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Preventing control constraint violations by use of energy balances for a class of coupled systems: applied to a power plant

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Abstract— In this paper a scheme is presented for preventing violations of control signal constraints in a class of coupled systems. The scheme is an add-on solution to the existing control system; it works like a fault tolerant scheme, by accommodating the problem then occurring. The proposed scheme recomputes the reference values to the system such that control signal constraint violations are avoided. The new reference values are found using an energy balance of the system. The scheme is intended to handle rarely occurring constraint violations, so the only concern is that the system should be stable and not to optimize performance during all conditions. The scheme is applied to an example with a coal mill pulverizing coal for a power plant.

I. INTRODUCTION

Performance of closed loop controlled systems can be defined in a number of ways, all dealing with some measure of how well the plant is doing. One way is to measure how well some relevant outputs follow specified references and suppress disturbances. The variations in the performance from these can be due to a number of different causes. E.g. faults, disturbances, badly tuned controllers, variations in the plant conditions and constraints on the control signals. In the remainder of this paper the focus is turned to the last kind of causes for the performance drop.

In this paper the attention is put to a class of MIMO plants which can be modeled by two coupled first order systems. Two decoupled SISO controllers control the plant. The controlled plant is performing as requested except in a few rare situations, where one of the control signals meets a constraint on the control variables in order to follow the reference. In order to accommodate this problem control signals are forced inside the constraints by recomputing the system references.

This problem is often dealt with by using reference governor schemes. [1] deals with a method for finding admissible reference signals given certain system constraints, and the methods are usable for non-linear as well as linear systems. This suggested method might be conservative since they do not take the actual system into account. In [2] an Lyapunov inspired method is proposed. This method is partly based on computational demanding optimizations. In [3] a method for designing reference governors is based on model predictive control. Knowledge of the control system

in question can of course be useful in the design of the reference governor, and consequently specific solutions is suggested in [4]. [5] suggests a method for designing a reference governor for linear SISO system by a constructive reference governor design. These reference governors do in addition optimize the performance of the plant while constraints are met, like model predictive control, see e.g. [6].

In the previous mentioned schemes performance optimization is an objective. However, implementation of these on an existing plant would require a redesign of the system, especially if model predictive control is considered. Industry is not always very interested in redesigning the control system, for handling some rarely occurring problems. A simple solution, which adds accommodation of the given problem, is more desired. These might better be handled using a fault tolerant scheme, where these events are considered as faults, which should be handled then occurring. So the idea should be to detect a possible violation of the constraints and then adjust the reference to the control system such that the constraint is not violated.

In [7] a method is suggested for handling a problem with control signal violation for a coal mill, due to a combination of high loads and moisture contents of the coal. These constraint violations occur rarely, meaning that is not necessary to redesign the existing control system, which perform well under normal conditions. Consequently it is also not of interest to optimize the performance during these constraint violations. Instead an add-on solution is proposed. The scheme uses an energy balance of controller energy and the needed energy to suppress the disturbances and follow the references. This method is in this paper generalized to a class of coupled first order systems, and stability and performance of the method is proven. In addition the method is tested on an experimental data set from a coal mill, where a control signal constraint is met.

In Section II the performance and faults in consideration are described. This is followed by a system description in Section III. After these definitions the constraint preventing scheme is presented in Section IV. In Section V the stability and performance of this scheme is considered. In Section VI this preventive scheme is tested on an example of a coal mill. In the end a conclusion is given in Section VII.

