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## **WATER LEVEL CONTROL SYSTEM FOR A BOILER DRUM OF A POWER BOILER RESISTANT TO MEASURING TRACK DAMAGE**

### **Key words**

Control system, fault tolerance, redundancy, boiler, power unit, boiler drum.

### **Abstract**

Design and operation methods of automated systems that tolerate measurement track damage are presented. This type of structure for feed water control systems in the drum boilers is described. The study presents a concept of an FTC (Fault Tolerant Control) system in the regulation system of the water level inside a drum. The creation and examination of partial models for the diagnostic system are described. Analytical redundancy has been applied in the presented regulation system. The effects of diagnostics and fault tolerance on the values of reliability and power block operational safety indexes have been determined in the study. Moreover, regulation systems in use are described and backup structures have been developed in order to create a regulation system that would be resistant to fault of the measurement tracks.

### **Introduction**

From the automation point of view, power drums are very complicated to control, and difficult to analyse and model [10]. In the entire power unit, there

are several dozen regulation algorithms, including the system regulating water feed to the boiler [3, 6].

The system that regulates the supply is designed to maintain balance between the water flow that reaches the boiler and the stream of steam passing through the turbine. The measurement of this balance is the level of water inside the drum [6]. If the deviation from this balance is too large, an emergency cut-off of the entire power unit will proceed [3].

In comparison to traditional diagnostics systems, Fault Tolerant Control systems are relatively novel solutions and a systematic development of those systems may be observed [1, 2, 4, 5, 7, 8].

When designing an FTC system, what should primarily be taken into consideration is the fault tolerance of the actuators and measurement devices as they are the most unreliable in a regulation system. Thanks to the FTC systems, in case of fault, the automation system adjusts its structure in order to mitigate the effects of the fault [2, 8].

The favourable effect of diagnostics performed in real time as well as the systems that tolerate faults on the reliability and safety of the system may be proven by analysing the indicators referring to these properties [9]. Figure 1 illustrates the course of the state of usability and the nonusability of the system, marking characteristic times:  $T_\lambda$  – average time to fault,  $T_\mu$  – average time of repair, which is the average time from the moment of fault occurrence to the time of the repair of the faulty device,  $T_D$  – average time between faults, average diagnostics times,  $T_N$  – average time of renewal.

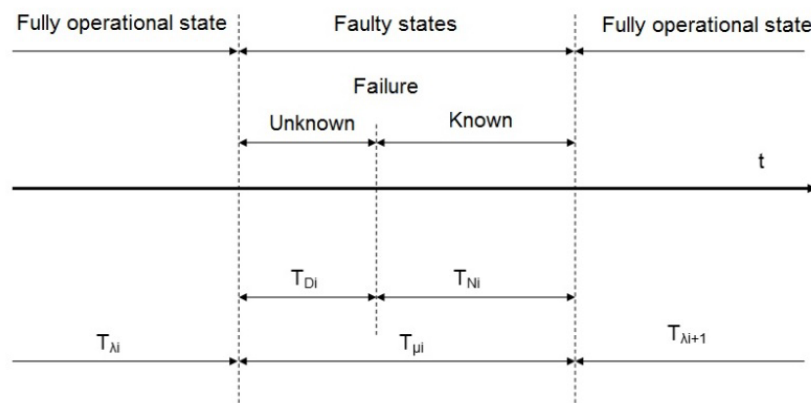


Fig. 1. Definition of the fully operational system state and the faulty system states [9]

The reduction of the diagnostic times has an effect on the reduction of  $T_\mu$ . In practice, the diagnostic time is close to zero:  $T_D \approx 0$ . In case of faults that are tolerated by the regulation system, however, the time of the automatically performed reconfiguration will be reduced to a minimum,  $T_N \rightarrow 0$ .

FTC systems have not become widely used in the power industry; however, there are works undertaken in the area of diagnostics and work safety of wind turbines.

The studies of water level regulation systems inside a drum with the use of an FTC system for measurement tracks presented in this article are original and constitute a new solution for this type of systems.

### 1. The water level control system in the drum

The drum is one of the most important technological elements of a power boiler. Every drum power boiler is equipped with a set of technological protective measures. The drum has a water gauge and a diagnostic system that initializes the disconnection of the boiler in case the level rises too high or falls too low. As this is a device that is subjected to high pressure, the protection systems must be approved by the Office of Technical Inspection. The point at which the protective measures are set into motion must be consistent with the indications of the water gauge. A binary signal sent by the water level meter is usually connected to the system of protections. It may have a correction for the temperature and pressure inside the drum or it may be without it.

Apart from the system of protections, the boiler has a water level regulation system inside the drum [3]. The system shown on Fig. 2, which is a 3-impulse system, was subjected to further analysis.

