Centralised multivariable feedback control of steam drums in combined cycle power plants

Ahmed El-Guindy, Fabian Nickel and Kai Michels

Kurzfassung

Mehrgrößenregelung für den Trommelfüllstand in GuD-Anlagen

Die Deregulierung des Energiemarktes und die zunehmende Integration erneuerbarer Energieerzeugung in das Netz haben zu neuen, hochdynamischen Anforderungen an die Kraftwerke geführt, die mit klassischen Regelungen vom PID-Typ teilweise nicht mehr zu bewältigen sind. In dem vorliegenden Beitrag wird ein moderner, multivariabler Regler zur Regelung des Füllstandes der Niederdrucktrommel im 450-MW-GuD-HKW München Süd der Stadtwerke München beschrieben. Die bisher eingesetzte Struktur aus zwei PI-Regler-Kaskaden setzte dem Betrieb enge Grenzen hinsichtlich der Blockdynamik und der entsprechenden Fähigkeit, Sollwerten aus der Netzregelung zu folgen. Daher wurde ein beobachtergestützter, multivariabler Zustandsregler konzeptioniert.

Der Beobachter wurde zunächst in MATLAB/Simulink implementiert und anhand der vorhandenen, umfangreichen Messdaten verifiziert. Realisiert wurden Regler und Beobachter dann im Leitsystem Mauell ME-4012. Die Regelung beinhaltet außerdem eine umfangreiche Umschaltlogik zwischen den fünf vorhandenen Dampfventilen, die jeweils für andere Betriebszustände aktiv werden. Der fertige Regler in der Anlage zeigt ein deutlich verbessertes dynamisches Gesamtverhalten des Systems, wie man anhand von Doppelhöckerkurven für die Präqualifikation für die Teilnahme am Regelenergiemarkt gut erkennen kann.

Authors

Ahmed El-Guindy, M.Sc.
Wissenschaftlicher Mitarbeiter
Formerly FWBI Forschungsges. GmbH
Technische Universität München
München/Germany

Dipl-Ing. Fabian Nickel
Projektleiter Automatisierung und Leittechnik
SWM Services GmbH
München/Germany

Prof. Dr.-Ing. Kai Michels
Institutsleitung
Universität Bremen
Bremen/Germany

Introduction

The integration of renewable energy sources has led to a continuous increase of complexity, design and management of power systems. The installed process controllers have to be designed in such a way, which can simultaneously offer a high degree of flexibility and at the same time, should bear in mind safety and lifetime of the plant crucial elements. The process controllers have to comply with the requirements imposed by load change demands preserving the grid stability and frequency, which is processed in primary grid control. In particular, control of the steam drum unit water level is very critical for boiler operation, and the controller should maintain it within safety limits over the complete operating range of the boiler.

The steam generation process using the drum unit is a multiple-input multiple-output (MIMO) system, with a strong coupling between its input channels and non-linear dynamics depending on the operating point. Additionally, it has a non-minimum phase behaviour, leading to an initial inverse response of the water level, which is associated with the shrink and swell physical phenomena of steam bubbles under the water level. This makes the control task extremely challenging with classical techniques using decentralised PID control loops, which regulate feedwater and steam flow rates separately from each other.

The industry standard 1-, 2- and 3-element cascaded architecture PID controllers can be found in nearly all current power plants [1]. Although they can behave fairly well with low load changes (≤20 MW) with long time interval between each transition, their performance can become unsatisfactory for higher steps (≥30 MW), thus resulting in large deviations in the system response. The modification of the controller parameters to improve the system performance is not a straight-forward task due to the strong coupling between different actuating variables. The adjustment of a particular loop, without considering the effects on the overall multivariable system, can result in instability of the plant and even worse tripping of the boiler unit. Statistically speaking, it was reported recently, that 30 % of emergency shutdowns in power plants are caused by poor level control of the steam drum unit [2].

The control theorists from academia have been proposing entirely new emerging concepts to solve this reoccurring problem, such as genetic algorithms (GAs), fuzzy logic, neutral networks, and norm-optimal control. As these modern techniques are only examined within simulation environments, i.e. MATLAB or Modelica, the same control performance cannot be guaranteed in practice because of the unavoidable mismatch between a mathematical model and reality. Furthermore, very small perturbations of modern controller coefficients can cause instability of the closed loop.

From a practical point of view, these controllers are unusable in a commercial distributed control system (DCS), for the following main reasons

Methodology: Plant operators are unfamiliar with state-of-the-art concepts. In addition, a very well established mathematical background is mandatory, to barely even understand the basics of a modern controller. This knowledge is not available among plant personnel, so that the controller will always act as a black box system from the operator's view, and therefore rarely accepted.