II. DEFINITION ON PERFORMANCE AND FAULT

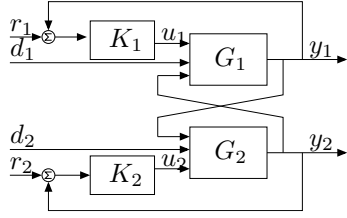In this paper performance is defined as how well the system follows specific reference signals as well as how

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Fig. 1. An illustration of the coupled SISO systems. G_1 and G_2 are the two SISO systems, K_1 and K_2 are the two controllers, y_1 and t_2 are the two system outputs, d_1 and d_2 are the two disturbances, r_1 and r_2 are the two references, and u_1 and u_2 are the two control signals.
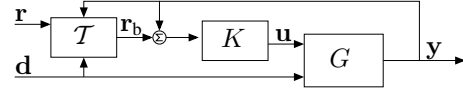

Fig. 2. An illustration of the accommodated system. G is the systems, K is the controller, $\mathcal{T}$ is the constraint handler, $\mathbf{y}$ is the vector of the system outputs, $\mathbf{d}$ is the vector of the disturbances, $\mathbf{r}$ is a vector the references and $\mathbf{r}_b$ is the vector of the bounded references, and $\mathbf{u}$ is a vector of the control signals.

well its disturbances are suppressed. The variation from the requested performance can be due to a number of factors. It could be actuator, sensor and process faults, all for which traditional fault detection methods would detect the fault. It could be due to badly tuned controllers, or it could be due to limitation in the control power, i.e. constraints on the control variables. These faults can be avoided if the constraints on the control variables are transformed to a set of constraints on the reference variables.

III. SYSTEM AND PROBLEM DESCRIPTION

The system in mind in this paper is a MIMO system represented by two coupled first order SISO systems, G_1 and G_2, as illustrated in Fig. 1. Let us assume that the two controllers K_1 and K_2 stabilizes G_1 and G_2 respectively, and achieves the required performance in terms of disturbance suppression and reference following.

The systems G_1 and G_2 can be linear or non-linear, but in cases where they are non-linear they should be of the following structure given in (1-4).

$$x_1[n+1] = G_{1,u}\left(x_1[n], u_1[n], y_2[n]\right)$$
$$+ G_{1,d}\left(x_1[n], d_1[n], y_2[n]\right), \quad (1)$$
$$y_1[n] = Cx_1[n], \quad (2)$$
$$x_2[n+1] = G_{2,u}\left(x_2[n], u_2[n], y_1[n]\right)$$
$$+ G_{2,d}\left(x_2[n], d_2[n], y_1[n]\right), \quad (3)$$
$$y_2[n] = Cx_2[n], \quad (4)$$

where

$$u_1[n+1] = \mathbf{K}_1\left(u_1[n], r_1[n], y_1[n]\right), \quad (5)$$
$$u_2[n+1] = \mathbf{K}_2\left(u_2[n], r_2[n], y_2[n]\right). \quad (6)$$

However, this ideal situation is not always the case. Constraints on the control signals are subsequently introduced. The static constraints are formulated as

$$\underline{u}_1 \leq u_1[n] \leq \overline{u}_1, \quad (7)$$
$$\underline{u}_2 \leq u_2[n] \leq \overline{u}_2, \quad (8)$$

where $\underline{u}_1$ and $\underline{u}_2$ are the two minimal values of the control signals, and $\overline{u}_1$ and $\overline{u}_2$ are the two maximal values of

the control signals. The "dynamic" constraints are given as slew rates on the control signals.

$$\underline{\Delta u}_1 \leq u_1[n] - u_1[n-1] \leq \overline{\Delta u}_1, \quad (9)$$
$$\underline{\Delta u}_2 \leq u_2[n] - u_2[n-1] \leq \overline{\Delta u}_2, \quad (10)$$

where $\underline{\Delta u}_1$ and $\underline{\Delta u}_2$ are the two lower slew rates of the control signal, and $\overline{\Delta u}_1$ and $\overline{\Delta u}_2$ are the two upper slew rate of the control signals.

IV. THE CONSTRAINT HANDLING SCHEME

In broader terms one can say that the controller needs to deliver energy in order to overcome the references and disturbances. I.e. the maximal energy in the control actions shall be at least as large as the energy required to follow the reference and to suppress the disturbances. A constraint on the possible control signal value consequently puts a constraint on the energy available to suppress and follow the disturbance and reference respectively. The basic idea is to introduce an add-on block, which limits the reference variables according to the constraints on the control variables. This system idea is illustrated in Fig. 2. In which $\mathcal{T}(d, n)$ represents the constraint handler, which limits the references so the constraints are not violated. The scheme computes the feasible system output set from which the references can be determined.