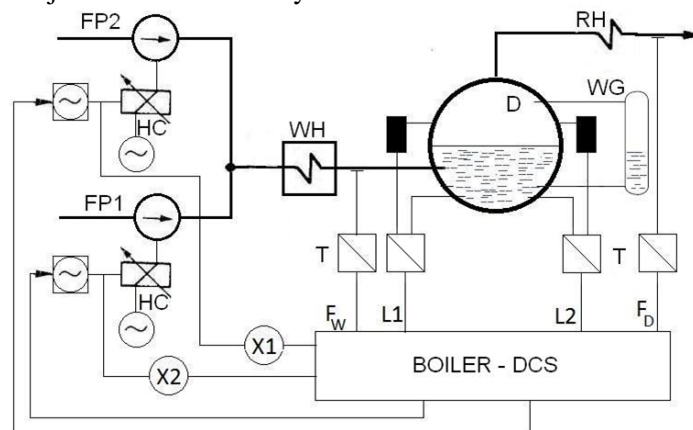


Fig. 2. Scheme of the water level control system in a steam drum (FP1, FP2 – feed water pumps, L1, L2 – water level in the boiler drum, HC – hydrodynamic clutch, T – transducers, WH – water heater, RH – steam superheater, D – boiler drum, WG – water gauge glass, X1, X2 controls signals,  $F_w$  – water flow,  $F_D$  – steam flow)

In the regulation system shown on Fig. 2, we may distinguish two water measurement systems (L1 and L2) where differential pressure transducers are used. The water flow supplied to the boiler ( $F_w$ ) and the steam supplied to the turbine ( $F_D$ ) serve as additional correction signals for the regulation system. The

water feed to the boiler is connected by means of two boiler feed water pumps (FP1 and FP2). Each of the two pumps can provide 100% of water demand so only one of them is started during regular operation and the other one serves as a backup. During the boiler's operation, with nominal steam parameters, the water feed separation is executed by the change in the pump's rotational speed. The changes in the rotational speed are made with the use of hydrodynamic clutches. The signals from the position of the relevant main engine that controls the clutch are delivered to the regulation system.

As a complement for the above described regulation system, a concept of an active FTC system [4, 7] whose function will be to detect faults of the parametric measurement tracks shall be presented. Inaccurate readings of the measurement values in the level regulation system may cause unnecessary disconnection of the power boiler by the technological lock system. Since we are analysing a double measurement system that uses differential pressure transducers, the diagnostic system must detect which measurement is faulty and switch the control system to a correct measurement. The measurement of the level inside the drum in the differential circuit may be false due to, for example, a leak on the joints or a blockage (mineral salts sedimentation) of the signal pipes.

The scopes of the differential pressure transducers are small. The measurements of about 10 cm are only approximately 1 kPa, so each leak in the signal pipe may cause a significant error in the measurement. When two measurements are used, we have a "1 of 2" alternative and the diagnostic system should automatically determine which of them is faulty.

An active FTC system should be divided into three principal procedures: fault detection, fault isolation, and the mechanism of the regulation system reconfiguration. Each procedure should be carried out as a separate task in the diagnostic algorithm of the regulation system.

## 2. Fault detection

Partial models of the process functioning as virtual sensors are used in order to detect faults. In this way, an analytical redundancy was obtained, which allowed the detection of measurement tracks faults. The principal objective of the fault detection algorithm is to be able to detect all foreseeable damage. This translates into the need for designing a set of diagnostic signals that would be sensitive to all kinds of damage. In the case of the supply system regulation, three partial models of the process have been created and they reproduced the following values: water level inside the drum, the flow of the water feed, and steam flow into the turbine, according to the following formulas (1), (2), and (3).

$$\widehat{L1} = f_1(F_w, F_D) \quad (1)$$

$$\widehat{L2} = f_2(F_w, F_D) \quad (2)$$

$$\hat{F}_w = f_3(X) \quad (3)$$

where: L1, L2 – the water level in the drum [mm],  
 $F_w$  – mass flow rate of water flow [t / h],  
 $F_D$  – steam mass flow [t/h],  
 $X$  – servo control signal [%], (X1 and X2).

Models (1) and (2) are structurally identical, and the only difference between them is the transducer that is being checked, L1 or L2. The level model ( $L = L1$  or  $L2$ ) was obtained with the use of the Strejc method.

