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Control reconfiguration of a boiler-turbine unit after actuator faults occurrence

A. Kazemi*, M. B. Menhaj, M. Karrari, A. Daneshnia

Department of Electrical Engineering, Amirkabir University of Technology, Tehran, Iran

ABSTRACT: Boiler-turbines are one of the most important parts in power generation plants. The safety problem in such systems has always been a special concern. This paper discusses the application of control reconfig uration by fault-hiding approach for a boiler-turbine unit. In Fault-hiding approach, after occurrence of a fault, nominal controller of the system remains unchanged; instead, a reconfiguration block is designed and placed between nominal controller and faulty plant to modify input signals. Three major faults are assumed to occur in three actuators of the system consisting of fuel flow valve, steam control valve and water flow valve. Faults cause the outputs of the plant to deviate from desired values and in some cases cause instability in the system. Setpoint tracking recovery and optimal performance recovery problems to diminish effects of the faults are investigated. The results of simulations show that the reconfiguration has been successful in both cases and also confirm the applicability of the method for the boiler-turbine unit since the reconfigured closed-loop system has had tolerable properties against faults.

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1- Introduction

In large industrial systems, every component has been designed to accomplish a certain function and the overall system works satisfactorily only if all components provide the usual service they are designed for. The Fault tolerant control (FTC) aims to prevent damage in overall system when a fault occurs in one component. FTC methods is considered in two general approaches: active control and passive control. In active approaches, when a fault occurs after detection, isolation and maybe identification of the fault, proper control law is designed and applied immediately to the faulty plant, but in passive control a fixed fault-tolerant closed-loop structure is already designed for the system such that it'll be able to tolerate some restricted classes of the faults. Control reconfiguration is an active FTC method that has been presented comprehensively in [1] and [2]. In this method, after detection and isolation of the faults (called "fault diagnosis"), the control law is immediately modified by a new structured controller for the faulty system.

A number of control reconfiguration approaches such as closed-loop eigenstructure assignment [3], model predictive control [4], controller redesign by pseudo-inverse method [5], optimal linear control (LQR) for control reconfiguration [6], the generalized plant transfer function using control [7], and fault-hiding approach in [1], [2] and [8] have been studied. Designing a FTC scheme for industrial processes has been carried out in several works. Control reconfiguration by means of virtual actuator for a thermofluid process was studied in [9]. In this experimental work, some actuator faults are applied to the real process and fault tolerability is investigated in real experiments. Experimental fault-tolerant control of a PMSM drive in [8] is an experimental verification of remedial strategies against failures occurring in inverter power devices of a permanent-magnet synchronous motor drive. A novel simultaneous fault detection and diagnostics (FDD) and fault tolerant control (FTC) strategy for nonlinear stochastic systems in closed-loops based on a continuously stirred tank reactor (CSTR) is described in [10]. The general fault tolerant control method in [11] addresses the actuator and sensor faults with the proposed fault estimation and compensation method based on LQR. Robust adaptive control for attitude tracking of spacecraft with unknown dead-zone has been presented in [12]. This paper examines the attitude tracking problem with unknown actuator dead-zone nonlinearity and proposes a robust adaptive controller with parameter update laws. FTC for boilers and turbines has been studied in the following six main works: 1) An adaptive robust sliding mode controller (SMC) has been proposed in [13] to overcome the faults in heat recovery steam generator boilers (HRSG boilers) as one of the main parts of combined cycle plant, 2) A fault tolerant model predictive control (FTMPC) has been developed to accommodate the fault in the fuel bed height sensor in a BioGrate boiler by the active controller reconfiguration in [14], 3) Reconfiguration of the air control system of a bark boiler has been studied in [15]. In this paper, the air control system of a bark boiler is considered as an interconnected multivariable system and the configuration of the controllers is adapted with the perspective of improving the closed-loop performance of the system. 4) In article [16], a fault-tolerant control scheme based on stable adaptive fuzzy/neural control for a turbine engine has been designed, where its online learning capabilities are used to capture the

Corresponding author, E-mail: Kazemi_ali@aut.ac.ir

unknown dynamics caused by faults, 5) paper [17] addresses the design and comparison of active and passive fault-tolerant linear parameter-varying (LPV) controllers for wind turbines, and 6) Robust fuzzy fault-tolerant control of wind energy conversion systems subject to sensor faults has been presented in [18]. In this work, a multi-observer switching control strategy for robust active fault tolerant fuzzy control (RAFTFC) of variable–speed wind energy conversion systems (WECS) in presence of sensor faults is proposed.

In this paper, control reconfiguration by fault-hiding approach is used to minimize harmful effects of actuator faults in a boiler-turbine unit. It is assumed that, diagnosis task has already been solved and the faulty actuator has been detected properly. The main advantage of fault-hiding approach over the other reconfiguration methods is that the nominal controller of the system remains unchanged; therefore, all of the pre-designed important features of the main controller are still available in closed-loop system after reconfiguration. Furthermore, the type of controller is not important for designing the reconfiguration structure in fault-hiding idea, so the solution can be obtained with all kinds of controllers. In this work, the state space equations of the reconfiguration solution is developed in consistent with the boiler-turbine dynamical equations. Also, we investigate stability recovery and performance recovery of the system as the main FTC problems after occurrence of a fault.

The paper is organized as follows: In section II boiler-turbine unit model, nominal controller and actuator faults modelling are introduced. In section III fault-hiding approach and its structure are discussed and a new reconfiguration block is presented. Also, in this section solutions of stability and performance recovery are proposed. In section IV Application of the proposed block on boiler-turbine unit and simulation results are presented. Finally, conclusion notes are in section V. The present paper, has been presented first in 4th International Conference on Control, Instrumentation, and Automation (ICCIA), 2016 and this paper is the extended version [19].

2- Boiler-turbine Model Description

In this paper, boiler-turbine model of Bell and Astrom is considered as a practical case that has been used in many of the previous works. Parameters of this model were estimated from experiments on the Synvendska Kraft AB plant in Malmo [20]. Bell and Astrom improved this model during the years 1971 to 1987 to obtain the most accurate equations of the real model. Schematic picture of the boiler turbine unit is shown in Fig. 1. Three valves of the system are used to control fuel flow, steam flow and water flow for the system. Drum boiler in the unit receives oil and water from fuel and feed-water valves; the water is heated in the boiler and the resulted steam leads into the turbine to produce electricity. There is also a control valve that determines the steam flow rate to the turbine. Each valve of the plant can confront some actuator faults while its operation and any small disorder in these valves can cause intense instability in the system.