In the following the basics of this constraint handler is described. It consists of two parts: a static and a dynamic. From the system description in (1-4) and assuming that nominal controllers perform as required, it can be seen that the reference can be followed and the disturbance suppressed in the static case by (11-12), since enough energy is available for control actions for suppressing the disturbances and follow the reference signals.

$$G_{1,u}\left(x_1, u_1, y_2\right) + G_{1,d}\left(x_1, d_1, y_2\right) = 0, \quad (11)$$
$$G_{2,u}\left(x_2, u_2, y_1\right) + G_{2,d}\left(x_2, d_2, y_1\right) = 0. \quad (12)$$

The introduction of the constraints on the control signal implies that for the upper bound on the control signal. Meaning that the available controller energy is larger than the required energy for suppressing disturbances and following references.

$$G_{1,u}\left(x_1, \overline{u}_1, y_2\right) \geq G_{1,d}\left(x_1, d_1, y_2\right), \quad (13)$$
$$G_{2,u}\left(x_2, \overline{u}_2, y_1\right) \geq G_{2,d}\left(x_2, d_2, y_1\right). \quad (14)$$

and for the lower bound on the control signal the inequalities changes their directions, see (15-16).

$$\left|G_{1,\text{u}}\left(x_1,\underline{u}_1,y_2\right)\right| \leq \left|G_{1,\text{d}}\left(x_1,d_1,y_2\right)\right|, \qquad (15)$$

$$\left|G_{2,\text{u}}\left(x_2,\underline{u}_2,y_1\right)\right| \leq \left|G_{2,\text{d}}\left(x_2,d_2,y_1\right)\right|. \qquad (16)$$

If a constraint violation is needed in order to suppress the disturbance and reference, it will result in some of (13-16) being false. These inequalities can be guaranteed true by limiting the feasible system outputs and thereby the feasible reference values, since the reference values are the only variables which one can manipulate. However, this constraint handling strategy is only possible if the disturbances are observable.

A set of inequalities similar to (13-16) can be stated for the dynamic constraints. These dynamic inequalities are required to be tested for each sample n.

$$
\begin{aligned}
h_1: &\left|G_{1,\text{u}}\left(x_1[n+1],u_1[n]+\overline{\Delta u_1},y_2[n+1]\right)\right| \qquad (17)\\
&- \left|G_{1,\text{u}}\left(x_1[n],u_1[n],y_2[n]\right)\right|\\
&\geq \left|G_{1,\text{d}}\left(x_1[n+1],d_1,y_2[n+1]\right)\right|\\
&- \left|G_{1,\text{d}}\left(x_1[n],d_1,y_2[n]\right)\right|,\\
h_2: &\left|G_{2,\text{u}}\left(x_2[n+1],u_2[n]+\overline{\Delta u_2},y_1[n+1]\right)\right| \qquad (18)\\
&- \left|G_{2,\text{u}}\left(x_2[n],u_2[n],y_1[n]\right)\right|\\
&\geq \left|G_{2,\text{d}}\left(x_2[n+1],d_2,y_1[n+1]\right)\right|\\
&- \left|G_{2,\text{d}}\left(x_2[n],d_2,y_1[n]\right)\right|,
\end{aligned}
$$

and similar for the lower bound on the control signal.

$$
\begin{aligned}
h_3: &\left|G_{1,\text{u}}\left(x_1[n+1],u_1[n]+\underline{\Delta u_1},y_2[n+1]\right)\right| \qquad (19)\\
&- \left|G_{1,\text{u}}\left(x_1[n],u_1[n],y_2[n]\right)\right|\\
&\leq \left|G_{1,\text{d}}\left(x_1[n+1],d_1,y_2[n+1]\right)\right|\\
&- \left|G_{1,\text{d}}\left(x_1[n],d_1,y_2[n]\right)\right|,\\
h_4: &\left|G_{2,\text{u}}\left(x_2[n+1],u_2[n]+\underline{\Delta u_2},y_1[n+1]\right)\right| \qquad (20)\\
&- \left|G_{2,\text{u}}\left(x_2[n],u_2[n],y_1[n]\right)\right|\\
&\leq \left|G_{2,\text{d}}\left(x_2[n+1],d_2,y_1[n+1]\right)\right|\\
&- \left|G_{2,\text{d}}\left(x_2[n],d_2,y_1[n]\right)\right|.
\end{aligned}
$$