Implementation: The controller is structurally unconstrained and its order is usually higher or equal to that of the plant, making it unrealisable, due to hardware and software limitations.

Tuning: Controller online re-tuning or re-adjusting is practically impossible, as the feedback parameters are neither set directly nor have a clear physical meaning that one can easily relate to. This matter is very critical in practical applications, since the operating mode may be redefined in different ways, or, more often, plant parameters may change caused by pipe contamination or actuator deterioration, thus re-tuning is necessary many times during the process lifetime.

Switching mechanism: The possibility to switch back from modern controller to conventional structure should be always given in case of any problem, especially for critical industries. The mechanism has to ensure, that both controller outputs are following one another, so that an output discontinuous course is avoided during transient switching.

Motivated by the above mentioned, a new control strategy for the low-pressure

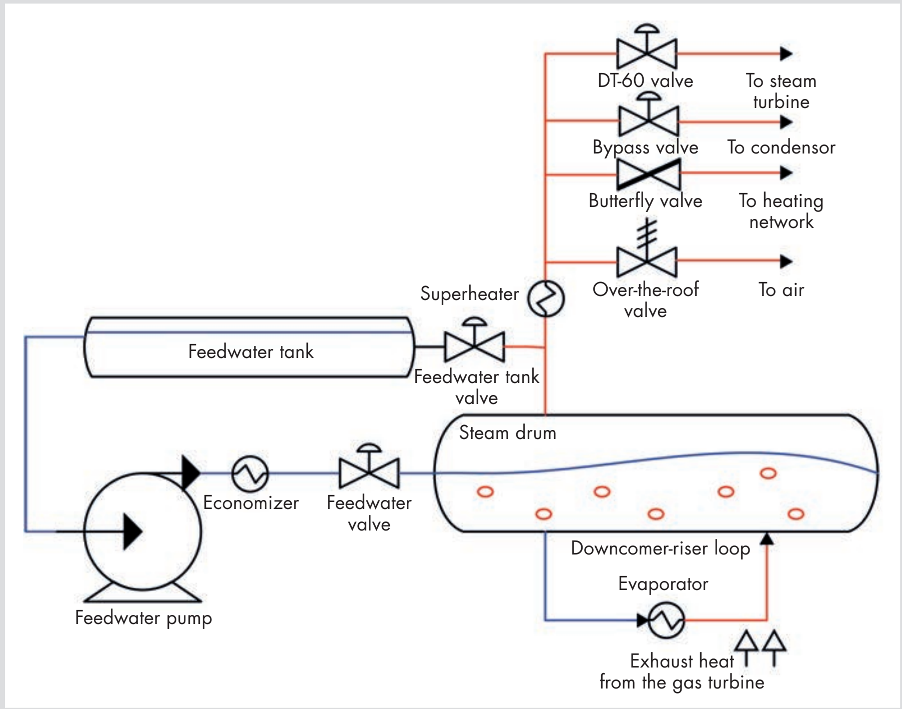

Fig. 1. Steam generation process using the steam drum.

steam drum unit of the 450 MW CCHPP (combined cycle heat and power plant) München Süd belonging to Stadtwerke München will be presented. The strategy offers the powerful features of state-space control, while at the same time complies with the practical requirements of a power plant. The work is a cooperation project between the University of Bremen, Institute of Automation (IAT), Chair of System Dynamics and Control Engineering, and Munich City Utilities – Stadtwerke München (SWM Services GmbH).

Process description

The simplified diagram of the steam generation process using the steam drum is shown in Figure 1. Cold water from the feedwater tank is pumped and heated at the economiser stage before going through the drum inlet. Due to gravitational force, the feedwater flows through the naturally circulated downcomer-riser loop, in which the liquid is converted into steam at the evaporator stage. The steam is collected through different riser tubes and fed back into the drum. As the drum contains a mixture of saturated liquid/steam and due to the difference in density between both, the steam starts leaving from the drum outlet to be superheated at the superheater stage.

The generated steam can flow throughout 5 different steam ways, according to the process requirements, in the following order.

Feedwater tank: A portion of the steam flow of approximately 1 kg/s is always supplied for preheating the feedwater tank, and the valve is kept fixed at a constant opening.

Over-the-roof: If none of the below paths is available, steam is simply released to the environment. Besides that, the respective valve is employed for safety measures, when the drum pressure exceeds certain limitations.

District heating network: Heat can be supplied through the heating network to the residents of Munich, using a butterfly valve.