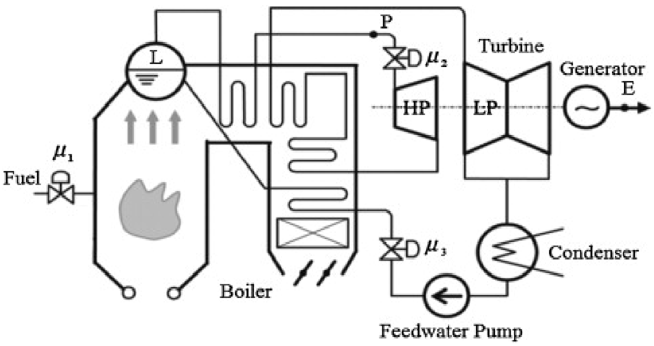

Fig. 1. Schematic of boiler-turbine unit [21]

2- 1- Bell and Astrom model of boiler-turbine unit

The boiler turbine dynamics of Bell and Astrom model is given by the following equations [20]:

$$\begin{cases} \dfrac{dP}{dt} = -0.0018u_2P^{\frac{9}{8}} + 0.9u_1 - 0.15u_3 \\ \dfrac{dP_o}{dt} = (0.073u_2 - .016)P^{\frac{9}{8}} - 0.1P_o \\ \dfrac{d\rho_f}{dt} = \left(141u_3 - (1.1u_2 - 0.19)P\right)/85 \\ y_1 = P \\ y_2 = P_o \\ y_3 = 0.5(.13073P + 100a_{cs} + q_e/9 - 67.975) \\ a_{cs} = \dfrac{(1 - 0.00153\rho_f)(0.8P - 25.6)}{\rho_f(1.0394 - .0012304P)} \\ q_e = (0.854u_2 - 0.147)P + 45.59u_1 - 2.514u_3 - 2.096 \end{cases} \tag{1}$$

where the state variable () denote drum pressure (kg/cm^2), turbine electric output (MW) and fluid density (kg/m^3), respectively. Input variables () denote the valves position of fuel flow, steam control and feed-water flow, respectively. The output is drum water level (m) and and denote steam quality and evaporation rate (kg/s). Due to actuator limitations, Control inputs of the system have the following constraints on magnitude and rate:

$$\begin{aligned} &0 \le u_i \le 1, \quad i = 1,2,3 \\ &-0.007 \le \dot{u}_1 \le 0.007, \\ &-2 \le \dot{u}_2 \le 0.02, \\ &-0.05 \le \dot{u}_3 \le 0.05 \end{aligned} \tag{2}$$

2- 2- State space linearization of boiler-turbine

Some typical operation points of Bell-Astrom model are shown in Table I. Linearization around half-load operation point (#4 in Table I) leads to the following state space equations:

$$\begin{cases} \dot{x}(t) = Ax(t) + Bu(t) \\ y(t) = Cx(t) + Du(t) \end{cases} \tag{3}$$

Where

$$A=\begin{pmatrix} -0.0025 & 0 & 0 \\ 0.0694 & -0.1 & 0 \\ -0.0067 & 0 & 0 \end{pmatrix}, B=\begin{pmatrix} -0.9 & -0.349 & -0.15 \\ 0 & 14.155 & 0 \\ 0 & -1.398 & 1.659 \end{pmatrix},$$
$$C=\begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0.0063 & 0 & 0.0047 \end{pmatrix}, D=\begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0.253 & 0.512 & -0.014 \end{pmatrix} \quad (4)$$

2- 3- Boiler-turbine nominal controller

Robust controller for the Bell-Astrom model of boiler-turbine has been presented in [22]. In this paper, a controller based on loop shaping method for tracking setpoints and robustness against disturbances and modelling errors has been designed.

Table 1. Typical operation points of the boiler turbine unit by Bell-Astrom [20]

	# 1	# 2	# 3	# 4	# 5	# 6	# 7
x_1^0	75.6	86.4	97.2	108	118.8	129.6	140.4
x_2^0	15.27	36.65	50.52	66.65	85.06	105.8	128.9
x_3^0	299.6	342.4	385.2	428	470.8	513.6	556.4
u_1^0	0.156	0.209	0.271	0.34	0.418	0.505	0.6
u_2^0	0.483	0.552	0.621	0.69	0.759	0.828	0.897
u_3^0	0.183	0.256	0.34	0.433	0.543	0.663	0.793
y_3^0	−0.97	−0.65	−0.32	0	0.32	0.64	0.98

The simplified form of this controller is in following multivariable PI controller:

$$K(s)=\begin{pmatrix} 0.0736+\frac{0.0034}{s} & 0 & 0.9338+\frac{0.0282}{s} \\ 0 & 0.0331+\frac{0.0121}{s} & 0 \\ 0 & 0 & 5.6035+\frac{0.1694}{s} \end{pmatrix} \quad (5)$$

Simulation results in [22] show that the designed controller has good tracking properties and acceptable disturbance rejection at both input and output channels. Fig. 2 shows the behavior of boiler-turbine outputs for a setpoint tracking in presence of the introduced controller in closed-loop form.

2- 4- Actuator faults modelling in boiler-turbine

Almost all kinds of actuator faults are modelled by changing input matrix B to the faulty matrix B_f in state space equations. Degradation of actuator can be modelled by scaling the corresponding input matrix column by factor , and failure of the actuator is modelled by setting the respective column to zero. Since the boiler-turbine model in (1) has three actuators, the following fault cases are investigated in the sequel:

1. Fault f_1 (fuel flow valve):
$$B_{f_1}=(\alpha_1 b_1 \quad b_2 \quad b_3),\ \alpha_1\in[0,1]$$
2. Fault f_2 (steam control valve):
$$B_{f_2}=(b_1 \quad \alpha_2 b_2 \quad b_3),\ \alpha_2\in[0,1]$$
3. Fault f_3 (feed-water flow valve):
$$B_{f_3}=(b_1 \quad b_2 \quad \alpha_3 b_3),\ \alpha_3\in[0,1]$$
4. Fault f_4 (degradation in all valves)
$$B_{f_4}=(\beta_1 b_1 \quad \beta_2 b_2 \quad \beta_3 b_3),\ \beta_{1,2,3}\in[0,1]$$

In order to include all kinds of boiler-turbine actuator faults in reconfiguration problem, we consider all faulty actuators as the failed ones in their operating point. Therefore there is no need to identify fault intensity for any of fault cases in one actuator. Actuator degradation generally is not a severe issue in fault problems and can easily be solved by all FTC solutions, but fail of an actuator is always an intense difficulty, and there are limited approaches to solve this kind of faults in the system. In the failed actuators, the valves stick in a position and a constant input signal is applied to the system in the following. If the system was basically linear, this constant value will be equal to zero, but if a nonlinear system is linearized around an operating point, the constant input signal will be equal to the value of input in that operating point. Next section addresses the solution by control reconfiguration in confronting with the explained faults.