These static and dynamic inequalities can be considered as energy relations. These can be viewed in such a way that given the disturbances etc, the static bounds on the references and reference changes can be determined based on (13-16) and the dynamic reference bounds can be determined by (17-20), simply by finding the maximal and minimal reference values and changes which do not violate these inequalities. An illustration of the maximal static and dynamical reference signals are compared with the required reference signal in Fig. 3. In this figure a limitation of the reference signal is required in order to avoid the violation of the reference signal constraint. These maximal reference signals and the minimal reference signals can be determined in two steps, and thereby $\mathcal{T}(d,n)$.

- Determine the maximal and minimal static reference values.
- Determine the maximal and minimal dynamic reference signals.

The static value is required initially to be computed, since it would be meaningless to compute the reference changes
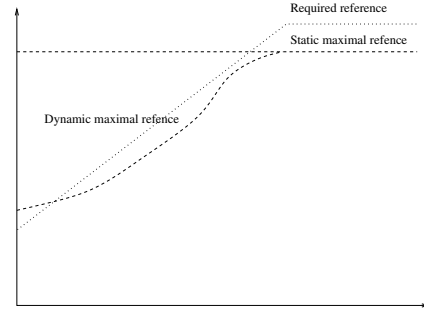

Fig. 3. An illustration of a situation with non-feasible required/desired reference signal, since it clearly above maximal feasible references.

for reference values, which is not achievable anyway. Subsequently the dynamical maximal and minimal values are computed for each sample following the reference "path" from the initial values to the required or maximal/minimal values are met. These two method parts are subsequently described.

A. Computing the maximal and minimal static references

Assuming that a maximal value of the disturbances are known $\overline{d}_1$ and $\overline{d}_2$. (13-14) can be turned into a static version.

$$\overline{G}_{1,\text{u}}\left(\overline{u}_1,\overline{y}_2\right) \geq \overline{G}_{1,\text{d}}\left(d_1,\overline{y}_2\right), \qquad (21)$$

$$\overline{G}_{2,\text{u}}\left(\overline{u}_2,\overline{y}_1\right) \geq \overline{G}_{2,\text{d}}\left(d_2,\overline{y}_1\right). \qquad (22)$$

Next find the static values of the minimal reference values by:

$$\underline{G}_{1,\text{u}}\left(\underline{u}_1,\underline{y}_2\right) \geq \underline{G}_{1,\text{d}}\left(d_1,\underline{y}_2\right), \qquad (23)$$

$$\underline{G}_{2,\text{u}}\left(\underline{u}_2,\underline{y}_1\right) \geq \underline{G}_{2,\text{d}}\left(d_2,\underline{y}_1\right). \qquad (24)$$

The task is subsequently to find these $\overline{y}_1$, $\overline{y}_2$, $\underline{y}_1$, $\underline{y}_2$ which are the maximal and minimal values in the sets of y_1 and y_2 fulfilling (21 and 24). The method for the computation of these system output values depends on the model, in some cases the values can be found analytically and alternatively in other cases an iterative method is required. These computed bounds define the feasible output set, from which the feasible reference set can be determined.

B. Computing the minimal and maximal dynamical reference signals

When the static constraint on the reference signals are computed, the next step is to include the system dynamics in the feasible output set computation during varying references. In this paper a reference signal is assumed to change from one value to another value following a predefined path. This path is predefined by other system requirements. Notice again that the feasible system output set is used to compute the minimal and maximal reference signals.

The task is to transform the constraint on the control signals for each sample to a constraint on the references signals for each sample. As long as the requested reference is feasible (not violating the constraints) the references are

not modified. However, if the requested reference values violate the transferred constraints, then the reference values are limited by the constraint. Consequently, a limited reference change will increase the number of samples it takes for the system to reach the required final reference value in side the constraints.

