Preprints of the 19th World Congress
The International Federation of Automatic Control
Cape Town, South Africa. August 24-29, 2014

Improved Load Tracking Performance for Combined Cycle Gas Turbine Plants through Flatness Based Feedforward Control

L. Hanel*, F. Gutekunst*, G. Scheffknecht*

**Dept. Power Generation and Automatic Control, Institute of Combustion and Power Plant Technology (IFK), University of Stuttgart, Stuttgart, Germany (Tel: +49 711 68566208; e-mail: lutz.hanel@ifk.uni-stuttgart.de)*

Abstract: The increasing competition on the energy market along with the highly variable feed-in from renewable energy sources have a far-reaching impact on the operation of conventional power plants. In order to stay competitive, utility companies need to adopt an operation regime that is characterized by fast cycling. At the same time, the operation has to remain as efficient as possible. In combined cycle gas turbine (CCGT) plants, the total power output is the combination of gas turbine (GT) power output and steam turbine (ST) power output. These are coupled through the dynamic behavior of the heat recovery steam generator (HRSG). A model based feedforward control concept can be used to improve the performance during load changes. Thereby, the process dynamics of the HRSG and the turbines are taken into account in the feedforward control algorithm. Thus, GT and ST power output are coordinated in an optimal way which in turn improves the load tracking capabilities as compared to standard control concepts. This is demonstrated in this contribution by simulations studies.

Keywords: Combined cycle power plants, feedforward control, differential flatness, trajectory planning, 2-degrees-of-freedom control, dynamic model

1. INTRODUCTION

The ambitious goal of the European Union (EU) is to raise the share of renewable energy sources in the total energy consumption to 20 % by the year 2020. Increased power generation from renewable sources plays a decisive role in this context. The installed wind power capacity has already risen considerably throughout Europe within the last two decades. Especially in Germany, the Renewable Energy Law (EEG) helped also to boost photovoltaics (PV). The development of the installed wind and PV generation capacity over the past years in Germany is shown in Fig. 1.

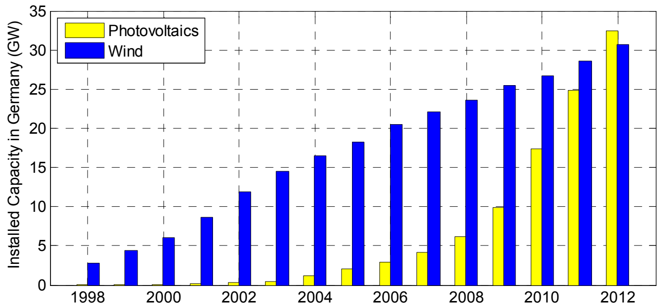

Fig. 1. Development of installed renewable generation capacity in Germany

Power generation needs to meet the total load (i.e. the power demand) at all times in order to guarantee a stable grid operation. This is accomplished by conventional power plants, as feed-in from renewable generation units is guaranteed by law in Germany (EEG). The power generation from conventional power plants, i.e. the difference between total load and renewable generation, is called "residual load". (Exchange power and biomass/water power is not considered for simplicity, see (von Roon and Huber, 2010) for a comprehensive explanation.) Fig. 2 shows the total load and the generation from renewable sources as well as the residual load of an exemplary week in Germany in 2012.

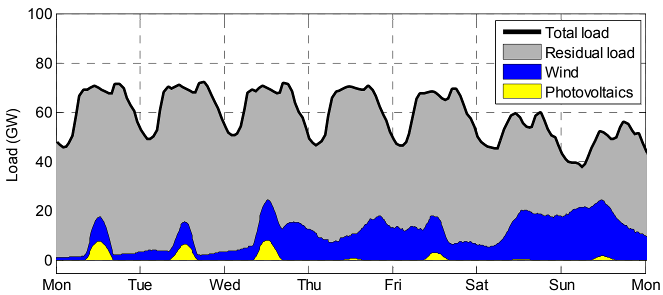

Fig. 2. Residual load and renewable generation in Germany (exemplary week in early 2012)

The total load is deterministic only to a certain extent. It shows daily peaks around noon and in the early evening and drops to lower levels during the night. On Saturdays and Sundays, the peak load is usually lower. The residual load is not only influenced by the variations of the total load but also by the intermittent generation from renewable energy sources. In this example, three sunny days with high feed-in from photovoltaics are followed by days that are characterized by high wind power generation. These two effects lead to less residual load and heavier fluctuations at the same time. As the installed renewable generation capacity is expected to rise further all over Europe (International Energy Agency, 2012), this fact is going to be amplified in the future. This will result in faster and more frequent load changes for conventional power plants.