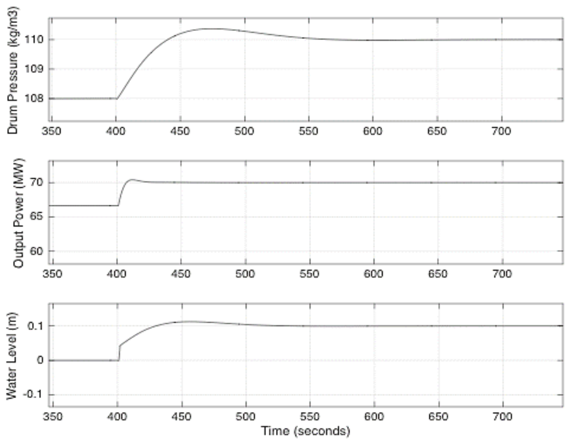

Fig. 2. Outputs of drum pressure, power and water level of the boiler-turbine unit for tracking a setpoint in closed loop form.

3- Control Reconfiguration of Boiler-turbine

3- 1- control Reconfiguration by fault-hiding approach

Fault-hiding idea is used in here for the reconfiguration of control in boiler-turbine unit. In this idea, a special structure is imposed on the reconfigured system such that a reconfiguration block is inserted between the nominal controller and the faulty plant. This block works by hiding the fault from the controller, thus allowing the nominal controller to remain in the loop. Dynamical reconfiguration block consists of virtual actuator and virtual sensor. For the actuator faults considered in this paper, the virtual actuator is used as a reconfiguration block to form the new closed-loop system. Fig. 3 clearly illustrates how the faulty plant is reconfigured by fault-hiding approach. The assumption below is always considered before the implementation of control reconfiguration.

Assumption 1. Nominal closed-loop system composed of nominal controller and nominal plant is input-to-state stable w.r.t reference and disturbance inputs (r,d).

The nominal linear plant and the faulty plant are defined as follows:

$$\Sigma_P:\begin{cases}\dot{x}(t)=Ax(t)+Bu_c(t)+B_d d(t), x(0)=x_0\\ y(t)=Cx(t)\\ z(t)=C_z x(t)\end{cases} \quad (6)$$

$$\Sigma_{P_f}:\begin{cases}\dot{x}_f(t)=Ax_f(t)+B_f u_f(t)+B_d d(t), x_f(0)=x_0\\ y_f(t)=Cx_f(t)\\ z_f(t)=C_z x_f(t)\end{cases} \quad (7)$$

where $x(t)\in\mathbb{R}^n$ is state vector, $u_c(t)\in\mathbb{R}^m$ is control input, $d(t)\in\mathbb{R}^q$ is disturbance input and $y(t)\in\mathbb{R}^r$ is output vector. A, B and C are state space matrices and C_z is controlled outputs matrix. Dynamical virtual actuator is obtained in following

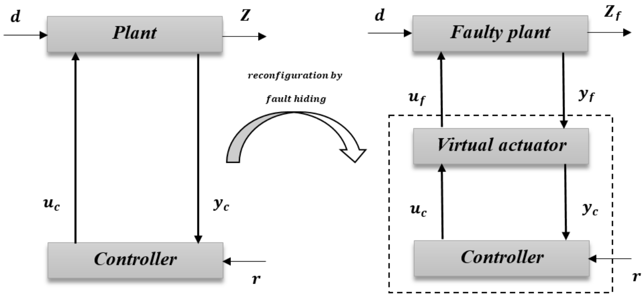

Fig. 3. Reconfiguration by fault-hiding approach

equations:

$$\Sigma_A:\begin{cases}\dot{x}_\Delta(t)=A_\Delta x_\Delta(t)+B_\Delta u_c(t), x_\Delta(0)=0\\ u_f(t)=Mx_\Delta(t)+Nu_c(t)\\ y_c(t)=y_f(t)+Cx(t)\end{cases} \quad (8)$$

$$A_\Delta \triangleq (A-B_f M), B_\Delta \triangleq (B-B_f N), x_\Delta(t)\in R^n$$

where difference state x_Δ denotes the difference of the nominal plant and the faulty plant states:

$$x_\Delta \triangleq x - x_f \quad (9)$$

$u_f(t)$ in (8) is the reconfiguration control law. Matrix M in the equation is inserted to stabilize the virtual actuator and in result guarantees the stability of the overall closed-loop system. Matrix N relies on changing zeros of virtual actuator that the equilibrium takes the required value.

Since, there is matrix D in state space equations of the boiler-turbine unit, we extend the virtual actuator dynamics with considering this matrix as the following equations:

$$\Sigma_A:\begin{cases}\dot{x}_\Delta = A_\Delta x_\Delta + B_\Delta u_c,\ x_\Delta(0)=0,\ x_\Delta\in\mathbb{R}^n\\ u_f = Mx_\Delta + Nu_c\\ y_\Delta = C_\Delta x_\Delta + D_\Delta u_c\\ z_\Delta = C_{z\Delta}x_\Delta + D_{z\Delta}u_c\end{cases} \quad (10)$$

$$A_\Delta \triangleq (A-B_f M),\quad B_\Delta \triangleq (B-B_f N)$$
$$C_\Delta \triangleq (C-D_f M),\quad D_\Delta \triangleq (D-D_f N)$$
$$C_{z\Delta} \triangleq (C_z - D_{zf}M), D_{z\Delta} \triangleq (D_z - D_{zf}N)$$

where D_f is obtained from D in the similar way as B_f is obtained from B. The reconfigured closed-loop system formed by the faulty plant (7), the nominal controller and the virtual actuator (10) are shown in Fig. 4.