In order to make this method description more specific, it is assumed that the references increase with equal step size from sample to sample. This means that the two referencee signals during the reference change is defined as the two signal series in (25 and 26).

$$\mathbf{r}_1 \in \{r_{1,A}, r_{1,A} + \alpha_1, r_{1,A} + 2 \cdot \alpha_1, \cdots, r_{1,B}\}, \quad (25)$$
$$\mathbf{r}_2 \in \{r_{2,A}, r_{2,A} + \alpha_2, r_{2,A} + 2 \cdot \alpha_2, \cdots, r_{2,B}\}. \quad (26)$$

The step sizes α_1 and α_2 are subsequently scaled by k_1 and k_2 in order to get feasible references.

$$\mathbf{r}_1 \in \{r_{1,A}, r_{1,A} + k_1 \cdot \alpha_1, r_{1,A} + 2 \cdot k_1 \cdot \alpha_1, \cdots, r_{1,B}\}, \quad (27)$$
$$\mathbf{r}_2 \in \{r_{2,A}, r_{2,A} + k_2 \cdot \alpha_2, r_{2,A} + 2 \cdot k_2 \cdot \alpha_2, \cdots, r_{2,B}\}. \quad (28)$$

In the subsequent computations these references replace the system output values, since the references are determined based on the possible output set.

Feasible and unconstrained violating reference signals can be achieved by introducing (25 and 28) into (13 and 16), and subsequently optimize (29 and 30) for positive αs and (31 and 32) for negative αs. A finite horizon method is used to compute these, as in [3] and [8].

$$k_{1,max} = \max_{k_1} (h_1), \quad (29)$$
$$k_{2,max} = \max_{k_2} (h_2), \quad (30)$$
$$k_{1,min} = \min_{k_1} (h_3), \quad (31)$$
$$k_{2,min} = \min_{k_2} (h_4). \quad (32)$$

V. STABILITY OF THE REFERENCE LIMITING SCHEME

In the system description see (Section III) it was assumed that the closed loop system consisting of the controllers K_1 and K_2, and the plants G_1 and G_2 is stable and that the disturbances are suppressed and the references are followed as required in the case of no constraint violations.

Now define the two admissible sets of control signals.

$$u_1[n] \in \mathsf{u}_1 \text{ if } \overline{u}_1 \geq u_1[n] \geq \underline{u}_1 \quad (33)$$
$$\wedge \overline{\Delta u_1} \geq u_1[n] - u_1[n-1] \geq \underline{\Delta u}_1,$$
$$u_2[n] \in \mathsf{u}_2 \text{ if } \overline{u}_2 \geq u_2[n] \geq \underline{u}_2 \quad (34)$$
$$\wedge \overline{\Delta u_2} \geq u_2[n] - u_2[n-1] \geq \underline{\Delta u}_2.$$

The constraint handling algorithm uses the mapping $\mathcal{T}(d,n)$, to find the maximal and minimal output values from which the bounded references can be determined.

$$\mathcal{T}(\mathbf{u}, \mathbf{d}) \to \mathbf{y}. \quad (35)$$

The mapping between these input and output sets is illustrated by Fig. 4, in which the unconstrained input and output sets are represented by $\mathbf{U}$ and $\mathbf{Y}$. The relation
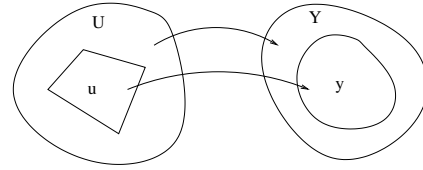

Fig. 4. Illustration of the input and output sets of the mapping represented by the constrained system, this mapping is related to a given $\mathbf{d}$. $\mathbf{U}$ and $\mathbf{Y}$ represents the unconstrained in and outputs. The mapping is given for each sample n.

between the feasible input set $\mathbf{u}$ to the feasible output given by the mapping $\mathcal{T}(d,n)$ is depending on both $\mathbf{d}$ and n. This mapping can consequently be used to determine the bounded reference values. This means that the mapping is required to be evaluated at each sample n.