Therefore, utility companies need to adopt an operation regime that is characterized by fast cycling instead of base load operation in order to stay competitive. Nonetheless it is of major importance to guarantee a high efficiency, at low loads as well as during load changes.

In the case of combined cycle gas turbines (CCGT) plants, the gas turbine (GT) power output and the steam turbine (ST) power output need to be coordinated in order to provide the electric power as desired (load tracking). In this paper, a model based feedforward (FF) control is proposed in order to improve the tracking performance during load changes.

Chapter 2 gives an introduction to combined cycle gas turbine plants. Furthermore, a CCGT plant model is developed and validated against measurement data.

Chapter 3 treats the plant control concept and shows how an additional feedforward path can be included.

In chapter 4, the feedforward control algorithm is presented along with the trajectory planning.

Finally, the performance of the feedforward control concept and its robustness against parameter uncertainties is demonstrated in chapter 5 by simulation results.

2. COMBINED CYCLE GAS TURBINE PLANTS

2.1 Configuration

CCGT plants are characterized by the combination of a gas turbine and a steam turbine (Fig. 3). Atmospheric air flows through the rotating compressor of the gas turbine to increase the pressure. In the combustion chamber, fuelled by natural gas, the temperature is increased. Afterwards, the hot gases are expanded in the gas turbine. The turbine shaft work is used to drive the compressor and a generator. The hot gas turbine exhaust powers a heat recovery steam generator (HRSG) which is equipped with a steam turbine. Such a combined cycle set-up results in improved overall efficiency (around 60 %) in contrast to single cycle gas turbines (approximately 40 %).

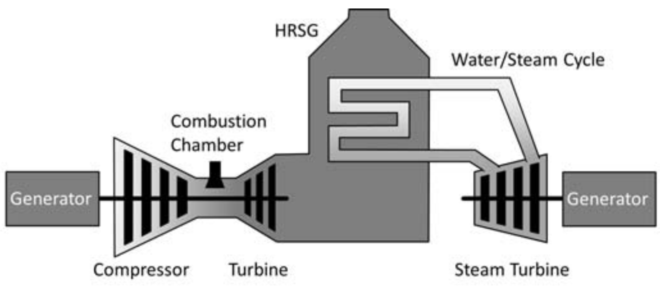

Fig. 3. CCGT plant set-up

CCGT plants exist in many different configurations. In this paper, the most basic combination of one gas turbine and one steam turbine is adopted. Each turbine is connected to a generator. For simplicity, a possible additional firing in the HRSG is not taken into account.

2.2 Plant Model

The CCGT plant model consists of two parts, the gas turbine model and the HRSG/ST model. A block diagram of the model is given in Fig. 4.

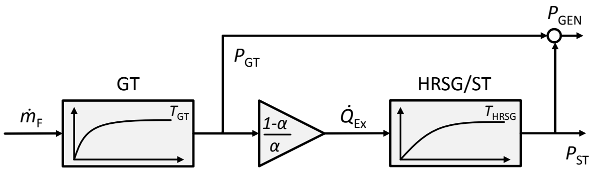

Fig. 4. CCGT plant model

The HRSG is modelled as a first order lag with the time constant T_{HRSG} as proposed in (Kunitomi et al., 2003). Since the ST dynamics are very fast compared to the long delay of the steam generation in the HRSG, the ST is not modelled separately but included in the HRSG dynamics. The GT has also fast dynamics compared to the HRSG, which is why another simple first order lag model is sufficient. The share of the GT power (P_{GT}) in the total net power (P_{GEN}) is described by the parameter α (≈0.6).

The HRSG is usually operated in sliding pressure mode, which means that the turbine inlet valves of the ST are fully open. This operation mode guarantees the highest possible efficiency as there are no throttle losses. It further implies that the ST power output only depends on the exhaust heat $\dot{Q}_{ex}$ of the GT which in turn is a function of the exhaust gas flow and temperature. The latter is controlled via the inlet guide vanes of the GT (Yee, Milanovic and Hughes, 2008) and is therefore assumed to be constant. This implies that the exhaust heat is only a function of the GT power output dependent exhaust gas flow where the factor $(1-\alpha)/\alpha$ is used to compensate the different power output of GT and ST. The GT power output is a function of the fuel mass flow $\dot{m}_F$ which represents the only input variable of the model.