3- 2- Reconfiguration problems

The main problems of control reconfiguration based on fault-hiding approach are as follows:

3- 2- 1- Stability recovery after fault occurrence:

This problem is solvable by means of virtual actuator if and only if (A, B_f) is stabilisable. According to separation principle, the closed-loop stability depends only on the stability of virtual actuator. This condition is satisfied only if there exists a matrix M that makes A_Δ Hurwitz. Therefore, matrix M can be found by using all pole-placement methods. To stably analyze the reconfigured closed-loop, it is better to represent a new form of the reconfigured closed loop system. Reconfigured system by means of virtual actuator.

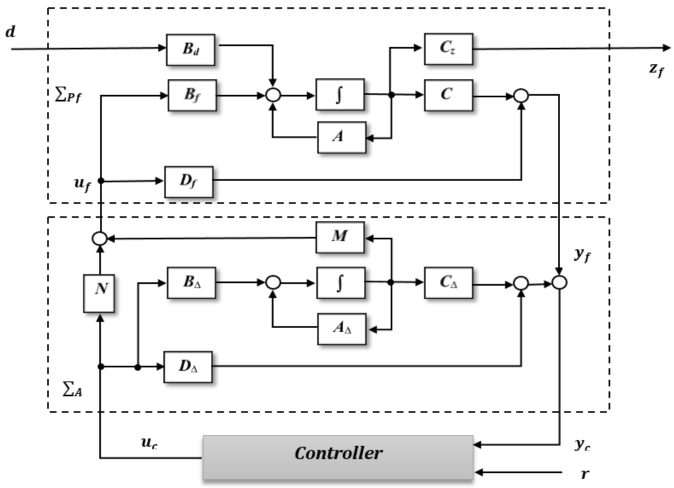

Fig. 4. Reconfigured system by means of virtual actuator.

The new transformed reconfigured system can be obtained by

$$\begin{pmatrix}\tilde{x}(t)\\ x_\Delta(t)\end{pmatrix}=\begin{pmatrix}I & I\\ 0 & I\end{pmatrix}\begin{pmatrix}x_f(t)\\ x_\Delta(t)\end{pmatrix}$$

then

$$\begin{pmatrix}\dot{\tilde{x}}(t)\\ \dot{x}_\Delta(t)\end{pmatrix}=\begin{pmatrix}A\tilde{x}(t)\\ Ax_\Delta(t)-B_f\left(Mx_\Delta(t)+Nu_c(t)\right)\end{pmatrix} +\begin{pmatrix}B\\ B\end{pmatrix}u_c(t)+\begin{pmatrix}B_d\\ 0\end{pmatrix}d(t) \quad (11)$$

$$\begin{pmatrix}y_f(t)\\ y_c(t)\end{pmatrix}=\begin{pmatrix}C & -C\\ C & 0\end{pmatrix}\begin{pmatrix}\tilde{x}(t)\\ x_\Delta(t)\end{pmatrix},\begin{pmatrix}\tilde{x}(0)\\ x_\Delta(0)\end{pmatrix}=\begin{pmatrix}x_0\\ 0\end{pmatrix}$$

The block diagram of the transformed closed-loop system is shown in Fig. 5. Equations of the system in (11) show that the dynamical equations for the reference state $\tilde{x}$ are decoupled from the difference state x_Δ, therefore the equivalent dynamics of the nominal plant is always seen from the controller. This state is called "*fault hides from controller*". The cascade connection of the two subsystems as shown in

Fig. 5 illustrates that by satisfying assumption 1, the stability of the overall system depends only on stability of virtual actuator [22].
Special case of stability analysis is when an actuator degradation fault occurs and the fault intensity is desired to measure. In this case, because of the presence of noises and inaccuracy in identification methods, exact obtaining of matrix B_f is not possible, therefore this uncertainty in designing the virtual actuator dynamics can cause instability in closed-loop system after reconfiguration. In order to investigate stability condition of the system in presence of the estimated matrix B_f.

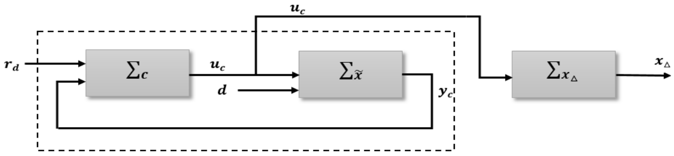

Fig. 5. Transformed structure of reconfigured system

ansformed structure of reconfigured systemwe use special form of the reconfigured closed-loop system which is introduced in (11):

$$\sum_{\tilde{P}}:\begin{cases}\dot{\tilde{x}}(t)=A\tilde{x}(t)+Bu_c(t)+B_f(Mx_\Delta(t)+Nu_c(t))\\ -\hat{B}_f(Mx_\Delta(t)+Nu_c(t))+B_d d(t)\end{cases} \quad (12)$$
$$\sum_\Delta:\{\dot{x}_\Delta=A\,x_\Delta(t)+Bu_c(t)-\hat{B}_f(Mx_\Delta(t)+Nu_c(t))$$

where $\sum_{\tilde{P}}$ denotes reference model of nominal plant (6), and $\sum_{\Delta}$ denotes difference system. By defining $\Delta B_f=B-\hat{B}_f$ we can write:

$$\begin{aligned}&\sum_{\tilde{P}}:\{\dot{\tilde{x}}(t)=A\tilde{x}(t)+Bu_c(t)+\Delta B_f(Mx_\Delta(t)+Nu_c(t))+B_d d(t)\\&\sum_\Delta:\{\dot{x}_\Delta=A\,x_\Delta(t)+Bu_c(t)-\hat{B}_f(Mx_\Delta(t)+Nu_c(t))\end{aligned} \quad (13)$$

The new reconfigured system in (13) is graphically represented in Fig. 6. Unlike cascade structure of the equations in transformed system (11), the new reconfigured system (13) is represented as feedback interconnection of subsystems $\sum_{\tilde{P}}$ and $\sum_{\Delta}$. Stability condition for the closed loop system in presence of the uncertain matrix ΔB_f can be obtained from theorem below.

