An optimization approach within supervisor architecture for boiler control

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***Abstract*— This paper presents an approach that uses a supervisor architecture structure with the intention to reach flexibility of the combustion process control during the boiler functioning on the example of the high qualified GETEC Heat & Power AG. For this case, adaptive distributed 3-layer boiler control system with the supervisor on top is invented, supported on the middle layer with load distribution on burners and maintenance of optimal fuel amount value. All layers are described in the paper, particular attention is paid to the optimization algorithm in the middle part. The approach determines how the efforts necessary if boarding conditions of the controller are changed could be reduced. This paper is in work-in-progress.**

***Keywords*— supervisory control, adaptability, flexibility, distributed system, optimization, boiler.**

I. INTRODUCTION

The ongoing global competition, intentions to retain monitoring of the product during the whole its production life-cycle [1] and to shorten product life cycles [2] lead to an increased demand at the European market for more effective methods of production. The research is being conducted in this direction, such as the Industrie 4.0 [3]. The initiative aims on flexible concepts and realize them in production, consistent integration of various data, provision services for control and ability of elements to communicate with each other is necessary [4,5]. While control quality improvement, concurrently many production plants remain to operate on previous architectures, so engineers still continue to work on legacy systems, giving us the possibility to provide horizontal integration during migration path. In the direction of system adaptability to process changes or flexibility of control research papers are published [6-14]. We present a distributed supervisory control architecture, where the middle layer provides combustion control based on load distribution between boilers and maintenance of optimal value during the control.

The boiler is taken to show the good example of control flexibility during dynamical functioning. Automatic control in coal boilers is obtained through simultaneous variations in the input rates of feed water, fuel doses, and air. The traditional technological algorithm (PID controllers) contains equally traditional circuit solutions in the parts for automation of the supply and air-gas operating mode of boilers. By reason of nonlinearity of combustion process the best boiler functioning is complicated to reach, also at present there are no universal circuit solutions for ensuring reliable and dynamic functioning of the controller, in either transient or stationary operation. In this case intellectual mathematic methods are used, such as fuzzy situation model for boiler modes. Inside our three layer control architecture (supervisor, adaptive controller and field control), mathematical adaptation of the controller model to different external information resources (material, environment or functioning conditions changes) was added to the controller as a new feature. The method will bring advantages because of its adaptability to operating conditions changes, for example efficiency increase and costs reduction (owing to the right usage of materials and no unwanted waste).

Motivation of the research work is to reach the highest effectiveness of boiler in functioning modes considering fuel type changes due to flexibility of controller settings within the supervisor architecture. This paper is organized as follows: In the next Section the boiler functioning will be described, weaknesses will be found, directions of improvement indicated. In the Section III and IV we introduce 3-layer architecture of the controller with load distribution control and optimal value determination, revealing the mathematical component of the controller.

II. PROBLEM STATEMENT

Many companies are experiencing an era of technological changes and the associated issues. We choose the technical process of fuel combustion due to the relevance of boiler control and its crucial value in power production. Modern mathematical achievements can help to resolve underlying difficulties associated with the expansion in capabilities of the boiler, for example in a case of fuel change. Hence we started cooperation with the GETEC Heat & Power AG, as interested in the development.

Fig.1 The boiler of the GETEC Heat & Power AG and sensors on the front part of the boiler.

The boiler works on the principle of cogeneration, and is operated with brown coal dust. The cogeneration plant diurnal has a steam output of 22 T/h, has maximum operating pressure of 21 Bar and a thermal output of 16.1 MW. This boiler type consists of two lines, each line is supported with fuel and air supplies, on the front side sensors are placed. Fig. 1 provides an overview of the boiler system and its components. Due to its importance, the power production control has been intensively studied in manufacturing systems [11-14], based on sensors activity [12]. To define the functioning mode of the boiler in GETEC Heat & Power AG ultraviolet sensors are used (Fig.1).

Generally, conditional monitoring is to apply appropriate sensors to reduce unnecessary waste of product [15]. The boiler control is significant but difficult to implement due to non-linear process, what is natural, through the flame inconsistency. That is why in the case of non-linearity artificial intelligence methods are used [15, 16]. Here is also reasonable to mention the optimization approaches [17, 18]. Those mathematical approaches together provide economical and convenient solution.

As it was mentioned, by the reason of nonlinearity of the combustion to control the technical process non-traditional methods should be used [15, 19], for example the help of experts in fuzzy logic control rules, or fuzzy situation model of reference modes of boiler functioning, where to each mode, there is a possibility to find the optimal value and to maintain it. Due to the possible fuel change the adaptability feature of the controller should be envisaged. In order to avoid fuel losses, continuously load redistribution, by observing depending fuel and air is scheduled. To carry all these operations, the supervisory control is needed, for example in the case of spontaneous re-adjustment of boiler work by the fuel type changes. We offer an approach that also has a right to exist; the new architecture of the controller uses old methods, such as service-oriented architecture (SOA) with its advantages [20], control optimization also by means of fuzzy logic, but new architecture solutions to reach more flexibility.