Steam turbine (DT-60): Additional electrical power can be generated by the steam turbine through the secondary steam inlet, if the corresponding valve is opened.

Condenser: Throughout this valve, the steam can be condensed directly by bypassing the steam turbine. Additionally, it is operated during start-up and shut-down of DT-60.

The level control is the industry standard, cascaded PID controller, with a level controller at the outer-loop and a flow rate controller at the inner-loop to adjust the control valve opening percentage (%). The pressure is controlled by PI steam pressure controllers with one controller for each steam valve.

This results in a total of six different PI controllers in a decentralised network, employed to regulate the water level and pressure of the steam drum unit. In the following section it will be shown how it is possible to improve the performance significantly with a centralised multivariable feedback control technique.

Controller development

The state-feedback methodology is a modern control strategy, which uses the inner states of the system, given by the vector x, for feedback. Using this internal knowledge of the system, the controller performance can be much better than the classical controller performance, where only output measurements are used for feedback and control error calculations.

The main disadvantage of the state space approach is the necessity of an observer to estimate the internal states that normally cannot be measured in practice. Moreover, since the observer is nothing more than a mathematical model, derived from first principles to capture dynamics of the system, its design can be an extremely time-consuming task. For correction of model errors, the model output is compared to the measured plant output, and the model error is multiplied with an observer feedback matrix L and fed back into the model as a correction term.

With a proper and guaranteed estimation of the inner states in the observer, the calculated states of the model can be used for feedback with the help of a matrix F. However, as this is merely a multidimensional proportional gain matrix, steady

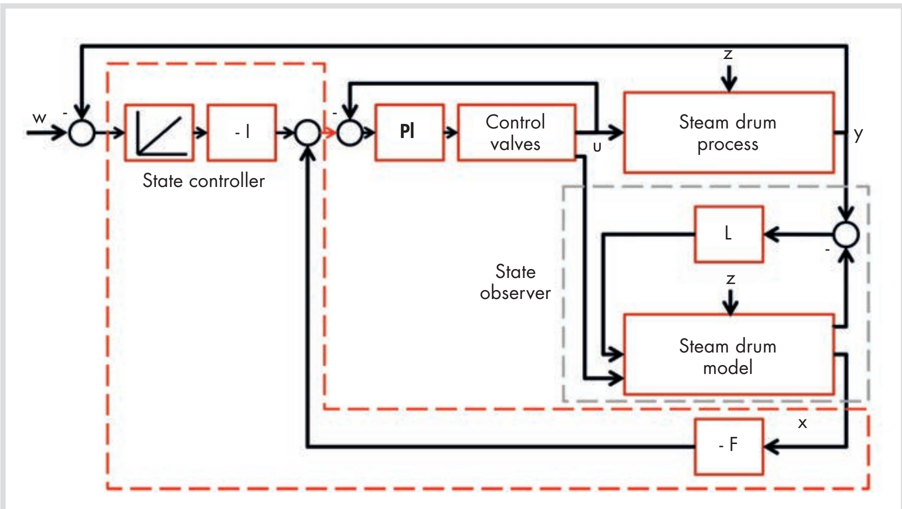

Fig. 2. Extended concept of state space control.

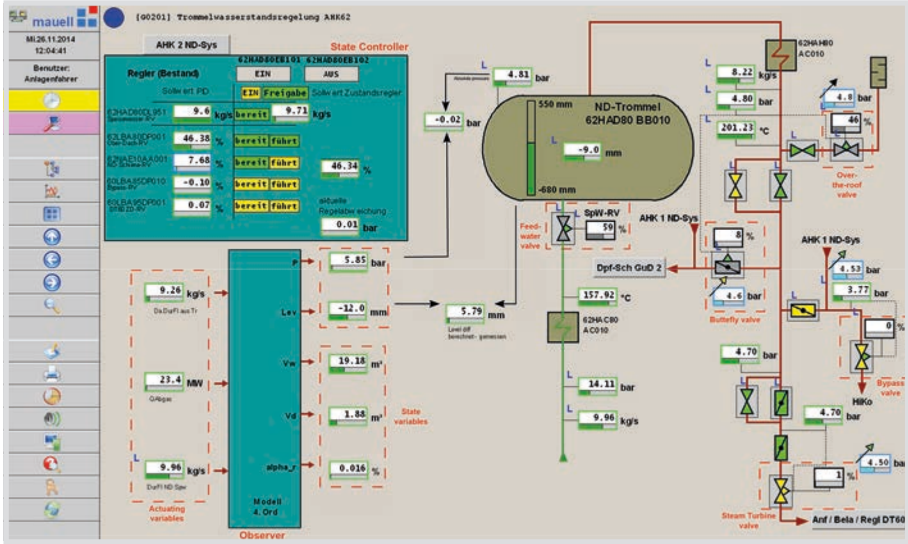

Fig. 3. New controller human-machine interface.