Theorem 1. (Small gain theorem) [22]. Let Σ_1 and Σ_2 be finite-gain $\mathcal{L}$ stable systems with respect to the input/output signals (u_1,y_1) and (u_2,y_2) and the $\mathcal{L}_2$-gains (H_∞ norms) β_1 and β_2. Then, the feedback interconnection $(u_1=y_2+r_1)$, $(u_2=y_1+r_2)$ is finite-gain stable if $\beta_1\beta_2<1$.
From Theorem 1, it follows directly that the designed reconfigured system using estimated matrix $\hat{B}_f$ (13) is stable if

$$\left\|\sum_{\tilde{P}}\right\|_{H_\infty}\times\left\|\sum_\Delta\right\|_{H_\infty}<1$$

3- 2- 2- Exact setpoint tracking recovery after fault occurrence:

All setpoints tracking recovery depends on the set of possible equilibrium states of the faulty plant and the resulting equilibrium outputs. This condition is reachable according to [1] if and only if condition (14) holds.

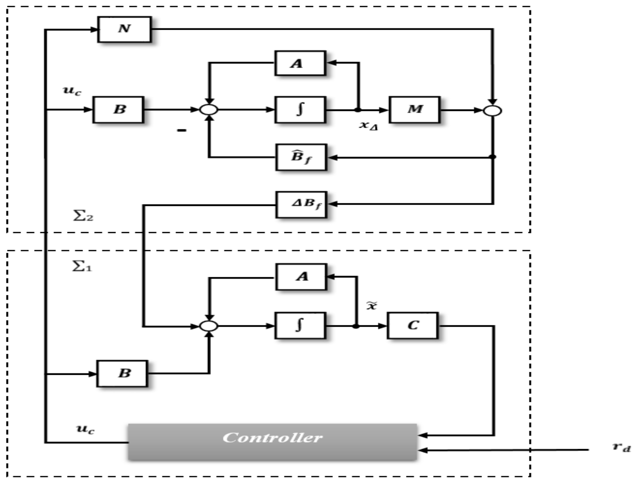

Fig. 6. Reconfigured closed loop system in presence of estimated matrix

$$rank\begin{pmatrix}A & B_f\\ C_z & D_{zf}\end{pmatrix}=rank\begin{pmatrix}A & B_f & B\\ C_z & D_{zf} & D_z\end{pmatrix} \quad (14)$$

This constraint means that the solution space for the faulty plant includes the solution space of the nominal plant. If the faulty system satisfy (14), matrix can be found by setting frequency zero of corresponding transfer function () equal to zero.

$$\begin{aligned}&T_{u_c\to z_\Delta}(0)=0\Rightarrow\\&N=(-C_\Delta A_\Delta^{-1}B_f+D_{zf})^\dagger(-C_\Delta A_\Delta^{-1}B+D_z)\end{aligned} \quad (15)$$

where † denotes pseudoinverse operator.
Obtaining matrix N from (15) guarantees that the difference state x_Δ finally will reach to zero and outputs will rebound to their primary value.

3- 2- 3- Optimal performance recovery:

Optimal performance problem for the faulty plant can be divided into two optimization problems: 1) minimum amplification of input signals, 2) minimum performance loss. These problems can be characterized by their transfer functions:

$$\begin{aligned}&T_{uc\to u_f}(s)=M(SI-A_\Delta)^{-1}B_\Delta+N\\&T_{uc\to z_\Delta}(s)=C_{z\Delta}(SI-A_\Delta)^{-1}B_\Delta+D_{z\Delta}\end{aligned} \quad (16)$$

Therefore, optimization problems can be defined as:

$$\begin{aligned}&\min_{N,M}\|T_{u_c\to z_\Delta}(s)\|_{H_\infty}=\gamma_1\\&\min_{N,M}\|T_{u_c\to u_f}(s)\|_{H_\infty}=\gamma_2\end{aligned} \quad (17)$$

H_∞ norm is chosen because it represents the largest peak-to-peak amplification of harmonic input signals by the system over the entire frequency range. Minimizing this norm in (17) means the size of signals z_Δ and u_f will be minimized to obtain maximum recovery of output's trajectory and minimum input amplification.

Theorem 2 [23]. Consider the linear system (3). H_∞ norm of the system Σ is denoted by $\|\Sigma\|_{H_\infty}$. Let $\gamma > 0$ be a scalar, then the two following statements are equivalent:

1. $\|T_{u_c \to y}(s)\|_{H_\infty} < \gamma$

2. There exists a feasible solution $P = P^T \succ 0$ to the LMI

$$\begin{pmatrix} A^T P + PA & PB & C^T \\ * & -\gamma I & D^T \\ * & * & -\gamma I \end{pmatrix} \prec 0$$

Optimization problems (17) can be solved by applying Theorem 2; a tradeoff between two problems is defined as $\lambda \in [0,1]$, which is specified by the system designer for each problem priority. Thus, optimal performance recovery problem is solvable by means of virtual actuator, if there exist feasible solutions to the following linear matrix inequalities:

$$\min_{N, X_a, Y_a} \lambda\gamma_1 + (1-\lambda)\gamma_2 \quad \lambda \in [0,1]$$
$$\text{Subject to}$$
$$\begin{pmatrix} AX + XA^T - B_f Y - Y^T B_f^T & B - B_f N & XC_z^T - Y^T D_{zf}^T \\ * & -\gamma_1 I & D_z^T - N^T D_{zf}^T \\ * & * & -\gamma_1 I \end{pmatrix} \prec 0$$
$$\begin{pmatrix} AX + XA^T - B_f Y - Y^T B_f^T & B - B_f N & Y^T \\ * & -\gamma_2 I & N^T \\ * & * & -\gamma_2 I \end{pmatrix} \prec 0 \tag{18}$$
$$X = X^T \succ 0, \;\; \gamma_1 \geq 0, \gamma_2 \geq 1$$
$$X \in \mathbb{R}^{n*n}, \;\; Y \in \mathbb{R}^{m*n}, \;\; N \in \mathbb{R}^{m*m}$$

LMIs (18) are obtained by applying the Schur lemma and congruence transformation $X = P^{-1}$ from left and right and substitution $M = YX^{-1}$.

Matrices X, Y and the feed-forward matrix N are directly obtained from solutions of the LMIs, and the matrix M is obtained by equation $M = YX^{-1}$.