III. SUPERVISOR CONTROL ARCHITECTURE CONCEPT

Currently in production migration path from existing architectures and technologies to fully Industrie 4.0 compliant systems is required.

Through the fact, that many companies don't plan big spending a lot of money in the changes of architectures, in the paper the controller reorganization is proposed that does not require huge investment. It affects the software transformation, separating, each system element and enveloping it in the administrative shell [1] that converts a system element into an Industrie 4.0 component (each element whether sensors, actuators or controllers). Modular approach is used to design the architecture with SOA. It divides the system into a large number of independent but logically connected modules. The motive of modularization is to ensure extensibility of the software. In the approach controller architecture is divided into 3 independent levels, which could cooperate with each other (Fig.2).

1st layer of the architecture is the supervisor that could be easy presented as an independent element, realized on a base of genetic algorithm on special controller. 2nd layer components reflect the flexibility of the object in case of fuel changes or increased load. The second layer contains the software-technical representation of behavior and other interdependencies of the system. Thus it forms a collection of possible processing options. It calculates optimal parameter sets and implements the sequencing and control on lowest level.

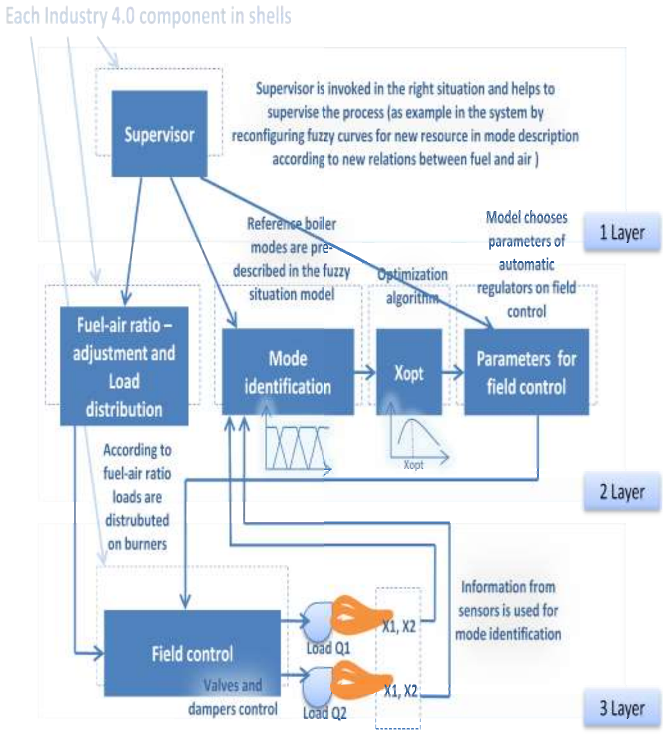

Fig.2 Supervisor control architecture

We use a low cost alternative to PLC based on Raspberry Pi computers and Logi.cad software for the architecture realization. The rendering of middle part of the controller is shown more detailed in the next chapter.

IV. OPTIMIZATION MODEL

On the second layer on Raspberry PI Structure of control algorithm is located. 2nd Layer contains the following blocks: model identification block that will allow based on assessments of the object state to make a conclusion if the operating mode belongs to one of the standard classes, which were earlier given by experts. Each of the reference classes is associated with the model that chooses parameters of automatic regulators (field control level) and the criterion [17] of optimality (a system of automatic optimization (SAO)).

As while constructing an optimal control system of complex objects [22], as well as the example with the boiler in GETEC Heat & Power AG, a number of difficulties, can occur, for example, lack of adequate mathematical description of the modes of an object. In the case of no possessing original mathematical model a variety of approaches can be used, for example, to use the expert's knowledge and build a model on the fuzzy logic base. The downside of this approach is the absence of adaptation to changes in the object (boiler) which can be offset by the complication of models by the addition of artificial intelligence above. Examples are neural network models, which require a long process of training before they join in the control loop or genetic algorithms [19]. The complexity of the formation of the initial state of the model based on the experience of object control forced us to apply the principle of multiple models and realize the hierarchical control system based on the decomposition of the space of object modes (reference modes could be starting, transient, stationary modes). Fuzzy situational models demonstrate the advantage in identifying previously unaccounted control situations. Adaptation, as it was mentioned in section 3, of both a fuzzy space of situations and a fuzzy controller (for parameters of field controller or for fuel-air ratio control on the burners) is possible with a help of genetic algorithm, which is located in the top layer of supervisory architecture, and, in the concept of Industrie 4.0, as long as shell encircling each element in the system, it can be seen and used from other elements in the system.