The model is a single-input single-output (SISO) system of order n=2. It consists of two states, the GT power output (x_1) and the ST power output (x_2). The input variable is the fuel mass flow to the gas turbine; the output variable is the combined power output. Furthermore, the described model is a linear time-invariant (LTI) system. The state-space representation with the matrices A, B, and C is given by (1):

$$\dot{x} = \underbrace{\begin{bmatrix} \frac{-1}{T_{GT}} & 0 \\ \frac{1-\alpha}{\alpha T_{HRSG}} & \frac{-1}{T_{HRSG}} \end{bmatrix}}_{A} x + \underbrace{\begin{bmatrix} \frac{1}{T_{GT}} \\ 0 \end{bmatrix}}_{B} u, \qquad y = \underbrace{\begin{bmatrix} 1 & 1 \end{bmatrix}}_{C} x \tag{1}$$

2.3 Model Validation

Given the significant delay of the HRSG dynamics, the GT dynamics are of subordinate importance. Therefore, a time constant $T_{GT} = 5$ s is assumed in this paper.

The HRSG/ST model is validated against two hours of measurement data of a CCGT plant. Fig. 5 a) shows the GT power output which is proportional to the exhaust heat flow according to the assumptions in section 2.2. Furthermore, it shows the comparison of measurement data with simulation data of the ST power output (Fig. 5 b)). With a HRSG time constant $T_{HRSG} = 180$ s, the simulation results fit the measurement data very well which justifies the assumption of section 2.2.

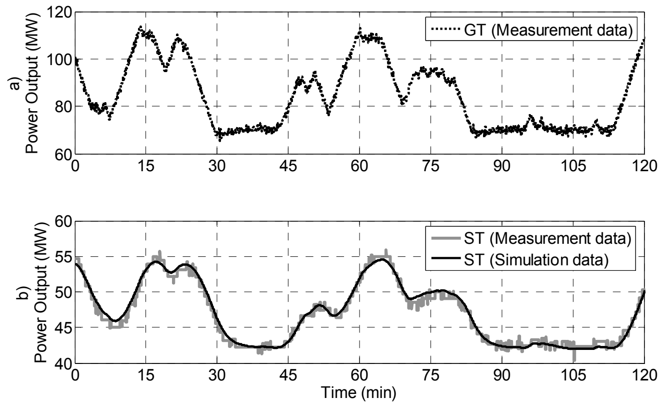

Fig. 5. Validation of HRSG model

3. CCGT PLANT CONTROL CONCEPT

3.1 State-of-the-Art CCGT Plant Control

State-of-the-art CCGT power output control consists of a simple feedback (FB) loop. An overview of the control system is given in Fig. 6. The instrumentation and control system (I&C) is indicated by the grey box.

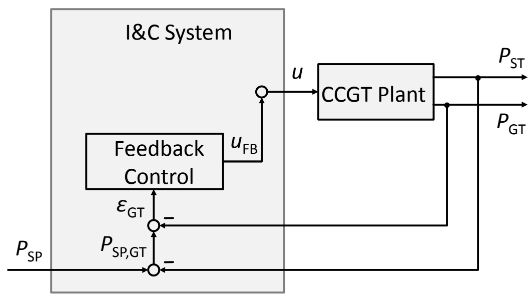

Fig. 6. Standard feedback control for CCGT plants

The HRSG/ST is operated in sliding pressure mode and the power output is controlled by the gas turbine. Therefore, the gas turbine power output set point $P_{SP,GT}$ is obtained from subtraction of the current ST power output from the total power output set point P_{SP}. $P_{SP,GT}$ is then used to control the GT power output in a PI control loop. In this set-up, the gas turbine set point is constantly adapted in consideration of the actual power output of the steam turbine.

This control system works well for disturbance rejection and set point control when load changes are sufficiently slow. Good control performance during load changes, however, requires a feedforward path in the control system as for example in the two-degrees of freedom (2-DOF) design.