A. Stability of the constraint handling scheme

The attention is now turned to the stability of scheme accommodating the system constraints. In Lemma 1 a necessary requirement for stability of the scheme is presented. This Lemma states that as long as the scheme keeps the control signals within the constraints then the system is stable.

Lemma 1 *The accommodated closed loop system illustrated in Fig. 2, is stable if the references $r_1[n]$ and $r_2[n]$ are contained in the feasible output sets $y_1[n]$ and $y_2[n]$. I.e.*

$$r_1[n] \in \mathbf{y}_1,$$
$$r_2[n] \in \mathbf{y}_2.$$

Proof of Lemma 1 *It is clear that the accommodated system illustrated in Fig. 2 is stable if $r_1[n] \in \mathbf{y}_1$ and $r_2[n] \in \mathbf{y}_2$, since these $r_1[n]$ and $r_2[n]$ corresponds to $u_1[n]$ and $u_2[n]$, in which the system is stable. If $r_1[n] \in Y_1 \setminus y_1$ and $r_2[n] \in Y_2 \setminus y_2$ the corresponding control signals will be contained in $U_1 \setminus u_1$ and $U_2 \setminus u_2$, for which stability cannot be guaranteed.*

This means that this scheme, for avoiding the constraint violation, is guaranteed stable if constraint violations are avoided. However, the stability criteria is only necessary and not sufficient meaning that other criteria is needed to be determined if constraint violations leads to an unstable close loop system.

B. Performance of the constraint handling scheme

In regard of the performance of the proposed constraint handling scheme a result similar to Lemma 1 is obtained in Lemma 2.

Lemma 2 *The accommodated closed loop system illustrated in Fig. 2, has a performance as required if the references $r_1[n]$ and $r_2[n]$ are contained in the feasible output sets $y_1[n]$ and $y_2[n]$. I.e.*

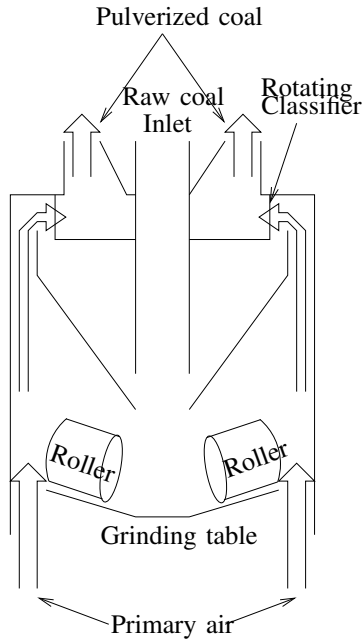$$r_1[n] \in \mathbf{y}_1,$$
$$r_2[n] \in \mathbf{y}_2.$$

Fig. 5. An illustration of the coal mill. The raw coal is fed into the mill through the inlet pipe, the coal is subsequently pulverized by the rollers on the grinding table. The primary dries and lift the coal particles through the classifiers and into the furnace.

Proof of Lemma 2 *It is clear that the accommodated system illustrated in Fig. 2 performs as required if $r_1[n] \in \mathbf{y}_1$ and $r_2[n] \in \mathbf{y}_2$, since these $r_1[n]$ and $r_2[n]$ corresponds to $u_1[n]$ and $u_2[n]$, in which the system performs as required. If $r_1[n] \in Y_1 \setminus y_1$ and $r_2[n] \in Y_2 \setminus y_2$ the corresponding control signals will be contained in $U_1 \setminus u_1$ and $U_2 \setminus u_2$, for which performance cannot be guaranteed.*