The dynamics of changes in the level of a mixture of steam and water in the drum can be described as the transmittance by the following formulas (4):

$$\begin{aligned} \Delta L(s) &= G_w(s) \cdot \Delta F_w(s) + G_D(s) \cdot \Delta F_D(s) \\ &= \frac{1}{(1 + Ts)^n} \cdot \frac{k}{s} \cdot \Delta F_w(s) - \frac{1 - as}{(1 + Ts)^n} \cdot \frac{k}{s} \cdot \Delta F_D(s) \\ &= \left[ \frac{1}{(1 + T_1 s)^{n_1}} \cdot \Delta F_w(s) - \frac{1 - as}{(1 + T_2 s)^{n_2}} \cdot \Delta F_D(s) \right] \cdot \frac{k}{s} \end{aligned} \quad (4)$$

where:  $\Delta L$  – change of the level of a mixture of steam and water in the drum,  
 $\Delta F_w$  – change of the mass flow of feed water,  
 $\Delta F_D$  – change of steam flow,  
 $T1, T2$  – constant inertia,  
 $n1, n2$  – range of inertia,  
 $k$  – gain,  
 $a$  – constant differentiation.

The value of the steam flow into the turbine has been established and the response to the increased water supply has been verified. For the nominal operational conditions of unit of 125 MW, the following transmutational model has been obtained (5):

$$G_w(s) = \frac{L'(s)}{F_w(s)} = \frac{0,015}{(1 + 9,68s)^6} e^{-5s} \quad (5)$$

where:  $L'(s)$  – Laplace transform of the derivative of the water level in the drum [mm],  
 $F_w(s)$  – Laplace transform mass flow of water to the boiler [t/h].

The second step in reproducing the complete model of the level inside the drum was to identify the level derivative depending on the steam flow into the

turbine. The best model obtained was the second order model with the delay of 3 s. The model has been approximated to the continuous model of order 3 and then decomposed using simple fractions to the sum of the first order inertia and the oscillating object. Finally, the following has been obtained (6):

$$G_D(s) = \frac{L'(s)}{F_D(s)} = \left( \frac{0,252}{1+21s} + \frac{0,237+2,16s}{1+22,5s+192s^2} \right) e^{-3s} \quad (6)$$

where:  $L'(s)$  – Laplace transform of the derivative of the water level in the drum [mm],

$F_D(s)$  – Laplace transform of the mass flow of steam to the turbine [t/h].

The final step in reproducing the water level was to add the exits of the obtained models of the level derivatives and subject those signals to integration.

The residuum value is determined as the absolute value of the difference between the modelling value and real value level for the measurements. An example of the residuum determined from the model (1) is shown in Fig. 3.

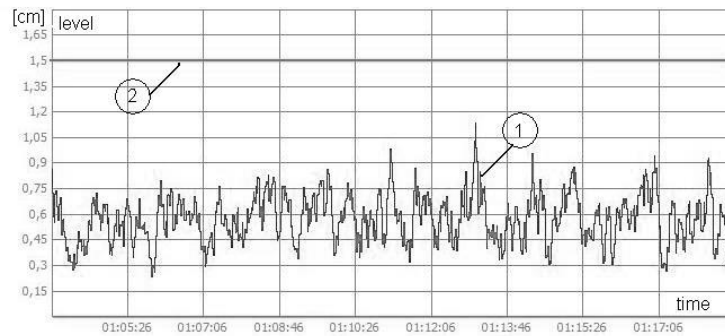


Fig. 3. Residuum r1 for model (1) (1 – residuum, 2 – detection limit)

Then, it is necessary to create a third model in order to obtain the detectability of the feedback signals  $X_1$  and  $X_2$  as well as the differentiability of faults. This is why another model of the feed water flow into the boiler has been identified.

A model of the water flowing through the pump that dependent on the control signal has been created (7). The best results for the pump identification were obtained with the model with continuous time of the order 2 that was manually adjusted in order to better reproduce the course of the flow. The following model has been obtained:

$$G_P(s) = \frac{F_w(s)}{X(s)} = \left( \frac{5-1,72s}{1+6,06s+11s^2} \right) e^{-1s} \quad (7)$$

where:  $F_w$  – Laplace transform mass flow of water to the boiler [t/h],

$X$  – Laplace transform pump control signal [%].

The resulting models define the residues used for the fault detection of measuring circuits (Tab. 1).

Table 1. Summary residuals

Residuums	Equations
$r_1$	$r_1 =  L1 - \widehat{L1}  =  L1 - f_1(F_w, F_D) $
$r_2$	$r_2 =  L2 - \widehat{L2}  =  L2 - f_2(F_w, F_D) $
$r_3$	$r_3 =  F_w - \widehat{F_w}  =  F_w - f_3(X) $
$r_4$	$r_4 =  L1 - L2 $

Due to the increase of discernible faults, extra residuum ( $r_4$ ) was added to the system to compare the levels of redundant measurements.

### 3. Fault isolation

A binary diagnostic matrix was used for the algorithm of the fault isolation [1]. After the performed analysis, a binary diagnostic matrix [1] that illustrates the relation between the measurement tracks fault and designed diagnostic signals was determined (Table 2).

