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113

Selected papers from the International Conference on *Turbines of Large Output* devoted to 100th Anniversary of Prof. Robert Szewalski Birthday, Gdańsk, September 22-24, 2003

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Transactions of the Institute of Fluid-Flow Machinery have primarily been established to publish papers from four disciplines represented at the Institute of Fluid-Flow Machinery of Polish Academy of Sciences, such as:

- Liquid flows in hydraulic machinery including exploitation problems,
- Gas and liquid flows with heat transport, particularly two-phase flows,
- Various aspects of development of plasma and laser engineering,
- Solid mechanics, machine mechanics including exploitation problems.

The periodical, where originally were published papers describing the research conducted at the Institute, has now appeared to be the place for publication of works by authors both from Poland and abroad. A traditional scope of topics has been preserved.

Only original and written in English works are published, which represent both theoretical and applied sciences. All papers are reviewed by two independent referees.

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TRANSACTIONS OF THE INSTITUTE OF FLUID-FLOW MACHINERY

No. 113, 2003, 3-4

Editorial

These Special Issues of the *Transactions of Fluid-Flow Machinery*, Nos. 113 and 114 contain selected papers from the International Conference on *Turbines of Large Output* devoted to commemorate 100th Birthday Anniversary of Prof. Robert Szewalski. The conference was held in Gdańsk, Poland on September 22-24, 2003.

The Conference is a continuation of previous conferences held at the Institute of Fluid-Flow Machinery PAS in former years dedicated to technology of steam turbines. Series of conferences bearing the same name took place in the years 1962, 1965, 1968, 1993. In 1997 organised has been a conference on steam turbines and related topics, but with a slightly amended title – *Problems of Fluid-Flow Machinery.* At present at the Institute of Fluid Flow Machinery there are conduced research of fundamental character encompassing both the issues related to steam turbines and fundamentals of power engineering.

Organisers of the present conference have returned to the traditional name, i.e. Conference on *Turbines of Large Output* to mark the respect to the memory of Professor Robert Szewalski (1903-1993), the founder and a director of the Institute of Fluid-Flow Machinery for several years, and initiator of the conference series devoted to the problems of steam turbines.

The Editors are very grateful to the referees of the papers presented in this issue of the *Transactions of Fluid-Flow Machinery*: J. Badur, W. Batko, E. S. Burka, J.T. Cieśliński, P. Doerffer, A. Gardzilewicz, B. Grochal, J. Kiciński, G. Kosman, T. Król, J. Krzyżanowski, J. Mikielewicz, A. Neyman, W. Ostachowicz, R. Puzyrewski, R Rządkowski, J. Świrydczuk, M. Trela, T. Uhl and Z. Walczyk.

We appreciate cordially the manifested authors interest in our conference. Special thanks are conveyed to Ms 'Maya' Bagińska, for her fruitful editorial help related to directing the papers to reviewers and correspondence with the authors of contributions.

Prof. Jarosław Mikielewicz
Editor-in-Chief

Dr Edward Śliwicki
Managing Editor

TRANSACTIONS OF THE INSTITUTE OF FLUID-FLOW MACHINERY

No. 113, 2003, 25-34

ZYGFRYD DOMACHOWSKI*

An impact of ambient parameters change on steam and gas turbosets control

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Abstract

An influence of ambient parameters change on performance of gas and steam turbines has been compared. On such basis an impact of such disturbances on combined cycle power plant has been analysed. A compensator for such changes has been suggested to eliminate the dependence of combined cycle power plant performance on ambient pressure and temperature.

Keywords: Combined cycle; Ambient parameters change, Performance steam and gas turbines

Nomenclature

- C – compensator,
- G – transfer function,
- m_F – fuel flow rate,
- p_o – ambient pressure,
- P_p – plant power output,
- R – plant power controller,
- S – power plant,
- t_o – ambient temperature,
- t_3 – gas turbine combustor exhaust temperature,
- z – disturbance signal.

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1 Introduction

Both gas and steam turbines are influenced by ambient disturbances such as pressure and temperature, or even air humidity. These disturbances involve turboset power output and efficiency transients. Applying proportional – integrating controller it is possible to avoid turboset power steady state error in both steam and gas turbosets. In the same time an impact of ambient disturbances is different on steam and gas turbosets. The relative influence of ambient temperature on the steam turboset power output is slight. On the other hand the absolute deviation of steam turboset power output can be considerable in large steam power plants.

This is different in gas turbosets. Both ambient pressure and temperature influence considerably gas turboset power output. Nevertheless gas turbines are mostly of smaller rated power, moreover they often operate in the cycle duty mode.