VI. AN EXAMPLE: LIMITING COAL FLOW THROUGH COAL MILL

In [7] a simple version of this proposed scheme was applied to an example of a coal mill used to pulverize the coal before it is blown into the furnace. In the coal mill the coal is pulverized into very small particles by some heavy rollers, in addition the primary air is used to dry the coal particles. If the pulverized particles are too large or not dry enough these particles are too heavy to be lifted into the furnace. Hot flue gas from the furnace heats the primary air. Under certain combinations of operational conditions, e.g. high plant load and high content of moisture in the coal, the primary air cannot be heated enough to evaporate the moisture from the coal. The coal mill is illustrated in Fig. 5. In the computational example a discrete time version of the continues time model derived in [7] is used. The model can be seen in (36-38).

$$
\begin{aligned}
m_{\mathrm{m}} C_{\mathrm{m}} \dot{T}(t) =\ & \dot{m}_{\mathrm{pa}}(t) C_{\mathrm{air}} \left(T_{\mathrm{PA}}(t) - T(t) \right) \\
& + \left(\dot{m}_{\mathrm{c,in}}(t) + \dot{m}_{\mathrm{c,a}}(t) \right) \cdot C_{\mathrm{c}} \cdot \left(T_{\mathrm{s}} - T(t) \right) \\
& + \gamma(t) \cdot \left(\dot{m}_{\mathrm{c,in}}(t) + \dot{m}_{\mathrm{c,a}}(t) \right) \cdot C_{\mathrm{w}} \cdot T_{\mathrm{s}} \\
& - \gamma(t) \cdot \left(\dot{m}_{\mathrm{c,in}}(t) + \dot{m}_{\mathrm{c,a}}(t) \right) \cdot H_{\mathrm{st}} \cdot T(t),
\end{aligned}
\tag{36}
$$

where: m_{m} is the mass of the mill, C_{m} is the specific heat of the mill, $T(t)$ is the mill temperature at the classifier, $\dot{m}_{\mathrm{pa}}(t)$ is the primary air mass flow in and out of the mill, C_{air} is the specific heat of air, $T_{\mathrm{PA}}(t)$ is the temperature
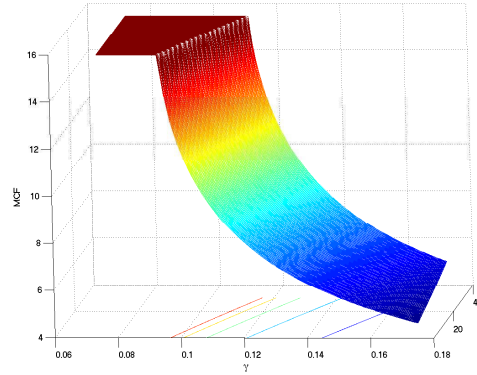

Fig. 6. Plot of the maximal static coal flow reference given by $\mathcal{T}$ depending on γ and T_{s}.

of the inlet primary air, $\dot{m}_{\mathrm{c,in}}(t)$ is the coal mass flow into the mill, $\dot{m}_{\mathrm{c,a}}(t)$ is the coal mass flow accumulated in the mill, C_{c} is the specific heat of the coal, T_{s} is the outside temperature, $\gamma(t)$ is the ratio of moisture in the coal, C_{w} is the specific heat of the moisture, H_{st} is a parameter combining the latent heat of the steam and specific heat of the water.

The accumulations of the coal dust, is assumed to depend on the temperature drop of the coal dust. $\dot{m}_{\mathrm{c,a}}(t)$ is modeled as the product of the input coal flow times the difference between $T(t)$ and $100°C$ times a constant. This value is subsequently low-pass filtered with a first order filter, see (37).

$$
\ddot{m}_{\mathrm{c,a}}(t) = \tau \cdot \dot{m}_{\mathrm{c,a}}(t) + \alpha \cdot \dot{m}_{\mathrm{c,in}}(t) \cdot \left(T(t) - 100 \right), \tag{37}
$$

where $\dot{m}_{\mathrm{c,in}}(t)$ is the input coal flow, τ and α are two model parameters. The coal flow out of the mill, $\dot{m}_{\mathrm{c,out}}(t)$, is modeled as (38).

$$
\dot{m}_{\mathrm{c,out}}(t) = \dot{m}_{\mathrm{c,in}}(t) - \dot{m}_{\mathrm{c,a}}(t) \tag{38}
$$

References to coal flow and primary air flow are given by the power plant master controller. The temperature of the primary air is used to control the temperature in the coal mill. The temperature controller is often required to keep temperature constant at $100°C$ in order to evaporate the moisture content in the coal. A PID-like controller is used to control the temperature, which often also contains anti-windup, however, this anti-windup scheme has not been able to accommodate the specific problem.

