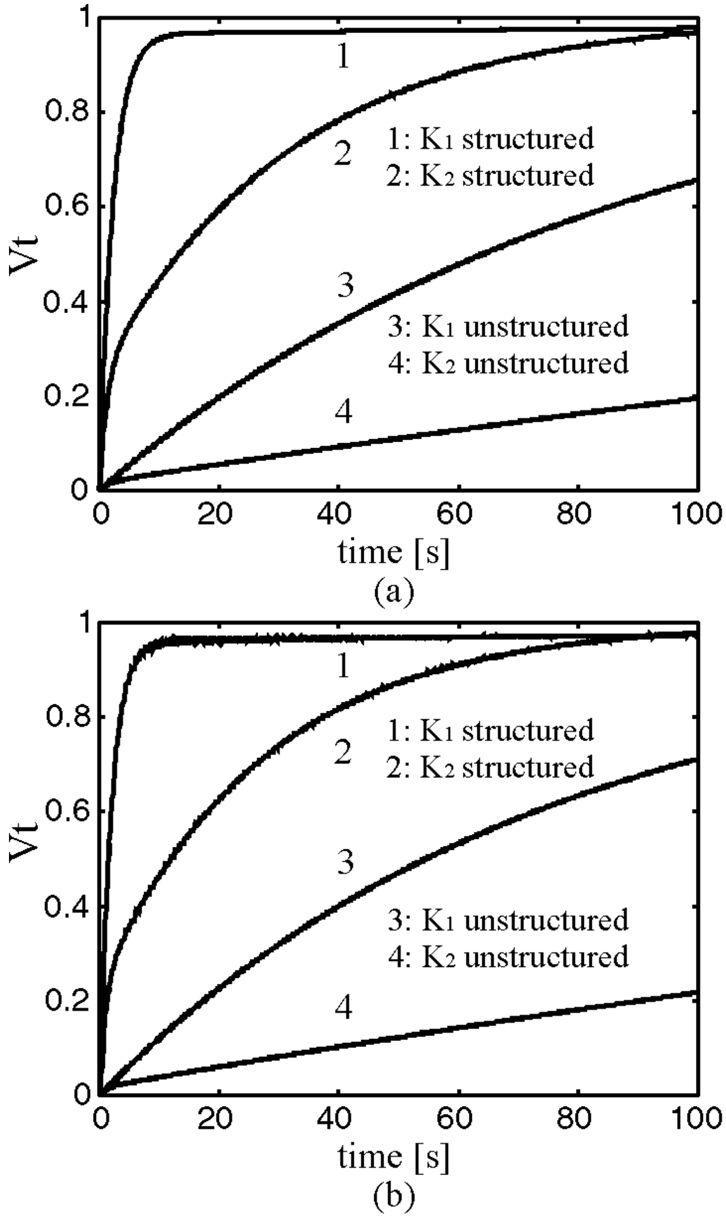

Figure 13. Response of the terminal voltage to a step setpoint change acting on v_{ref} (exciter references), (a) case ($\tilde{P} = P$), (b) case ($\tilde{P} \neq P$).