In the middle layer the load distribution model is also placed. The model is based on the information from the sensors X_1 and $X_{2\ \text{that}}$ is also used in the mode identification, and makes a decision about distribution of fuel and air to reach the best fuel-air value [21]. The well-known algorithm of Ivahnenko is taken as a basis, it is known for its use concerning not-fuzzy initial parameters. We suggest expanding the scope of the algorithm for fuzzy parameters, which allows obtaining a plurality of values of guaranteed solutions and the tolerance range. This largely meets the real situation [22].

By itself object control model, based on the experience of experts, without the block of adaptation enables operation of the plant in a trouble-free mode in the process of plant adaptation but doesn`t have optimal performance. SAO, during operation, finds and maintains optimal parameters for the functioning of the control object without an operator. The advantage of the SAO is the need for a minimum amount of prior information about the object. There are two types of SAO, with the searching model and no searching model, in case of lack of data for use SAO with the no searching model, there is no alternative for search strategies. Under the intelligent searching strategy a set of rules for executing the actions that aimed at finding an extremum of a characteristic and a set of conditions that form the sequence of operations (rules for the selection of actions) is understood. These strategies are called intelligent because they present themselves as not fixed algorithms but flexible algorithms with reconfigurable structure depending on of the current situation, based on the experience of operation of the object. In the process of extremum finding and tracking, a dynamic object model update is performed. With the accumulation of information, the search step decreases and the system convert into tracking mode. In this mode, to obtain information about the object natural disturbances influencing on the object can also be used. Considering the model of adaptive search with a local identification of the object model, let the object has a characteristic $y = f(x, \lambda) + \varphi$, where x - parameter to be optimized, λ - modal parameter or basic disturbance, φ - uncontrolled disturbance [22]. Let us suppose that in the certain area of modes space our characteristic can be approximated by a polynomial of the following form:

$$y = a_1 + a_2x + a_3\lambda + a_4x^2 + a_5\lambda^2 + a_6x\lambda \tag{1.1}$$

The coefficients $a_1 ... a_6$ may be determined by the results of pilot testing of the object by the method of least squares by compiling and solving the system of normal Gaussian equations. We denote the variables $\xi_1 = 1$, $\xi_2 = x$, $\xi_4 = x^2$, $\xi_5 = \lambda^2, \xi_6 = x\lambda$. At time $k = 1..N$ values x^k, λ^k are obtained and value of quality index y_{1k} is measured, $i = 1..6$. The system of normal equations relatively unknown coefficients of the model can be written as

$$HA^T = Y \tag{1.2}$$

where

$$A = \|a_1, a_2, .. a_6\|^T, H = \|h_{ij}\|, \quad Y = \|g_i\|, i, j = 1..6 \tag{1.3}$$

$$h_{ij} = \frac{1}{N}\sum_{k=1}^{N} \xi_i^k \, \xi_j^k, g_i = \frac{1}{N}\sum_{k=1}^{N} y_i^k \, \xi_i^k$$

Matrix (1.3) are computed sequentially, as they become available each new search. By a solution of the system of normal equations the vector of unknown coefficients is determined $A^T = H^{-1}Y$. Accuracy of coefficients assessment is determined by the covariance matrix

$$R = \|r_{ij}\| = \frac{1}{N}\sigma_y^2 H^{-1}, i, j = 1..6 \tag{1.4}$$

A posteriori dispersion σ_y^2 may be determined according to the formula (1.5), also allowing performing calculations consistently.

$$\sigma_y^2 = \frac{N}{N-6}\left(\sum_{i=1}^{6}\sum_{j=1}^{6} a_i a_j h_{ij} — 2\sum_{i=1}^{6} a_i g_i + + \frac{1}{N}\sum_{k=1}^{N} y^2\right) \tag{1.5}$$

The principle of adaptive research is as follows. On the object are made tentative steps, the results of which are used to identify the model (1.1). According to the results of pilot tests, operational steps to access the neighborhood of the extreme value of the parameter x can be performed. Along with the pilot test area, the possible position of extreme is estimated. For the model (1.1) position of the extremum is defined by characteristic $x(\lambda)$, which determined from the condition (1.6).

$$\frac{\partial y}{\partial x} = a_2 + 2a_4x + a_6\lambda = 0 \rightarrow \ x = -\frac{a_2 + a_6\lambda}{2a_4}. \tag{1.6}$$