3.2 Two-Degrees-of-Freedom Control

The 2-DOF control structure is widely used in industry applications (Zeitz, 2010 and Treuer et al., 2007) and is shown in Fig. 7 for the CGGT plant. It consists of two parts, a feedback control and a feedforward control where the control variable u is defined as the sum of u_{FB} and u_{FF}. Feedback control is important for closed loop stability and is designed for disturbance rejection. The feedforward control, however, is designed to improve the set point tracking performance of the system which is particularly important during load changes. The feedforward control is independent from the feedback control and does not influence system stability (Zeitz, 2010).

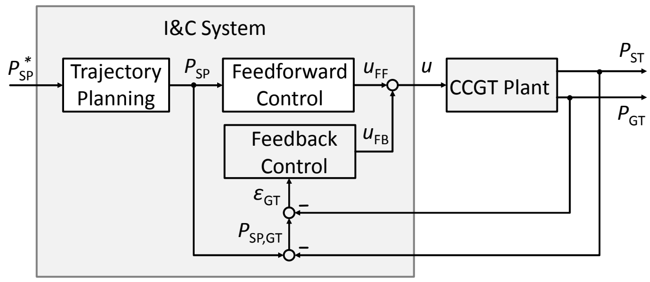

Fig. 7. 2-DOF control with model based feedforward control for CCGT plants

3.3 Model Based Feedforward Control

In model based feedforward control, a dynamic model of the process is incorporated in the control algorithm. The advantage is twofold:

Improved control performance: The process dynamics are taken into account in the computation of the control variable u_{FF} (in this case the fuel mass flow) by means of the process model. This leads to better control performance during set point changes, i.e. improved load tracking.

Less actuator wear: The better the feedforward control, the less feedback control action is required. The synthetic feedforward control signals are smooth and are not affected by measurement noise as is the case with feedback control. Hence, less stress is put on actuators.

In absence of disturbances, set point changes such as load ramps can be accomplished by the feedforward control alone. Feedback control is only necessary to compensate disturbances during the set point change. These disturbances are for example measurement noise and model inaccuracies.

4. FLATNESS BASED FEEDFORWARD CONTROL

4.1 Differential Flatness

A useful approach to model based feedforward control is the notion of "differential flatness". Differential flatness is a structural property of a class of dynamic systems that was first described in (Fliess et al., 1995). Since then it has also been used in industry applications (Rudolph, 2005). For differentially flat systems, all system variables can be written as a function of the so-called flat outputs and their derivatives. For linear systems as in this case, differential flatness is equivalent to controllability (Zeitz, 2010) and therefore easy to prove.

Equation (2) is the system equation of a general SISO system.

$$\Sigma: \ \dot{x} = f(x,u),\ x(0) = x_0 \in \mathbb{R}^n,\ y = h(x) \tag{2}$$

The system is called differentially flat if there is a flat output $z = \lambda(x)$ with relative degree $r = n$ such that the following parameterizations exist (The relative degree corresponds for a linear system Σ to the pole excess of the transfer function G_Σ (Skogestad, 2005)):

$$\Sigma^{-1}\text{: States: } \quad x = \psi_x(z, \dot{z}, \ldots, \overset{(n-1)}{z}) \tag{3}$$

$$\text{Input: } \quad u = \psi_u(z, \dot{z}, \ldots, \overset{(n-1)}{z}) \tag{4}$$

$$\text{Output: } \quad y = \psi_y(z, \dot{z}, \ldots, \overset{(n-1)}{z}) \tag{5}$$

These equations define the inverse of the system Σ^{-1} with respect to the flat output z with $z(t) \in \mathcal{C}^n$. For a given trajectory $z(t)$, the evolution of all other system variables, most importantly the input variables $u(t)$, is given. As system inversion is the basis for perfect feedforward control these properties can be used in the design of the feedforward control for the system Σ.

4.2 Control Algorithm

As described above, the differential flatness of the linear model of chapter 2.2 can be proven by the rank of the controllability matrix:

$$rank([B, AB]) = rank\left(\begin{bmatrix} \frac{1}{T_{GT}} & \frac{-1}{T_{GT}^{\;2}} \\ 0 & \frac{1-\alpha}{\alpha}\frac{1}{T_{GT}T_{HRSG}} \end{bmatrix}\right) = 2 \tag{6}$$

The rank of the controllability matrix is equal to the system order and hence the system is differentially flat.