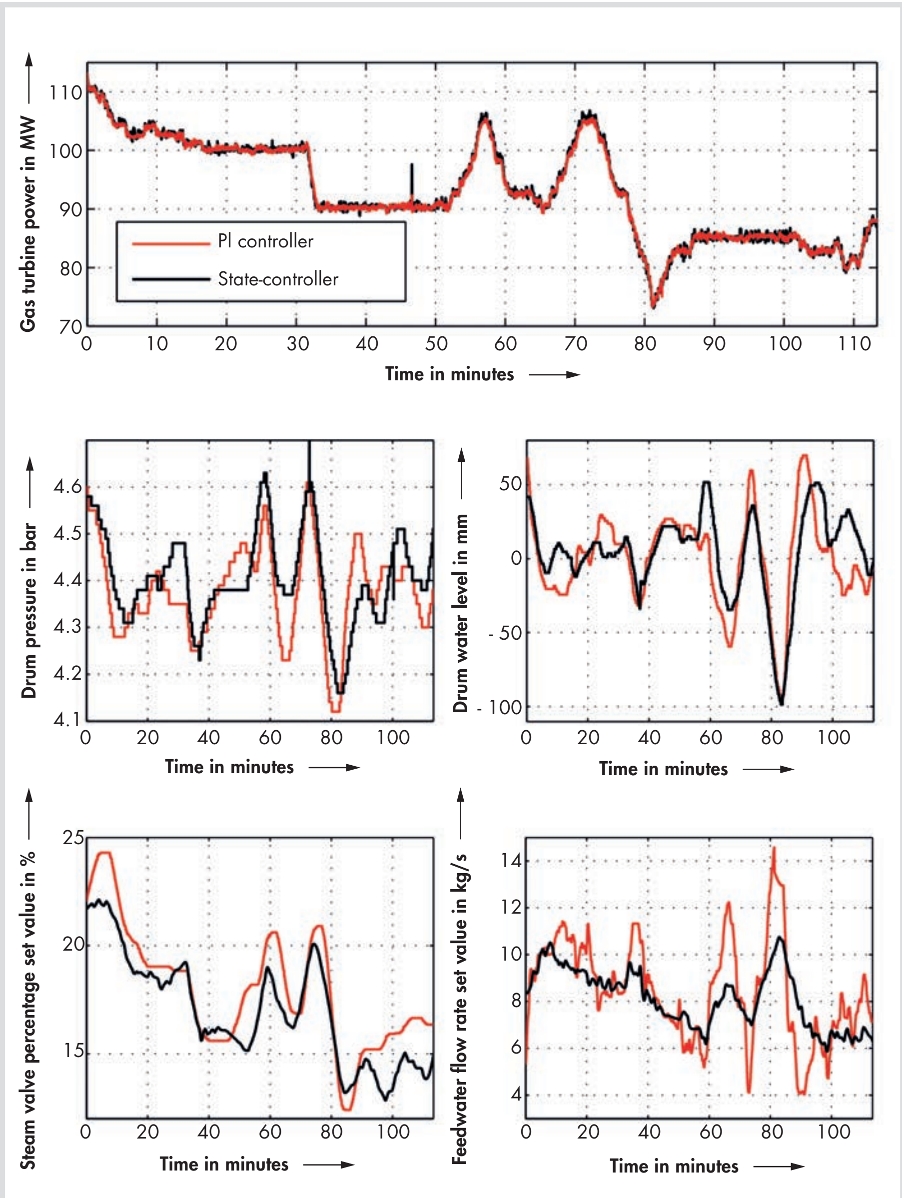

Fig. 4. Comparison between the PI-controller and the state-controller under normal operation of the gas turbine using the butterfly valve.

state accuracy cannot be achieved, similar to the classical problem with the pure proportional controller. Therefore, an integral part is required, which is a multidimensional integral controller in addition to the state-feedback controller. The coefficient matrix of the integral part I has to be designed together with the state-feedback matrix F, as the outputs of the multidimensional integrator have to be treated as additional state variables of the system.

The key advantages of this extended structure when compared to a decentralised network of PI controllers, is that all effects, that have to be neglected for PI controller design (strong coupling, non-linearity, non-minimum phase behaviour) are automatically taken into account by state-space controller design.