Relation (1.6) is only true in the area $\widetilde{D}_v$, in which approximation (1.1) is valid. Determining the interval estimations of coefficients $\tilde{a}_i$ of (1.4), as the corresponding confidence intervals, we obtain the relation

$$\tilde{x}(\lambda) = -\frac{\tilde{a}_2 + \tilde{a}_6\lambda}{2\tilde{a}_4}. \tag{1.7}$$

Then we localize extremum, which will be in the area $\tilde{x}(\lambda)$. The purpose of the adaptation is to reduce the interval of uncertainty $\tilde{x}(\lambda)$. While searching limitations are defined as the intersection $\tilde{x}(\lambda) \cap C(\lambda)$. Selection of parameters of search algorithm is associated with the uncertainty of the model (1.1). The intersection $\tilde{x}(\lambda) \cap C(\lambda)$ will be the search interval for the model. With a wide range of the possible interval the tentative steps must be large enough; work steps are chosen smaller next to the extremum, so the system couldn`t come out from the neighborhood of the extremum. Since the areas $\widetilde{D}_v$ are fuzzy defined and can be intersected, in the work process the regression model, corresponding to the current situation with a degree of $\mu_v = \mu_{\tilde{D}_v(\lambda)}$, are selected. In this case, the following relation for the coefficients of the system of normal equations is used:

$$h_{ij}^{v} = \frac{1}{M}\sum_{k=1}^{N} \xi_i^k \xi_j^k \mu_{\tilde{D}_v(\lambda_k)}, g_i^v = \frac{1}{M}\sum_{k=1}^{N} y_i^k \xi_i^k \mu_{\tilde{D}_v(\lambda_k)},$$

$$M = \sum_{k=1}^{N} \mu_{\tilde{D}_v(\lambda_k)} \qquad (1.8)$$

Dispersion is defined as

$$\sigma_y^2 = \sum_{i=1}^{6} \sum_{j=1}^{6} a_i^v a_j^v h_{ij}^v — 2 \sum_{i=1}^{6} a_i^v g_i^v + + \frac{1}{M} \sum_{k=1}^{N} y^2 \qquad (1.9)$$

Area of extremum localization is defined as a fuzzy set $\tilde{x}(\lambda)$ with membership function $\mu_{\tilde{x}}(\lambda) = \vee_{v=1}^{s} (\mu_{\tilde{D}_v(\lambda)} \wedge \mu_{\tilde{x}_v(\mu)})$. The decision about transition into the neighborhood of extremum after the formation of model is carried out some external to the model decision-making procedures. Model (1.1) - (1.9) has been implemented (Fig.3). Results of research model developed adaptive search on a computer in the annex to object showed that the proposed approach is efficient, provides a convergence to the optimal solution under conditions of noise measurements. For efficient operation model is desirable that tentative steps should be made irregularly (randomly) and should have a different amplitude. The study considered the possibility of the model as part of an adaptive fuzzy SAO with automatic correction of the test steps and it is found that the model allows us to obtain satisfactory results, and convergence in terms of committing tentative steps in the immediate vicinity/neighborhood of extremum. Assessment of extremum is shown on Fig 3. The extremum searching model is proved in MATLAB R2015a with different characteristics, including noise influences, as we can see here the convergence of the confidence interval [x_b; x_a] is visible with the different optimum values in 1.08, 0.05, for different running models.

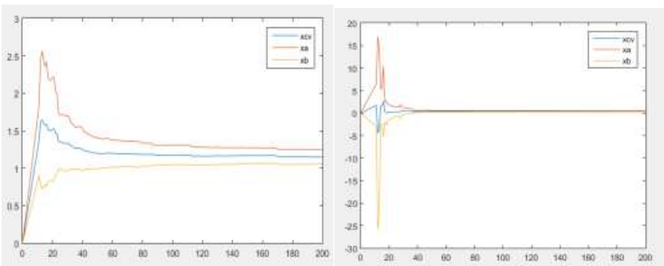

Fig.3 Convergence of the confidence interval for different models

As this paper is still in progress, future work will be done, starting from the partial implementation of supervisor architecture on the real boiler in GETEC Heat & Power AG.

V. CONCLUSIONS

Advanced flexible production systems as envisioned in the Industrie 4.0 initiative are a key stone for economic success of European industries. But they will only be successful, if they can be implemented on the basis of existing architectures and technologies for production system control. The possible way of implementation of new control strategies and strategies by themselves was described. The representation of middle level shows, how the life-cycle of the production can operate continuously with external interference, carrying flexibility by means of horizontal integration. The combustion process is constantly optimized by the criterion of efficiency under different modes of operation. Among the advantages of the model the avoidance of reprogramming if boarding conditions of the controller are changed and the use of not pre-given data about the processes can be named.

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