Combined cycle power plants, as sets of large gas and steam turbines, are sensitive to ambient pressure and temperature. Therefore any change of ambient pressure and temperature results in combined cycle power plant transients. This is some problem for any design of combined cycle power plant control system.

The compensation of ambient pressure and temperature is possible by two ways:

- closed loop power plant controller,
- open loop compensator.

Description of the second item is the main topic of the paper.

2 Steam turboset as multivariable controlled plant – influence of ambient temperature

Denoting changes of

- steam turbine power output, $\nu = \frac{\Delta P}{P_n}$,
- control valve setting, $\mu = \frac{\Delta h}{h_n}$,
- live steam pressure, $\rho_1 = \frac{\Delta p_1}{p_{1n}}$,
- live steam temperature, $v_1 = \frac{\Delta T_1}{T_{1n}}$,
- reheated steam temperature, $v_r = \frac{T_r}{T_{rn}}$,
- condenser pressure, $\rho_c = \frac{\Delta p_c}{p_{cn}}$,

where the subscript n denotes the nominal values, the linear model of the steam turbine as controlled plant can be represented as follows

$$\nu = G_{ST} \cdot u. \tag{1}$$

In the relationship (1)

$$G_{ST} = \left[G_{ST}^{\mu},\, G_{ST}^{\rho_1},\, G_{ST}^{\vartheta_1},\, G_{ST}^{\vartheta_r},\, G_{ST}^{\rho_c} \right] \tag{2}$$

is the steam turbine transfer function matrix, and

$$u = \begin{bmatrix} \mu \\ \rho_1 \\ \vartheta_1 \\ \vartheta_r \\ \rho_c \end{bmatrix} \tag{3}$$

is the steam turbine input signal vector.

Elements of steam turbine transfer function matrix are transfer functions with regard to individual input signals mentioned above. They correspond to change in

- control valve setting, G_{ST}^{μ},
- live steam pressure, $G_{ST}^{\rho_1}$,
- live steam temperature, $G_{ST}^{\vartheta_1}$,
- reheated steam temperature, $G_{ST}^{\vartheta_r}$,
- condenser pressure, G_{ST}^{c}.

It appears that all coefficients of the steam turbine transfer function matrix elements, with the exception of the transfer function with regard to a change in the condenser pressure, are of the same order [2]. The effect of the change in the condenser pressure on the change in the steam turbine power is considerably smaller.

The steam turbine transfer function, as the relationship between the steam turbine power output and the condenser pressure, can be represented as follows [2]:

$$G_{ST}^{\rho_C} = -k_{LP} \cdot k_H^{LP}, \tag{4}$$

where $k_{LP} = P_{LP}/P_n$ denotes the low pressure turbine power coefficient ($k_{LP} = 0.7 \div 0.8$), and

$$k_H^{LP} = \frac{R \cdot T_r \left(p_c/p_r\right)^{\frac{\kappa-1}{\kappa}}}{H_{LP}}, \tag{5}$$

H_{LP} – low pressure turbine enthalpy drop,
p_r, T_r – reheated steam parameters,
R – gas constant,
κ – adiabatic coefficient.

It turns out that in large steam power plants

$$\frac{p_c}{p_r} < 0.01, \tag{6}$$

and according to (5),

$$k_H^{LP} < 0.1. \tag{7}$$

Therefore in large steam power plants, see (4),

$$\left|G_{ST}^{\rho_C}\right| = k_{LP} \cdot k_H^{LP} < 0.07 \div 0.08. \tag{8}$$

An ambient temperature change influences a change in the condenser pressure. According to (8) the effect of the change of condenser pressure on the change of steam turbine power is small. Moreover any such change of condenser pressure is slow. Therefore an ambient temperature compensation in steam turbine can be achieved as an implicit result of the closed-loop turboset power controller with no scheduled temperature compensator. The action of the closed loop responding to turboset power will vary the control valve setting to achieve commanded power for any ambient temperature. Such behaviour, where control systems are desensitized to external disturbances, is typical of closed-loop control applications. The disadvantage of such implicit ambient temperature compensation is that such temperature compensation is totally dependent on the turboset power governing loop. An advantage of the implicit ambient temperature compensation by means of the closed-loop power control is it simplicity, eliminating the ambient temperature sensor and compensator.

