9th International Workshop on Simulation for Energy, Sustainable Development & Environment
18th International Multidisciplinary Modeling & Simulation Multiconference

ISSN 2724-0061 ISBN 978-88-85741-67-6 © 2021 The Authors.
doi: 10.46354/i3m.2021.sesde.008

Optimized power plant control via compound modeling of structural integrity and plant dynamics

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Abstract

The increasing share of uncontrollable renewable energy sources in the energy mix shifts the strict demand for maneuverability to other power plants, including even big-sized ones as well. This way of operation with many load changes has to be managed by the controllers, which were tuned for assuring optimal behavior under the original circumstances of the plant, that is, for long-term permanent-load operation. The term optimization assumes a clearly defined target by all means, which, in this case, should be extended by the consideration of the thermal stresses and the resulted structural damages caused by the rapid load-changes. Advanced control algorithms are capable of weighting between several targets, hence they are appropriate for an optimized power plant control also under the actually changing environment. In this paper, several solutions will be introduced, together with the new model development approach that also includes the description of the controller's effects on structural integrity.

Keywords: Structural integrity; Power plant control; Life extending control; Damage mitigating control

1. Introduction

High number of control loops are used in all power plants required to operate absolutely reliably and accurately. Advanced control techniques offer a wide variety of advantages resulting in direct economical benefits through more accurate and flexible operation while also taking predefined constraints into account. Further, the application of advanced control techniques are capable of resulting in direct economic benefit!

Real-time optimization takes place practically in all power plants. The main task of all automatic controllers is to assure the optimal values of their controlled variables under all circumstances. The quality of operation of these controllers have evidently a crucial effect on the way of operation of the entire power plant. Whether a power plant – based on either renewable resources or fossil fuels – is operated on a highly effective way, or is a rather resource-consuming one, is evidently of very high importance regarding emissions and other ecological aspects. This fact is the reason for discussing in this conference paper the possible ways for increasing the level of control quality in power plants.

According to a very simple example, a better control may keep the superheated steam temperature of a thermal power plant within a narrower band. This decreased fluctuation in turn allows a higher set-point of the same temperature, since the properties of the steel material used determine the maximum permissible steam temperature. And a higher average live steam temperature directly increases the efficiency of the plant, which means a direct decrease in fuel expenses. This simple example alone shows an obvious case of obtaining direct economic benefit in the steady state operation only. It is important to mention that modern control techniques offer a much wider range of areas where direct economic benefits can be expected. Based on many published cases, the most important such benefits in a power plant can be listed as follows.

- Efficiency increase in steady states can be achieved (which directly means lower fuel costs and emission – as introduced in the example above).
- The limits of steady state operations can be extended.
- Dynamic changes can be made smoother and less resource-consuming. (This covers start-up, shut-down and load change periods. In the first two cases the sped up processes directly result in savings in fuel cost, while considering and limiting thermal stresses also results in an increased life-time.)
- The level of supply can be increased by making the power plant a more flexible one in the energy market.

What is the secret behind advanced control techniques that allows them to offer such benefits? Let's answer this question using the example of one of the most frequently used techniques, Model Predictive Control. Its most important properties are that

- its control actions are based on future values calculated by an integrated process model,
- it can inherently consider constraints regarding, e.g., allowed operating areas and actuator position and speed limits, and
- multivariable control is naturally handled allowing an integrated compensation of cross effects.

2. Brief introduction to plant dynamical modeling

Modeling is "as much an art as a science" (Ljung and Glad, 1994) because the expression *good model* does not exist. While setting up a model, it must be carried out according to the specific targets in all cases. Because of several reasons, for applying a theoretical model within a controller, the so called *lumped model* is the best choice, the general form of which is as follows

$$\dot{x} = f(x, u, d) \tag{1}$$

$$y = g(x, u, d) \tag{2}$$

the linearized form of which is

$$\dot{x} = Ax + Bu \tag{3}$$

$$y = Cx + Du \tag{4}$$

where u and y are process input and output, respectively, d is disturbance (see also Figure 1); x is the state variable, $\dot{x}$ is its time derivative, and A, B, C, and D are matrices.

Note that the linear system has an analytic solution which is called the Cauchy-form as follows

$$x(t) = \Phi(t, t_0) \cdot x_0 + \int_{t_0}^{t} \Phi(t, \tau) \cdot B(\tau) \cdot u(\tau)\, \mathrm{d}\tau \tag{5}$$

where Φ is a specific matrix to be determined separately.

Further, the Laplace transform is of high significance the definition of which is as follows

$$\mathcal{L}\left\{f(t)\right\} = \int_{0}^{\infty} f(t) \cdot e^{-st}\, \mathrm{d}t = F(s) \tag{6}$$

which is only valid for functions that $f(t) \equiv 0$ if $t < 0$. Based on this, the transfer function can already be defined as

$$W(s) = \frac{Y(s)}{U(s)} = \frac{\mathcal{L}\left\{y(t)\right\}}{\mathcal{L}\left\{u(t)\right\}} \tag{7}$$

where y and u are as above. Finally, the relationship between the time-domain and frequency-domain descriptions can also be given as follows

$$W(s) = C(sI - A)^{-1}B + D \tag{8}$$

where I is the identity matrix.