Observer design

The observer used to estimate the steam drum states is the very well developed Åström-Bell model [2]. It went through several iterations since the seventies, which resulted nowadays in a 4th order non-linear model that can predict the drum pressure and water level by means of defining energy and mass balance. The four chosen state variables have a good physical interpretation: The steam drum pressure P is obviously chosen as it describes the total energy of the system. The accumulation of water, related to the total water volume V_w in the system is selected since it represents the storage of mass. Steam quality α_r in the riser tubes and steam bubbles volume under the liquid level V_d are chosen as well to describe distribution of steam under the water level, thus estimating the level inside the drum.

The model actuating variables u are the feedwater and steam flow rates, while the heat flow rate is considered as a model input disturbance z, due to the power plant combined cycle working principle. Its amount is associated with the gas turbine exhaust heat, which in return corresponds to its electrical output power. The relation between both was assumed to follow a performance of 1st order lag element PT_1, where its time constant T and gain P were chosen according to measurements of the real process.

The observer model was validated in MATLAB/Simulink against data measurements from the plant with very rich excitation, covering a wide spectrum of operating conditions. For further details concerning the observer model, the reader can refer to a previous publication by the authors [3].

Controller design

The design of the above-mentioned controller matrices L, F and I can be achieved using different mathematical algorithms. We are using the Linear-Quadratic method for optimal control, in which the resulting controller is known as a Riccati Controller.

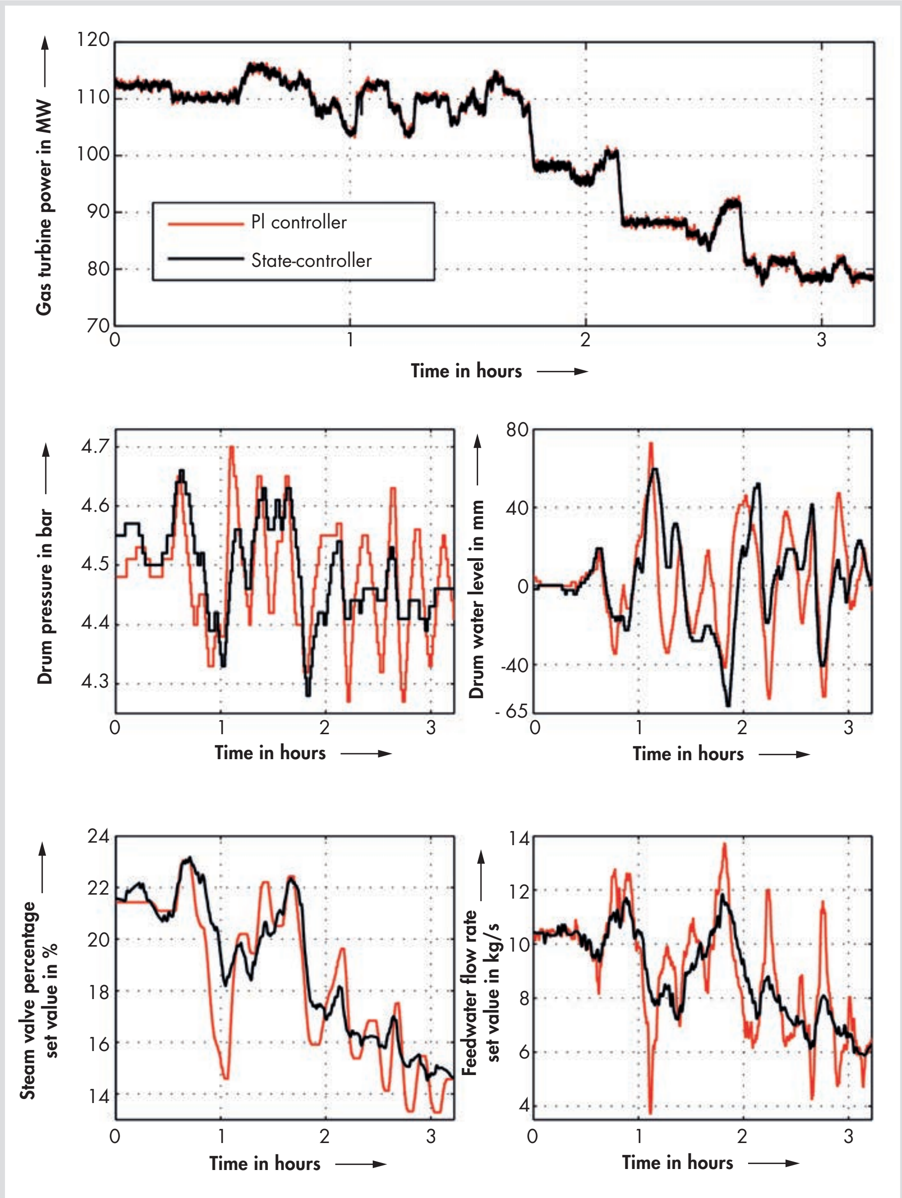

Fig. 5. Comparison between PI controller (butterfly valve) and state controller (steam turbine valve) under normal operation of the gas turbine.