4- Simulation Results

In this section, all actuator fault scenarios mentioned in section II-D are investigated for the boiler-turbine unit. For each actuator, we have considered setpoint tracking recovery and optimal performance recovery after occurrence of a fault. Setpoint tracking recovery for all outputs is not possible due to state space equations of the plant. Therefore, we have considered two outputs of the boiler-turbine as controlled outputs in each reconfiguration. Checking condition (14) for all fault scenarios yields:

$$rank\begin{pmatrix} A & B_f \\ C_z & D_{zf} \end{pmatrix} = rank\begin{pmatrix} A & B_f & B \\ C_z & D_{zf} & D_z \end{pmatrix} = 5$$

It is assumed that all actuator faults occur at t_f=780s and after applying fault diagnosis algorithms to determine the faulty actuator, the reconfiguration block is activated at t_r=800s.

4- 1- Reconfiguration after fault f_1 (failure of fuel flow valve)

In this case, an actuator blockage at the operating point in the fuel flow valve at t_f=780s is considered. Furthermore, to find out disturbance effects on the system a step input disturbance of magnitude 0.1 at all input channels is inserted after reconfiguration (t_d=1200s). Feedback gain M and the feed-forward gain N are obtained in two cases:

4- 1- 1- Exact setpoint tracking recovery

M: using pole placement with the target poles $\sigma = 40\sigma_{Plant}$. where σ_{Plant} is the nominal eigenvalue given in (3,4).
N: is obtained from (15).

$$M_1 = \begin{pmatrix} 0 & 0 & 0 \\ -0.0747 & -0.0187 & -0.073 \\ 1.9251 & -0.6023 & 2.3532 \end{pmatrix}$$

$$N_1 = \begin{pmatrix} 0 & 0 & 0 \\ -25.5496 & 1 & 0 \\ -760.4823 & 0 & 1 \end{pmatrix}$$

4- 1- 2- Optimal performance recovery

Virtual actuator parameters are obtained from (18) for ($\lambda = 0.8$):

$$M_{1o} = \begin{pmatrix} 0 & 0 & 0 \\ -593.341 & 0.1875 & -59.4101 \\ -127.1144 & 0.0401 & -12.6136 \end{pmatrix}$$

$$N_{1o} = \begin{pmatrix} 0 & 0 & 0 \\ -1.8887 & 1.0001 & 0.0001 \\ -1.5841 & 0.0004 & 1.0003 \end{pmatrix}$$

Fig. 7 shows the setpoint tracking recovery results. It is clearly seen that after failure of fuel flow valve, two outputs of the system have deviated from their normal direction (red lines), but after activating the designed virtual actuator, behavior of the closed loop system is completely modified; green dashed lines indicate the following outputs trajectories. Output power of the boiler turbine is not considered in tracking recovery, thus it has not been able to recover its primary value however it is in stable condition. New generated input signals by reconfiguration block is also shown in Fig. 7.

Fig. 8 illustrates optimal performance recovery simulations. It is seen that setpoint tracking recovery is almost satisfactory with lower recovering speed, although generated input signals are in lower energy level. Moreover, results in both cases show that disturbance input has been rejected well and is not able to affect the stability of closed loop system.

4- 2- reconfiguration after fault f_2 (failure of steam control valve)

4- 2- 1- exact setpoint tracking recovery:

(t_f=780s, t_r=800s, t_d=1350s)

$$M_2 = \begin{pmatrix} 4.4410 & 0 & 0.0010 \\ 0 & 0 & 0 \\ -0.004 & 0 & 0.0060 \end{pmatrix}, N_2 = \begin{pmatrix} 1 & 905.7967 & 0 \\ 0 & 0 & 0 \\ 0 & -1.8943 & 1 \end{pmatrix}$$

4- 2- 2- optimal performance recovery for λ=0.8:

(t_f=780s, t_r=800s, t_d=1350s)

$$M_{2O} = \begin{pmatrix} 0.0085 & 0.0001 & 0.0066 \\ 0 & 0 & 0 \\ -0.0011 & -0.0005 & 0.0064 \end{pmatrix}$$

$$N_{2O} = \begin{pmatrix} -0.0816 & 0.9559 & 0.0042 \\ 0 & 0 & 0 \\ 0.0003 & -0.3824 & 0.7377 \end{pmatrix}$$