3 Influence of ambient pressure and temperature changes on gas turboset

Similarly to (1) and (2), the gas turbine transfer function matrix can be represented as follows

$$G_{GT} = \left[G_{GT}^{m_F},\, G_{GT}^{m_C},\, G_{GT}^{\vartheta_o},\, G_{GT}^{\rho_o}\right]. \tag{9}$$

The elements of this transfer function matrix correspond to a change in

- fuel flow rate, $G_T^{m_F}$,

- air flow rate, $G_T^{m_c}$,
- ambient temperature, $G_{GT}^{\vartheta_o}$,
- ambient pressure, $G_{GT}^{p_o}$.

Changes of environmental conditions such as ambient temperature and pressure, or even humidity, provoke losses of power and efficiency in a gas turbine. Table 1 gives an example of impact of such changes [1].

Table 1. Impact of environmental disturbances on the gas turbine power output and efficiency.

Parameters	Parameter change	Power output change [%]	Efficiency change [%]
Ambient temperature	10°C	−6.5	−2
Ambient pressure	10 mbar	0.9	−0.9
Ambient relative humidity	10%	−0.0002	−0.0005

There are also several other reasons for losses that can be encountered in a gas turbine. They are, e.g. air pressure drop across the inlet filter, compressor fouling, fuel lower heating value. Those losses can be considered as controllable as the operator can take corrective actions. The environmental conditions, such as temperature, pressure, and humidity are uncontrollable. Their compensation to eliminate the dependence of gas turbine power on ambient parameters can be achieved as a result of a closed loop gas turbine power controller action or an open loop ambient parameters compensator action.

As usual a closed loop control is applied in power gas turbosets. However in industrial gas turbosets, which are often operating in open loop, e.g. ship propulsion gas turbine engines, a feed forward ambient parameters compensator is recommended [5]. Additionally such an open loop control can avoid potential instabilities and control system cycling.

4 Impact of environmental disturbances on combined cycle power plant

Combined cycle power plants operate at thermal efficiency approaching 60 percent. At the same time their performance presents several specific problems owing to the complex structure. The entire system of combined cycle power plant is very intertwined. Any deterioration of one parameter will lead to off – design change of other parameters, which will result in overall change of plant performance characteristics. Environmental disturbances, such as ambient temperature

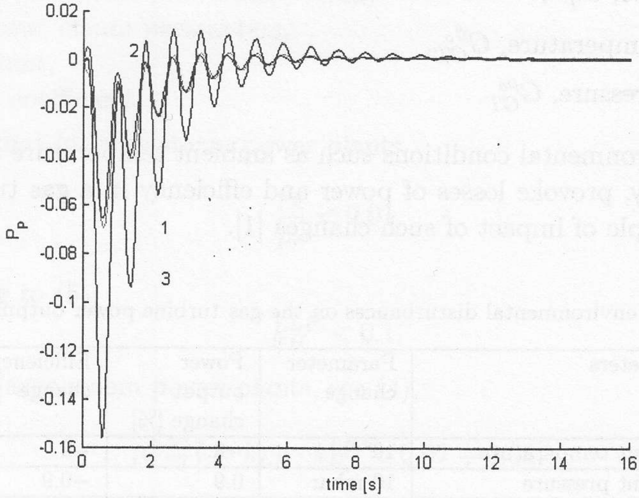

Figure 1. Response of plant power output to step changes of ambient parameters, 1 – $\Delta p_o = 0.2\, p_{on}$, 2 – $\Delta t_o = -15$ K, 3 – $\Delta p_o = 0.2 p_{on}$ and $\Delta t_o = -15$ K.

and pressure influence the power output and the efficiency of gas turbine. As a result a corresponding change of performance of both gas turbine and steam turbine takes place. In such circumstances the combined cycle power plant controller has to maintain overall production of plant power.

Simulating combined cycle power plant transients under external disturbances a proportional – integrating plant power controller has been assumed. The following values of step changes have been taken into account as external disturbances:

- ambient pressure,

$$\Delta p_o = 0.2\, p_{on}, \tag{10}$$

- ambient temperature

$$\Delta t_o = -15\,\mathrm{K}\,(\text{from } 15^\circ\mathrm{C} \text{ to } 0^\circ\mathrm{C}\,), \tag{11}$$

where p_{on} denotes ambient pressure nominal value.