It offers a trade-off between the amplitude of the actuating variables u and performance of the state variables x over the course of time, by minimising a cost function J described in equation (1). The controller performance depends on the weighting matrices Q and R, that have to be chosen by the design engineer like the parameters of a PID controller: gain K_p, integrator time constant T_i and derivative gain K_D.

Yet, the synthesis principle is still the same, as a trial-and-error process takes place until a satisfactory performance is attained. The initial choice of the matrices is straightforward, with the help of the Bryson's rule. Then if a faster convergence of a particular state towards zero is required, its equivalent coefficient inside the matrix Q should increase, and if a slower response of the actuating variables is preferred to lower the energy consumption, then the coefficients of R have to be chosen larger.

$$J = \int_0^\infty \left(x^T(t)\mathbf{Q}x(t) + u^T(t)\mathbf{R}u(t)\right)dt \;.. \; (1)$$

The block diagram for the proposed control strategy using the state-space controller is shown in Figure 2. The non-linear model combined with the error feedback matrix L_{2x4} is the observer of the real steam drum process. The four estimated variables are fed to the state feedback matrix F_{2x4}, and the output of this matrix stabilises the system. Additionally, integral controllers for two inputs and two outputs for steady-state accuracy of the system were coupled, represented by matrix I_{2x2}. This results in the computation of two set values, e.g. the feedwater flow rate kg/s and the respective steam valve opening position (%).

The highlighted red path in the block diagram between matrix I_{2x2} and PI controllers for the valves includes the switching logic to switch between old and new control set values. The switching for the feedwater flow rate set value is self-explanatory, since there exists only one single valve to regulate the feedwater. However, the issue becomes more complicated with the steam flow rate, which leads to the design of a special switching mechanism with several selection criteria, to ensure that the correct valve is being controlled, according to the process requirements.

Switching mechanism

Figure 3 shows an illustrative description of the new HMI to use the new controller. A modification of the existing HMI of the steam drum unit was necessary to include the observer state variables and the binary signals of the switching circuit.

The switching unit has to cover many different operation scenarios that cannot be explained here completely. In the following, only the switching from the PI controller to the state controller is explained. All control valves' opening percentages are supplied to the logical circuit, to decide which steam way, e.g. district heating network, condenser or steam turbine, is currently in use according to the following decisions:

Ready – Bereit: A valve is ready according to feedback signals from the Mauell DCS system.

The valves are being controlled automatically.

No measurement errors or disturbances are present.

Leading – Führt: If two or more valves are ready, then it must be decided which one is leading. The highest opening percentage gives a good indication, which steam way is currently in operation, since only one steam way can be used at time.

The opening percentage is only considered when the valve is operated automatically, otherwise it is regarded as closed.

The over-the-roof valve is only employed for safety measures and rarely operated by itself, it has to be opened more than 30 %, otherwise it is considered as closed.

Due to the fact that both boilers are using the same bypass valve, another criterion is included using the preceding one-way valve: The opening percentage is considered only if its one-way valve is opened.

Tracking signals: Once a valve is ready and leading, its opening percentage is supplied to the state-controller integrators to ensure that they are following the corresponding PI control loop output. This will ensure a continuous output course during switching between both controllers.

Released – Freigabe: The state-controller performs one final check before allowing the operators to turn it ON (EIN).

The electrical load of the gas turbine should be higher than 65 MW, to avoid operation during start-up, which is handled