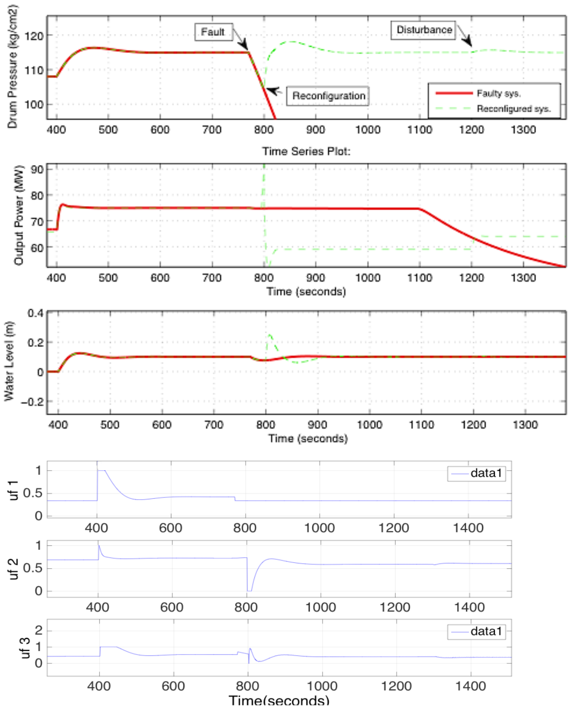

Fig. 7. Exact setpoint tracking recovery after fault f_1

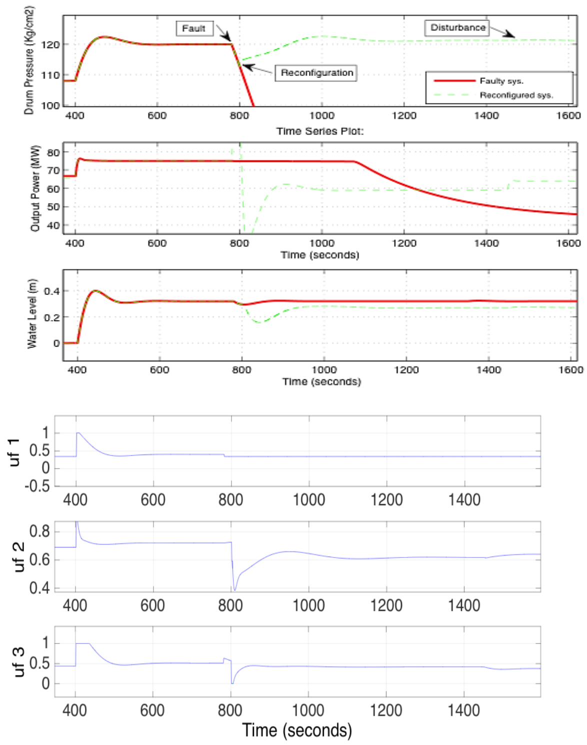

Fig. 8. Optimal performance recovery after fault f_1

Failure of steam control valve causes intense deviation in output power trajectory as shown in Fig. 9 (red line). In exact setpoint tracking problem, the output of drum pressure was not considered in reconfiguration solution and two other outputs was included. Results in Fig. 9 show that reconfiguration is completely successful for power output and water level. In optimal recovery case, results illustrate that setpoint

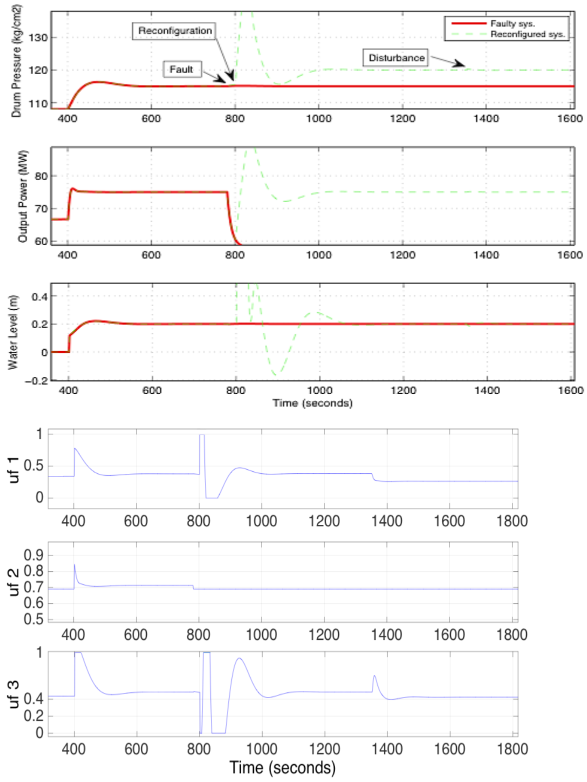

Fig. 9. Exact setpoint tracking recovery after fault f_2

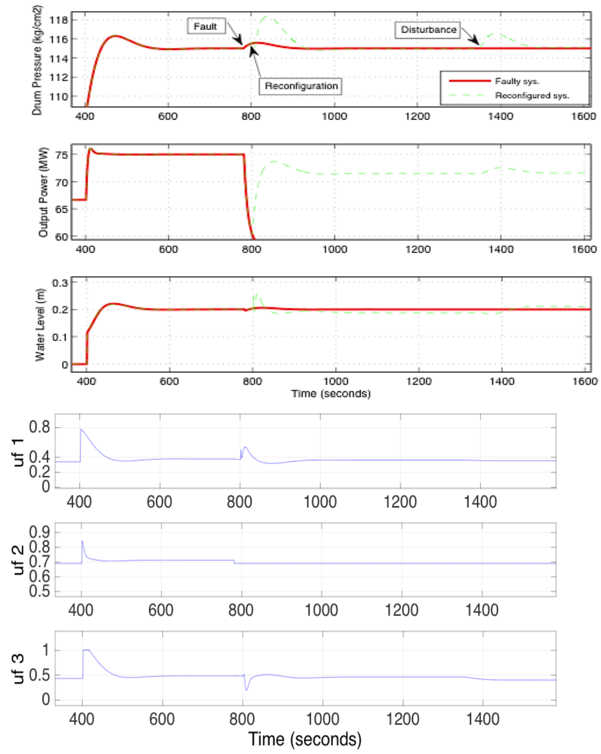

Fig. 10. Optimal performance recovery after fault f_2

tracking recovery is almost satisfactory for all outputs, and input signals are in their lowest energy level (Fig. 10). It is clearly perceived that like previous simulation, the inserted disturbance input in all channels is rejected well by controller.

4- 3- reconfiguration after fault f_3 (feed-water flow actuator)

4- 3- 1- exact setpoint tracking recovery

(t_f=780s, t_r=800s, t_d=1200s):

$$M_3 = \begin{pmatrix} 3.4205 & -1.7782 & 2.3036 \\ -.0984 & 0.0555 & -0.0789 \\ 0 & 0 & 0 \end{pmatrix}$$

$$N_3 = \begin{pmatrix} 1 & 0 & 670.1835 \\ 0 & 1 & -23.2452 \\ 0 & 0 & 0 \end{pmatrix}$$

4- 3- 2- optimal performance recovery for $\lambda=0.8$:

(t_f=780s, t_r=800s, t_d=1200s)

$$M_{3O} = \begin{pmatrix} 29.9624 & 0.0249 & -27.1927 \\ 35.4619 & 0.0358 & -42.7111 \\ 0 & 0 & 0 \end{pmatrix}$$

$$N_{3O} = \begin{pmatrix} 1.0004 & 0.0008 & -0.6264 \\ 0.0002 & 1.0004 & -1.1912 \\ 0 & 0 & 0 \end{pmatrix}$$

As shown in Fig. 11, failure of feed water valve causes quick deviation in drum pressure and water level of the boiler turbine. Power output was not considered in this setpoint tracking recovery problem. After reconfiguration, it is seen that two other outputs have completely satisfactory setpoint tracking recovery and the system becomes stable in all states. In optimal case (Fig. 12), it is perceived that the setpoint recovery is still satisfactory for two outputs, and we can be confident again that the generated input signals by new structured controller are in their optimal case.