In the next step, the flat output has to be determined. As the flat output has to be of relative degree $r = n = 2$ (Zeitz, 2010), the ST power output x_2 is a valid candidate. This is verified since (3), (4), and (5) can be derived for $z = x_2$:

$$\psi_x = \begin{bmatrix} \frac{\alpha}{1-\alpha}\left(T_{HRSG}\dot{z} + z\right) \\ z \end{bmatrix} \tag{7}$$

$$\psi_u = \frac{\alpha}{1-\alpha}\left(T_{GT}T_{HRSG}\ddot{z} + \left(T_{GT} + T_{HRSG}\right)\dot{z} + z\right) \tag{8}$$

$$\psi_y = \frac{\alpha}{1-\alpha}\left(T_{HRSG}\dot{z} + z\right) + z \tag{9}$$

The feedforward control law is given by (8), where the control variable trajectory $u(t)$ is given as a function of the flat output $z(t)$ and its derivatives. In order to apply (8) in the CCGT plant control, the trajectory $z(t)$ for the ST power output (i.e. the flat output) has to be two times continuously differentiable. This is subject of the "trajectory planning", see Fig. 7.

4.3 Trajectory Planning

Besides the control algorithm, the trajectory planning is the second import aspect of model based feedforward control (see Fig. 7). For the control variable (i.e. fuel mass flow) to be derived according to (8), adequate trajectories for the flat output z are required.

Traditionally, load changes are realized as ramps. This is convenient from a practical point of view as it is the simplest way to connect two load levels $P_{GEN,0}$ and $P_{GEN,1}$ in a given timespan. However, a dynamic system is not able to perfectly track a ramped set point change as this requires discontinuous control variables.

There are various approaches to trajectory planning. In order to remain close to the original set point change for the total power output P_{GEN}, a modified ramp is used with rounded transitions from and to the steady state, respectively. The so-called spline function for the trajectory is described in (Treuer et al., 2008). It is shown in Fig. 8 for a load change from $P_{GEN,0}$ to $P_{GEN,1}$. The ramp is reduced to a shorter timespan such that the transitions comply with the differentiability requirement described above.

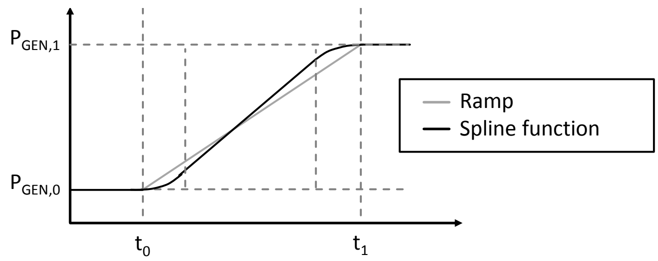

Fig. 8. Set point trajectory planning for power output

As the physical output P_{GEN} and the flat output P_{ST} are not the same, the set point trajectory for P_{GEN} has to be converted into a trajectory for the flat output. This is accomplished by application of (9), i.e. by solving an ordinary differential equation (ODE). Sufficient differentiability of the flat output is therefore guaranteed.

5. SIMULATION RESULTS

The set point trajectory (chapter 4) and the feedforward control algorithm (chapter 3) are tested in simulations studies on existing control concepts.

5.1 Positive Load Change

A positive load change of 30 MW in one minute shall be investigated. Therefore, a spline trajectory is derived as described in the preceding chapter. Fig. 9 shows the input variable fuel mass flow and the resulting exhaust mass flow to the HRSG. Both signals are given in the equivalent megawatts for comparability. It can be seen that the fuel mass flow has no oscillations and is very smooth as expected for a synthetically generated signal.

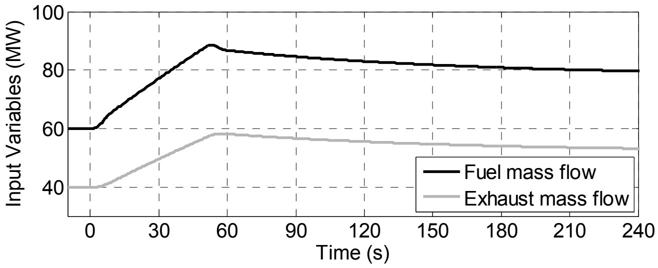

Fig. 9. Input variables during load change

GT and ST power output sum up to the total power output P_{GEN} as described above (see also Fig. 10 a)). After 60 seconds, P_{GEN} reaches a steady state at the new load level whereas the GT power output is reduced again in order to compensate for the delay of the HRSG/ST. Fig. 10 b) indicates how the gas turbine power output is increased. As the exhaust mass flow adapts, the ST power output follows accordingly. This demonstrates how incorporation of the process model in the feedforward control algorithm leads to better coordination of GT und ST power output.