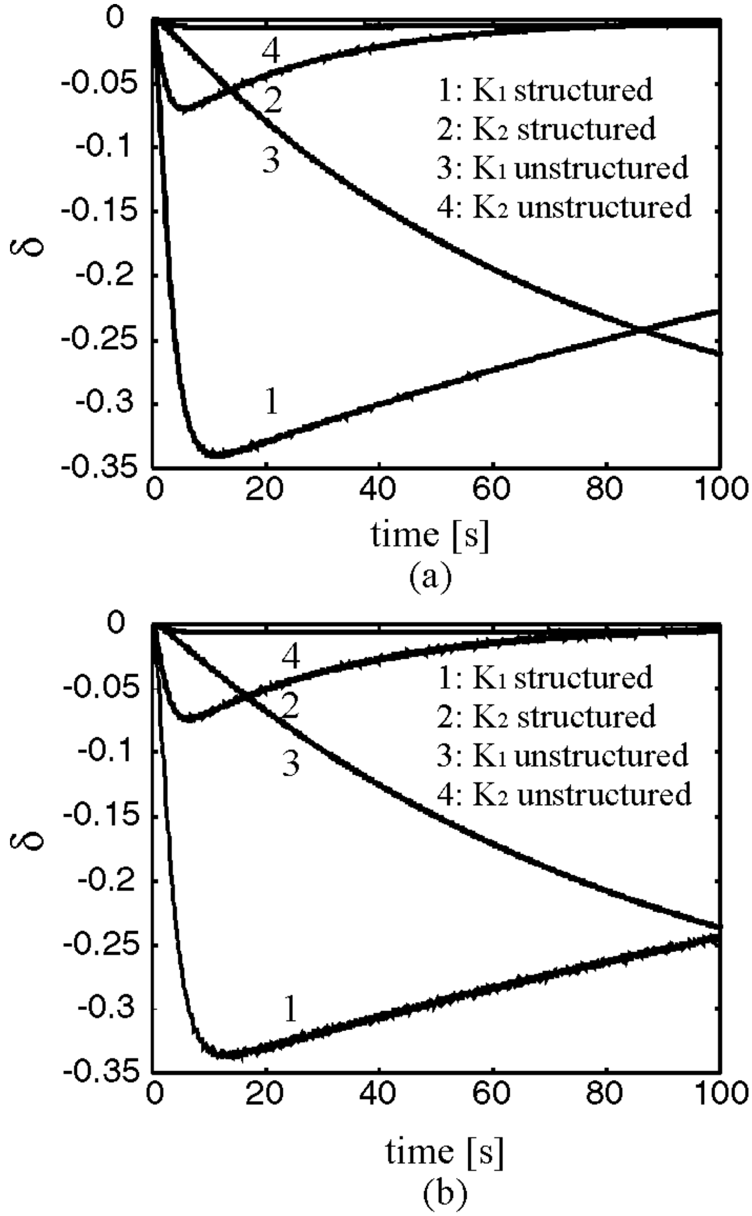

Figure 14. Response of the load angle to a step setpoint change acting on v_{ref} (exciter references), (a) case ($\tilde{P} = P$), (b) case ($\tilde{P} \neq P$).

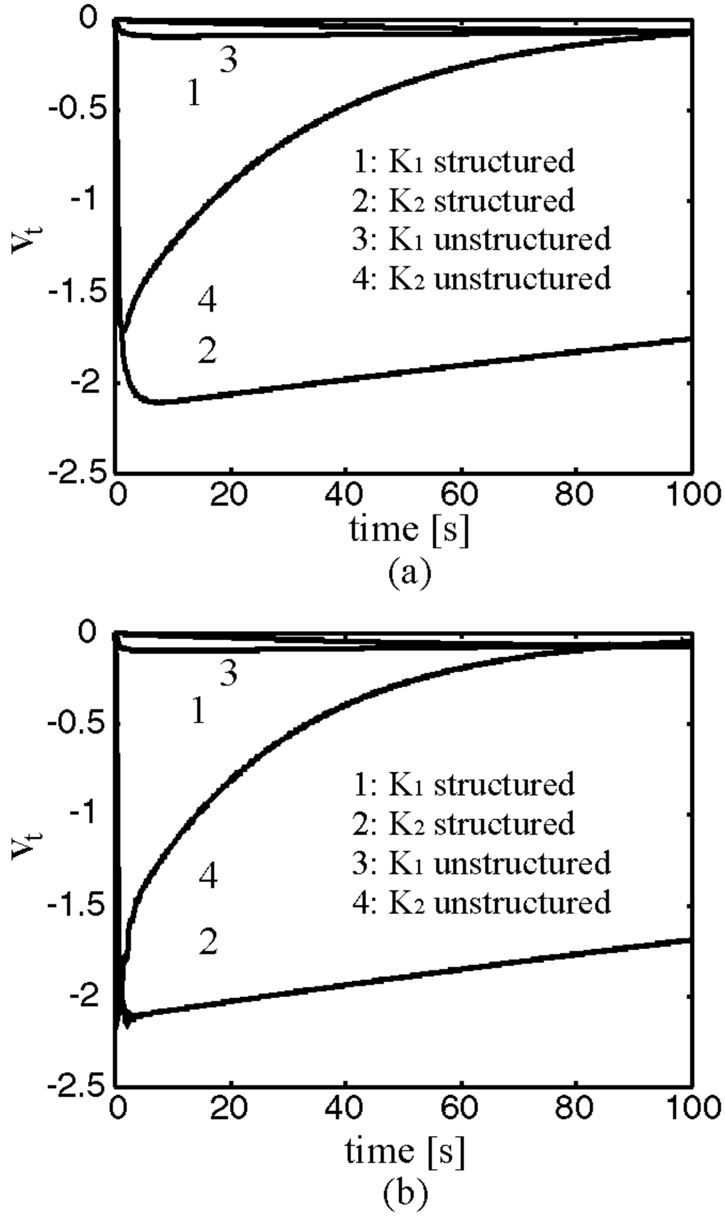

Figure 15. Response of the terminal voltage to a step setpoint change acting on t_m (mechanical power), (a) case ($\tilde{P} = P$), (b) case ($\tilde{P} \neq P$).

7. Conclusions

A general conclusion is that a good analysis of the structure of uncertainty is crucial for the design of decentralized control. If this part of the job is done properly, then can be, with relatively simple and easy–to–understand weighting functions (W_p, l_u), assign the closed–loop parameters and design of the controllers. In other words, the better our knowledge of the plant is, the better the control action will be. This example clearly illustrates that the controllers designed for structured uncertainty have a better RP measure and a better transient behavior than their counterparts designed for unstructured uncertainty.

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