4- 4- reconfiguration after degradation fault in all valves f_4

(α_1=.3, α_1=.5, α_1=.1)

It was mentioned before that actuator degradation was not an intense issue in FTC designing scheme compared to actuator failing. In this section, three degradation faults are assumed to occur simultaneous in boiler turbine valves. In this case, we just consider the optimal performance recovery problem. Virtual actuator parameters are obtained from LMI (19):

$$M_D = \begin{pmatrix} 29.9624 & 0.0249 & -27.1927 \\ 35.4619 & 0.0358 & -42.7111 \\ 0 & 0 & 0 \end{pmatrix}$$

$$N_D = \begin{pmatrix} 1.0004 & 0.0008 & -0.6264 \\ 0.0002 & 1.0004 & -1.1912 \\ 0 & 0 & 0 \end{pmatrix}$$

Fig. 13 shows the simulation result for control reconfiguration of boiler-turbine in presence of actuator degradation fault. Red line trajectories indicate faulty outputs of the system that are unstable after occurrence of the fault; after activating the reconfiguration structure, it is seen that all three output's trajectories are rebounding exactly to their primary values (green dashed lines) and input signals are applied in optimal level of energy.

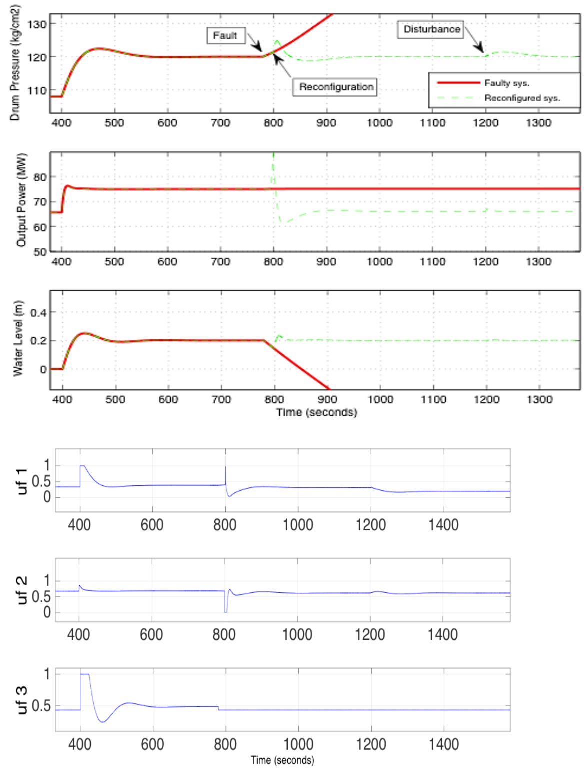

Fig. 11. Exact setpoint tracking recovery after fault f_3

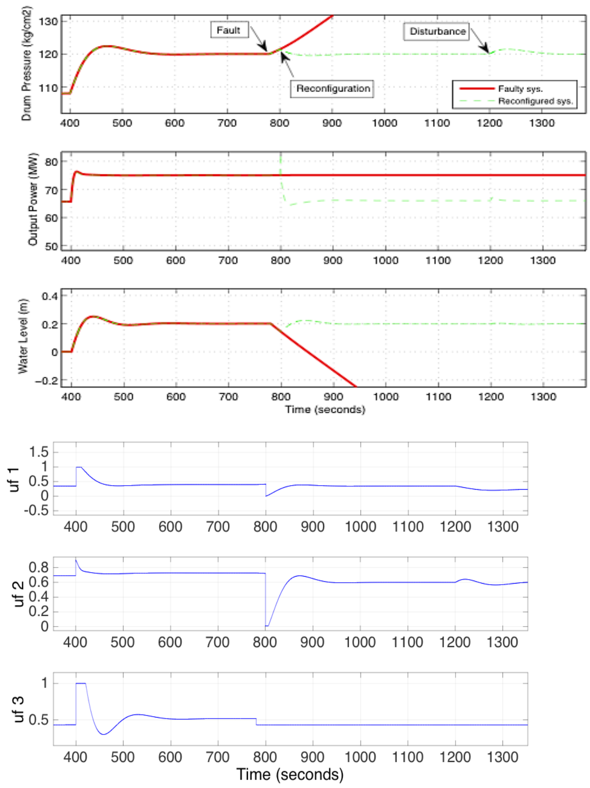

Fig. 12. Optimal performance recovery after fault f_3

5- Conclusion

This paper presents the application of control reconfiguration by fault-hiding approach for a boiler-turbine unit. Advantages of this work are that after occurrence of a fault, nominal controller of the system remains unchanged, therefore all of the pre-designed features of the nominal controller are still available after reconfiguration. Also, this method is not dependent on type of controller used for the system, so any other types of controllers can be replaced with the controller we use here. Famous Bell-Astrom model of boiler turbine is studied in this work. This model has three valves of fuel flow, steam control and feed water flow that are assumed to get into faults respectively in simulations. We investigate both exact setpoint tracking recovery and optimal performance recovery problems after two main types of actuator faults occur in this system. In setpoint tracking recovery, exact rebounding of deviated outputs of the system to their primary values are obtained and in optimal performance recovery, the solution of minimum performance loss and minimum amplification of input signal for the faulty plant is presented. The results of simulations for all fault scenarios show that control reconfiguration of the boiler-turbine unit is indeed successful when the system is operating near the equilibrium point.

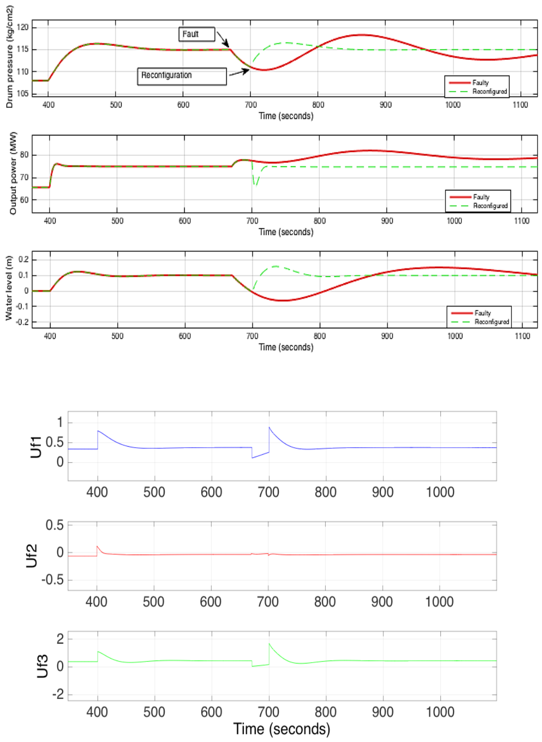

Fig. 13. Optimal performance recovery after fault f_4

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