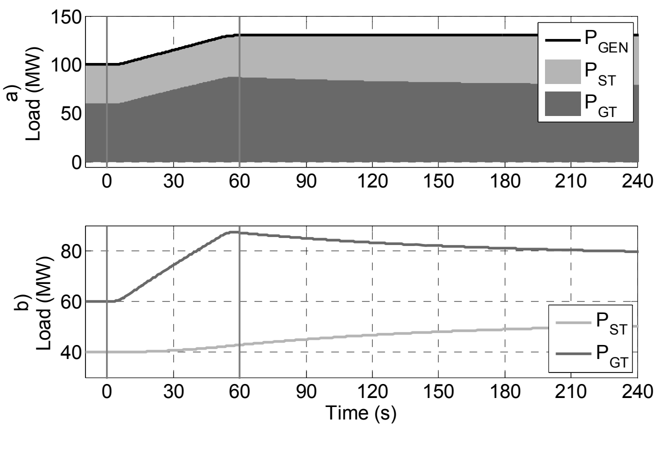

Fig. 10. Power output during positive load change

5.2 Comparison of Different Control Concepts

The model based feedforward control is compared with exclusive feedback control in order to demonstrate its performance. The simulation results are shown in Fig. 11. The feedback control is applied with a ramped set point as well as with the trajectory proposed in chapter 4.3.

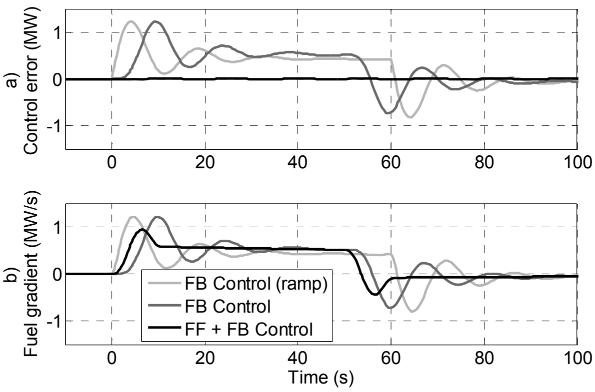

Fig. 11. Control error and fuel mass flow gradient for positive load change with different control concepts

The improved trajectory has only a marginal effect on the control error and the control variables (Fig. 11) when it is applied with feedback control alone. Although the spline trajectory is smoother, the simulation results show that the control error is not smaller.

As discussed in chapter 5.1, the combination of feedback and feedforward yields the best results because the process dynamics are perfectly incorporated in the control algorithm. Therefore, the control error remains zero (see Fig. 11 a) and there is no feedback control action.

The improved control performance does not come at the expense of greater control action. On the contrary, control action is actually reduced which is illustrated in Fig. 11 b) by the rate of change (gradient) of the fuel mass flow. A small rate of change and few oscillations indicate an operation that is characterized by only marginal actuator wear. In the case of feedback control, the fuel mass flow shows characteristic oscillations as expected in feedback systems. The fuel mass flow gradient in the feedforward control (black) is smooth and has smaller amplitude. This implies less actuator wear and therefore a more efficient operation.

The results depend on the actual parameters of the feedback controller. The parameter choice is a trade-off between control error and aggressive control action. Therefore, a quantitative analysis of the potential for improvement is not considered. However, the control performance is increased through an additional model based feedforward control for any choice of feedback control parameters.

5.3 Robust Performance Analysis

As the feedforward control is model based, the control performance depends on the model quality. Obviously, the model is an approximation of the real process. In order to analyze the robustness of control performance against uncertainties in the model parameters, the simulations of chapter 4 are run with variations in the parameters of the model in the control algorithm. The process model remains unchanged.

The control performance was analyzed for different parameter variations. Two exemplary parameterizations A and B are given in Table 1.