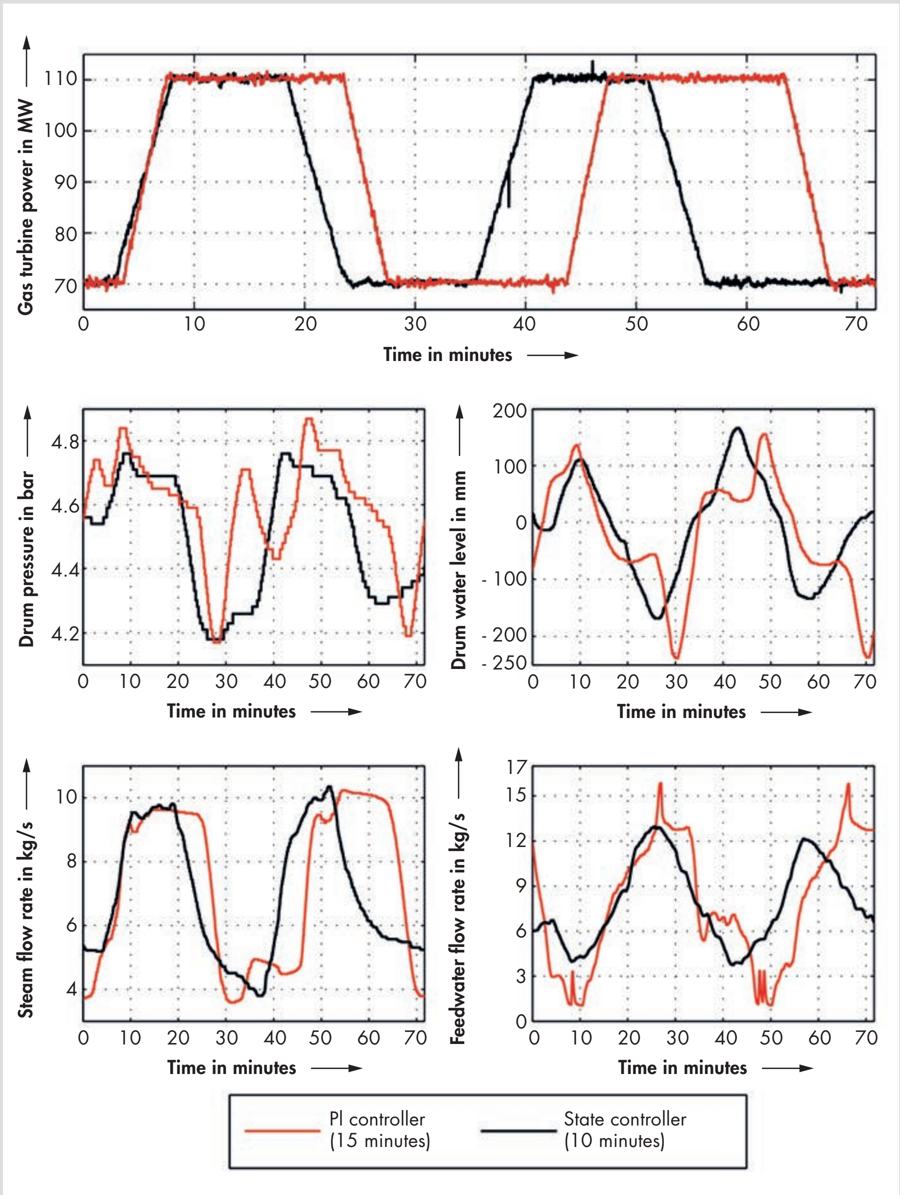

Fig. 6. Performance comparison between controllers against the prequalification curve for secondary grid control.

by a separate controller and is not part of the state-controller tasks.

The leading steam valve opening percentage should be higher than 3 %.

The errors between the observer and actual measurements have not exceeded the predefined limits for more than 5 minutes, i.e. 0.1 bar pressure or ±20 mm level errors.

Finally, if all previous criteria are met, the operator can turn the controller ON (EIN).

Once the state-controller is turned ON, its set values are provided to the respective steam valve which was previously regulated by the old PI controller, while the other valves are not affected. Switching off the state controller takes place automatically, if one of the above-mentioned rules is no longer met. Additionally, it can be turned OFF (AUS) by the operators manually.

Results

This section compares the old PI controller and the new state-controller under different conditions.

Control performance comparison under normal operation

Figure 4 shows a comparison, which covers almost the entire operating range of the gas turbine during normal operation, i.e. 70 MW to 115 MW, using low gradients for changing the set points. The conditions are identical to one another and take place at the same time frame, where boiler 1 and boiler 2 are utilising the PI controller (red) and state-controller (black), respectively. The steam flow rate was regulated using the butterfly valve.

It is easy to see, that there is not much difference between the control performances of both controllers. The reason is, as pointed out earlier in the introduction, that the industry standard 2-element PID controller is actually sufficient and can provide fairly satisfying results for small transition gradients. However, by examining the feedwater flow rate set values computed by both controllers, the ones computed by the state-controller are favourable in terms of energy consumption. This effect will be more noticeable when we present the results for fast load-changes ≥40 MW.