The set of diagnostic signals  $S = \{s_j; j = 1, 2, \dots, J\}$  is determined based on the analysis of the residues set  $\{r_1, r_2, r_3, r_4\}$ . A threshold value analysis residuum was adopted here. Faults are defined as follows:  $f_1$  – fault measurement  $L1$ ,  $f_2$  – fault measurement  $L2$ ,  $f_3$  – fault measurement  $F_w$ ,  $f_4$  – fault measurement  $F_D$ ,  $f_5$  – fault measurement  $X$ .

Table 2. Binary matrix Diagnostic

	$f_1$	$f_2$	$f_3$	$f_4$	$f_5$
$s_1$	1	0	1	1	0
$s_2$	0	1	1	1	0
$s_3$	0	0	1	0	1
$s_4$	1	1	0	0	0

The value of signal  $X$  comes from the main engine control of the currently working pump. The system must be programmed in order to identify this pump.

The location is based on inferences based on zeros and ones in the diagnostic matrix. This means that a fault is determined at the moment when the values of diagnostic signals correspond to its signature. Fault signature is determined by the column of the diagnostic matrix.

This form of binary diagnostic matrix also provides the ability to detect multiple failures [1], e.g., simultaneous measurement of faults to the  $L1$  and  $L2$

is distinguishable from damage  $F_w$ ,  $F_D$ ,  $X$  in the system automation (DCS / SCADA), and such a state should be included in the alarms.

#### 4. Reconfiguration control system

The final step of the design of the regulation system resistant to faults of the measurement tracks is to determine backup structures to which the regulation system should be switched on or off after a fault is identified.

When designing a regulation system resistant to the faults of the measurement tracks, a set of possible states of system operation should be determined, in case any of the following faults should occur.

Table 3 illustrates the description of the possibilities of introducing a change in the operation mode of the system in case a fault occurs in any of the measurement tracks.

Table 3. Reconfiguration control system in the states of fault measuring tracks

Measurement tracks	Reconfiguration
Level (L1)	Switch to track measuring reserve (L2)
Level (L2)	Switch to track measuring reserve (L1)
Flow of water ( $F_w$ )	Switching system to 2-pulse system or analytical redundancy by formula (3)
Flow of steam ( $F_D$ )	Switching to 1-pulse system
Signal (X1) from pump 1	Use scaled variable equivalent ( $F_w$ )
Signal (X2) from pump 2	Use scaled variable equivalent ( $F_w$ )

The regulation system uses water and steam flow measurements. In situations when the measurements are wrong, they should not be considered for the water level regulation inside the drum. Two possibilities of tolerance for those faults have been considered: switching the measurement to the virtual measurement and the change of regulation system structure. The use of the flow models is possible after obtaining a sufficiently exact model, and works on the use of a model of the neural network diffused structure have been undertaken, as in the study [8]. In the examined regulation system, the second option was selected. It may result in lower regulation quality indicators, especially with large differences in steam flow to the turbine; however, this method guarantees safe operation of the regulation system.

#### Conclusion

The article presents only a part of studies on the construction of the water level control in a power plant boiler system with fault-tolerant measurement channels. It presented the concept of the system and presented models for diagnostic purposes. The procedures used in the designed system FTC are also



described. Based on the presented concept, we made many trials and tests on real objects. The tests confirmed the effectiveness of the algorithm fault detection and fault isolation.

The reconstructed models of water levels and flows get the job done. In the state of an object without fault, we avoided erroneous diagnoses, and the values of all the residues were below the threshold of detection. Further development work will rely on the adaptation of the models based on artificial intelligence systems: neural networks and fuzzy logic systems. For example, systems and fuzzy logic can be used to analyse the residuals.

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### **Układ regulacji poziomu wody w walczaku kotła energetycznego odporny na uszkodzenia torów pomiarowych**

#### **Słowa kluczowe**

Diagnostyka, układ regulacji, tolerowanie uszkodzeń, redundancja, rekonfiguracja, kocioł parowy, blok energetyczny, regulacja poziomu, walczak.

#### **Streszczenie**

Przedstawiono sposób projektowania i działania układów automatyki tolerujących uszkodzenia torów pomiarowych. Opisano układ tego typu dla systemu regulacji zasilania w wodę kotła walczakowego. Praca przedstawia koncepcję systemu FTC (*Fault Tolerant Control*) w układzie regulacji poziomu wody w walczaku. Opisano sposób tworzenia i badań modeli cząstkowych dla systemu diagnostycznego. W opisywanym układzie regulacji zastosowano redundancję analityczną. W pracy określono wpływ diagnostyki i tolerowania uszkodzeń na wartości wskaźników niezawodności i bezpieczeństwa pracy bloku energetycznego. Opisano także stosowane układy regulacji i opracowano struktury rezerwowe, aby powstał układ regulacji odporny na uszkodzenia torów pomiarowych.