Table 1. Parameter variations for robust performance analysis

Parameter	nominal	A	B
T_{GT} (s)	5	7,5	2,5
T_{HRSG} (s)	180	216	144

In parameterization A, the gas turbine time constant is increased by 50 %, the HRSG time constant is increased by 20 %. For parameterization B, both time constants are reduced by the same fraction.

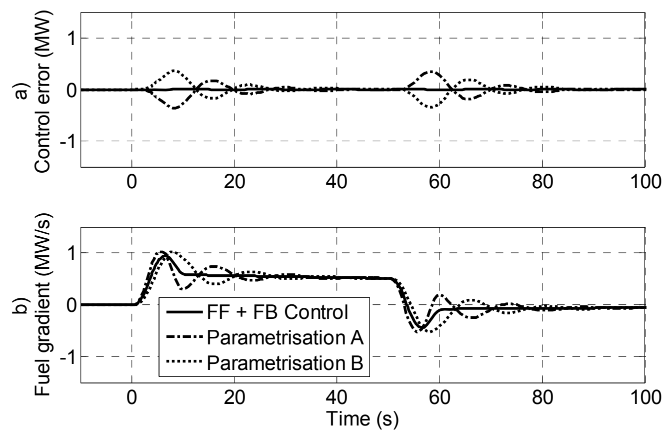

Fig. 12. Robust performance analysis: Control error and fuel mass flow gradient

Despite the significant uncertainties of the parameterizations A and B, the control error (Fig. 12 a)) is small compared to the other two control concepts described in chapter 5.1 (see Fig. 11). As there is now feedback control action in addition to the feedforward control, the fuel mass flow gradient becomes higher and more variant but is again lower than in the cases without feedforward control.

6. CONCLUSIONS

Feedforward control is particularly beneficial when it comes to set point changes. In this contribution, a model based feedforward control based on differential flatness is proposed in order to improve the load tracking performance for combined cycle gas turbine plants. It is important to notice that it complements the existing feedback control system and does not influence the overall system stability. The benefits are twofold:

On the one hand it yields better control performance. The control variable is calculated with respect to the system dynamics which leads to smaller control errors.

On the other hand, operational efficiency is improved as there is less actuator wear. Control action is shifted from the feedback control to the feedforward control resulting in smoother control variables which in turn results in less stress on actuators and therefore less actuator wear.

As a dynamic process model is required for the derivation of the control algorithm, it is important to have an adequate process model. The robustness of the control performance was analyzed by different parameter variations. Nevertheless is it worthwhile to apply the same approach to a more detailed model.

Another important aspect is the impact of fast load changes on the life time consumption of HRSG components through thermal stress. Thermal stress depends on the operation regime and can therefore also be addressed by model based feedforward control.

REFERENCES

Fliess, M. et al. (1995). Flatness and defect of non-linear systems: introductory theory and examples. *International Journal of Control*, **61**, 1327-1361.

International Energy Agency (2012). *World energy outlook 2012*. IEA Publications, Paris.

Kunitomi, K. et al. (2003). Modeling combined-cycle power plant for simulation of frequency excursions. *IEEE Transactions on power systems,* **12,** 724-729.

Rudolph, J. (2005). Flachheit: Eine nützliche Eigenschaft auch für Systeme mit Totzeiten. *Automatisierungs-technik*, **4-5**, 178-188.

Skogestad, S. and I. Postlethwaite (2005). *Multivariable feedback control*, Wiley, Chichester, UK.

Treuer, M. et al. (2007). Flatness-based two-degree-of-freedom control of a pumped storage power station. In: *Proceedings of the European Control Conference 2007*, 4087-4094, Kos, Greece.

Treuer, M. et al. (2008). Trajectory planning for flatness-based two-degree-of-freedom control of a pumped storage power station. In: *Proceedings of the 17th World Congress,* IFAC (Ed.), 11080-11085, Seoul, Korea.

Von Roon, S. and M. Huber (2010). Modeling spot market pricing with the residual load. *Enerday – 5th Conference on Energy Economics and Technology*.

Yee, S.K., J.V. Milanovic and F.M. Hughes (2008). Overview and comparative analysis of gas turbine models for system stability studies. *IEEE Transactions on power systems*, **23**, 108-118.

Zeitz, M. (2010). Differenzielle Flachheit: Eine nützliche Methodik auch für lineare SISO-Systeme. *Automatisierungstechnik*, **1**, 5-13.