Figure 5 illustrates a different comparison for a longer duration, lasting approximately 3 hours. The main difference here is that boiler 1 (red) and boiler 2 (black) are regulating the steam flow rate using the butterfly (PI Controller) and steam turbine (State Controller) valve correspondingly. The oscillations caused by the PI controller (red) are obvious, compared to the curves of the state controller. As shown in the previous results, the optimisation of the closed loop using the state-controller can be justified only at high load, thus offering more flexibility for the power plant.

Control performance comparison against the prequalification curve

Special emphasis was to examine the performance against the prequalification curve for secondary grid control ("Sekundärregelung" – SRL), which is part of the transmission code 2007 [4]. The current requirement is to supply a load difference equivalent to ±40 MW within 5 minutes, keep the load constant for 10 minutes, return to the original operating point within 5 minutes and repeat the same process again. This spans a curve known in German by the "Doppelhöckerkurve". Such operation condition is the worst-case scenario the plant must be able to go through, in terms of meeting load change demands by the transmission grid provider.

Figure 6 illustrates the comparison between both controllers for 40 MW load changes of the gas turbine. The tests were performed on different time frames, e.g. March 2013 and April 2014, where the one attempted with the old PI Controller (red) does not even comply with the exact regulations. As the drum water level was getting too close to the tripping condition (–350 mm), the operators had to wait for 15 minutes on the new set point before driving down the gas turbine to avoid any risk of boiler shutdown. On the other hand, the new state-controller (black) managed to keep the water level between approximately ±200 mm, so that the exact prequalification curve could be performed by the gas turbine, i.e. the set point could be left after 10 minutes.

The main problem of the old PI controller can be seen at the feedwater flow rate. The PI level controller considers neither the process coupling nor the initial inverse response, dominated by the steam flow rate. Considering a decrease of the gas turbine load, the PI controller only reacts on the level drop, by merely opening the feedwater valve and feeding more cold water into the drum, to restore the level back to its initial position. However, this control action affects the overall process badly, as adding more cold water to the system affects the steam pressure and its corresponding control loop. This problem does not appear in the state-controller, as this considers the inner states of the system as well as the strong coupling between both input and output channels.

Conclusion

An implementation of a modern multivariable feedback control strategy was presented to regulate pressure and water level of a steam drum unit within a 450 MW CCHPP in Munich, Germany. Although, a modern multivariable control scheme was used, the entire control structure was kept close to classical control schemes, to simplify integration into the existing control structures. Contrary to other publications presented by academia, which consider only simulation results, the presented results were obtained from real data measurements and our strategy is realisable from a practical perspective.

The mathematical model used to design the state-controller achieves a high degree of re-usability. By simply adjusting its parameters, which are extracted from construction data, it can be fitted to any class of power plants, for both low- and high-pressure steam drum units. Retuning of the controller gains during process lifetime is possible online within the DCS or offline through MATLAB/Simulink environment.

The water level performance at München Süd control was significantly improved at high load changes of the gas turbine, thus offering more flexibility to the power plant to meet load changes according to the transmission grid provider. A special switching mechanism was introduced, allowing the new controller to regulate 5 different valves simultaneously. The controller is 100 % operational and has officially replaced the industry standard decentralised PI control scheme since November 2014.

References

[1] Asea Brown Boveri: *Drum Level Control Systems in the Process Industries*, 1997.

[2] Åström, K.J., and Bell, B.: *Drum Boiler Dynamics*. Automatica, 36: 363-378, March 2000.

[3] Elguindy, A., Rünzi, S., and Michels. K.: *Optimizing Drum-Boiler Water Level Control Performance: A Practical Approach. Conference proceedings of the IEEE Multi-Conference on Systems and Control*, pp. 1675:1680, October 2014, Antibes – France.

[4] Verband der Netzbetreiber e.V. beim VDEW: TransmissionCode 2007: Netz- und Systemregeln der deutschen Übertragungsnetzbetreiber. Version 1.1, August 2007.

VGB | POWERTECH

International Journal for Electricity and Heat Generation

Please copy >>> fill in and return by mail or fax

☐ Yes, I would like order a subscription of VGB PowerTech.

The current price is Euro 275.– plus postage and VAT.

Unless terminated with a notice period of one month to the end of the year, this subscription will be extended for a further year in each case.

Name, First Name

Street

Postal Code City Country

Phone/Fax

Date 1st Signature

Cancellation: This order may be cancelled within 14 days. A notice must be sent to to VGB PowerTech Service GmbH within this period. The deadline will be observed by due mailing. I agree to the terms with my 2nd signature.

Date 2nd Signature

Return by fax to

VGB PowerTech Service GmbH
Fax No. +49 201 8128-302

or access our on-line shop at www.vgb.org | MEDIA | SHOP.