3. Brief introduction to process control

The practically exclusively used control method in power plants is currently the PID (Proportional-Integral-Derivative) algorithm. The well known, clear-sighted effects of its three parameters, the easy and uniform methods for setting them, and the multiply proofed, stable operation assure its widespread success in many industrial branches, including energy industry (Evans, 1954). Besides these clear advantages, the PID controller does have its limitations, and at the same time, modern control theory offers a wide range of advanced control methods. The general configuration of a control loop is depicted in Figure 1.

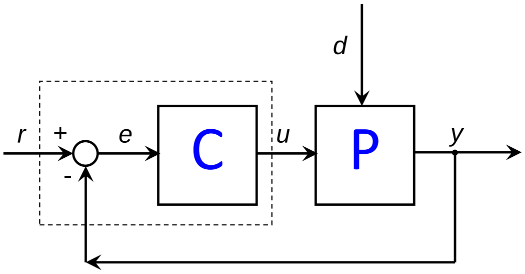

Figure 1. General structure of a control loop. "C" is the controller, and "P" is the process

In the case of advanced control methods, the same structure can be used in most cases, like the one shown in Figure 1, however, some generalizations have to be considered. Firstly, (i) the controller "C" does not necessarily input the $e = r - y$ variable, it may consider both r and y, separately – as indicated by the dash-dotted border of this extended controller. Secondly, (ii) all arrows in the a.m. figure can be considered as vector variables. It practically means that any variables can be constituted of several scalars on the following example

$$y = \begin{pmatrix} p_{\text{steam}} \\ T_{\text{water}} \\ h_{\text{water}} \end{pmatrix} \tag{9}$$

where p_{steam}, T_{water}, and h_{water} are the pressure, temperature, and level of steam / water in a steam generator, respectively.

The limitations of the traditional control were introduced above. Advanced control overperforms it in two senses outlined above, but there is also another important characteristic of it, namely, its capability for weighting between control accuracy and control aggressivity. The first term can be expressed by the control error (see $e = r - y$ in Figure 1), the second one by the derivative of the controller output u (as shown in the same figure). If the controller is a discrete-time one with a constant time-step, this aggressivity can also be characterized by the Δu change between two time steps. Based on these considerations, a simple form of a cost function can be formulated as follows

$$J = (r - y)^{\mathrm{T}} \, Q \, (r - y) + \Delta u^{\mathrm{T}} R \Delta u \tag{10}$$

the minimum of which has to be determined and applied by the controller.

4. Structural integrity as part of control optimization

Structural integrity (SI) became a crucial discipline throughout the last century, and its development also resulted in several calculation methods. Some of them are laid down in national or international standards (ASME_III, 2019; ASME_VIII, 2019; EN12952-3, 2011), while others can be considered as the advances of scientific researches (Lorenzo, 1994; Ray et al., 1994; Anderson, 2017). As visible, structural integrity became matured for being modeled similarly to other parts of a process, so, its outputs can also be included into any modeled (vector) variable like in the following example

$$y = \begin{pmatrix} p_{\text{steam}} \\ T_{\text{water}} \\ h_{\text{water}} \\ \dot{\delta} \end{pmatrix} \tag{11}$$

where $\dot{\delta}$ is the calculated damage rate. Accordingly, the entire above discussed optimization procedure with the cost function (10) can be carried out without any changes while considering the effect of all control actions also on structural integrity, that is, structural health of the equipment.

5. Conclusions and outlook

The problem discussed in this conference paper is a rather unusual one! No compromise must be namely made between economical and ecological interests, because the benefits of applying advanced control methods in power plants serve both in the same time. It is evident namely, that increasing the efficiency or decreasing the resource-consuming manner of operation (referring to any sorts of fuel, water, air, or even valuable components under decreased thermal stress) serves both of those goals in the same time.

The total number of industrial applications of advanced control techniques has increased rapidly worldwide, but the distribution of these applications among industry branches is considerably unequal. Chemical industry had more than 60% of the running applications of the most popular solution (Model Predictive Control, MPC) in one year, the share of similar applications in power plants at that time was definitely below 5%. Interesting is also the dynamic rate of increase of those applications in the chemical industry: their number has been doubled practically every five years since 1995.

Funding

The research reported in this paper and carried out at BME has been supported by the NRDI Fund (TKP2020 NC, Grant No. BME-NCS) based on the charter of bolster issued by the NRDI Office under the auspices of the Ministry for Innovation and Technology.

Acknowledgements

The kind help of Á. Horváth and J. S. Jánosy is gratefully acknowledged.

Author Contributions

Both authors have a reasonable track record on the two disciplines of the topic. Tamás Fekete has reasonable results on structural integrity, while Pal Szentannai has an outstanding theoretical and practical background on process control. The sections of this conference paper were written accordingly.

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