A coal mill is a harsh environment to perform measurements in. This means that not all the variables are measurable. E.g. the actual coal flows in and out of the coal mill are not measurable, (the coal flow into the mill is controlled but not measured). However, the primary air flow and temperature can be measured, as well as the coal dust temperature. The moisture content can, however, be estimated, see [9]. For this problem only the maximal value is of interest. The static maximal value is computed and represented by Fig. 6. In order to see how the constraint violation prevention scheme performs, a couple of simulations are shown. These simulations illustrate a couple of
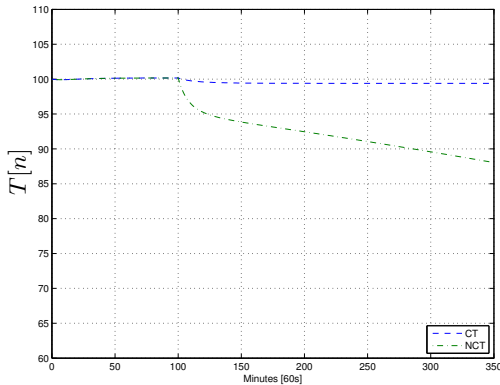
Fig. 7. A plot of the mill temperature $T[n]$ during a simulation with a coal moisture content at $\gamma = 0.12$, and a reference change occurring at sample $n = 100$. CT is the simulation of the corrected system. NCT is the simulation of the non-corrected system.
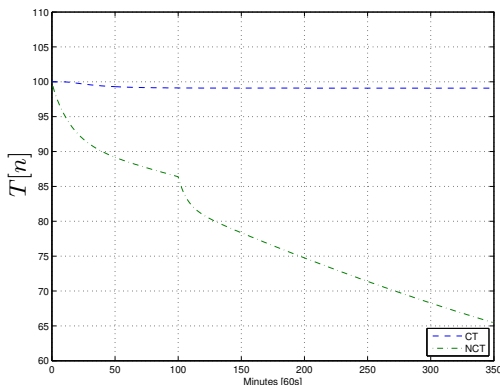

Fig. 8. A plot of the mill temperature $T[n]$ during a simulation with a coal moisture content at $\gamma = 0.15$, and a reference change occurring at sample $n = 100$. CT is the simulation of the corrected system. NCT is the simulation of the non-corrected system.

load changes from a high load to very high load, with moisture contents respectively on 12% and 15%. For both simulations the temperature is shown for non-corrected and corrected cases. Fig. 7 shows the temperature for the case with $\gamma = .12$ and Fig. 8 shows the case with $\gamma = .15$. For both examples the constraint violation preventing scheme proposed in the paper succeeds in keeping the temperature at the required one, where the non-corrected ones do not keep the temperature at the requested $100°C$. I.e. the simple prevention scheme keeps the system out of the control signal constraint violation, which would have caused a drop in the temperature.

VII. Conclusion

In this paper a method for preventing control signal constraint violations for a class of coupled first order systems is presented. The principle is to view these violations as rare occurring events, which shall be avoided. However, performance of the system during these is not an issue as long as the constraint violation is avoided, due to designed nominal controllers. Consequently a fault tolerant like scheme is proposed. In which the events are accommodated then occurring. The proposed scheme uses energy balance considerations to transfer the control signal constraint to the constraints on the reference signals. Stability and performance of this scheme are considered as well. The proposed scheme is applied to a coal mill where violation of constraint on the heating energy, results in an accumulation of coal in the mill, in cases of high coal moisture content in combination with a high plant load. The proposed scheme shows a potential for preventing this accumulation of coal in the mill.

VIII. Acknowledgment

IX. References

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