Any change of ambient pressure as well as any change of ambient temperature involve a change in fuel flow rate to maintain the power produced by the plant. The steady state error of plant power output is equal to zero due to integrating action of power plant controller. At the same time plant power output transients occur with a considerable overshoot and oscillations, see Fig. 1, resulting from gas turbine transients, see Fig. 2. As it has just been mentioned, gas turbine

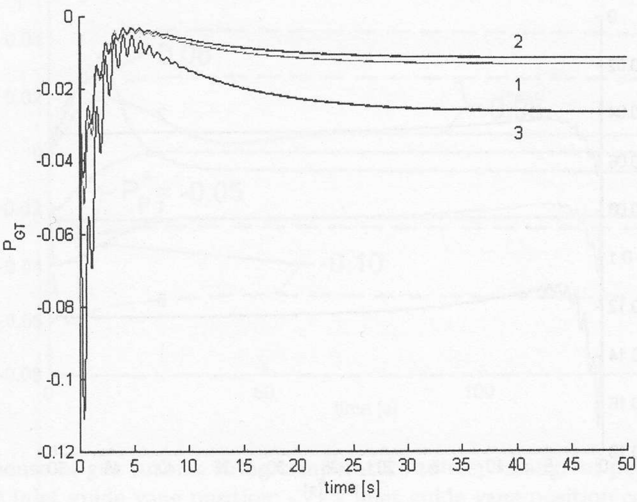

Figure 2. Response of gas turbine power output to step changes of ambient parameters, 1 – $\Delta p_o = 0.2\ p_{on}$, 2 – $\Delta t_o = -15$ K, 3 – $\Delta p_o = 0.2\ p_{on}$ and $\Delta t_o = -15$ K.

characteristics are very sensitive to any ambient parameter variation.

As consequence of the above inputs a change of both the compressor airflow and the gas turbine firing temperature occur, see Fig. 4. Any decrease of the gas turbine firing temperature provoke a corresponding change in gas turbine efficiency and further of the whole combine cycle power plant. To avoid such a combined cycle power plant efficiency decrease, under conditions of external disturbances, an application of the inlet guide vane position control is recommended.

In a combined cycle power the plant load control is done by controlling the fuel flow rate of the gas turbine. The gas turbine combustor exhaust temperature depend on both the fuel flow rate and the airflow. Therefore the inlet guide vane position control is expected to maintain the exhaust temperature of the gas turbine by controlling the airflow.

Figure 4 represents the gas turbine combustor exhaust temperature responses to the plant's power set point, P_p^*. In the temperature response to $P_p^* = \pm 0.05$ the steady state error is near to zero. In the case of a higher change of plant's power set point, that temperature steady state error is higher due to the approximation of the compressor characteristics.

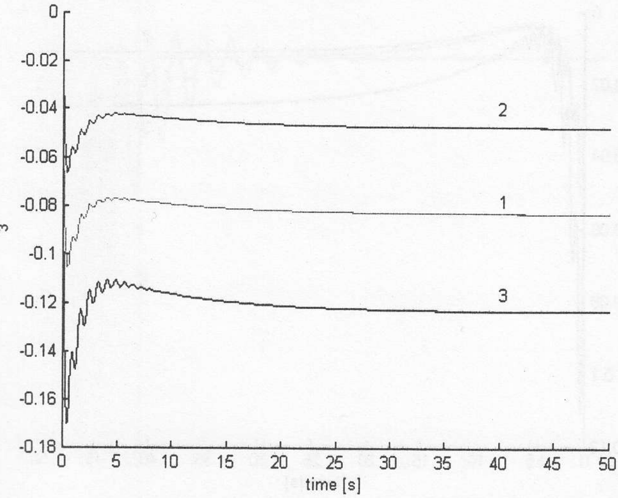

Figure 3. Response of gas turbine firing temperature to step changes of ambient parameters, 1 – $\Delta p_o = 0.2\, p_{on}$, 2 – $\Delta t_o = -15$ K, 3 – $\Delta p_o = 0.2\, p_{on}$ and $\Delta t_o = -15$ K.

5 Ambient pressure and temperature compensation

Combined cycle power plant performance is very sensitive to the ambient conditions. Both ambient pressure and temperature are measurable. Thus, a compensation of these environmental disturbances is possible according to the simplified block diagram represented in Fig. 5.

Assume that pressure and temperature invariant control is required for the combined cycle power plant control system. Then, in the following relationship, see Fig. 5,

$$(1 + G_R \cdot G_S^{m_F}) \cdot P_p = (\mathbf{G}_S^z - \mathbf{G}_C \cdot G_R \cdot G_S^{m_F}) \cdot \mathbf{z} + G_R \cdot G_S^{m_F} \cdot P_p^* \tag{12}$$

the relation must hold

$$\mathbf{G}_C = \left(G_R \cdot G_S^{m_F}\right)^{-1} \cdot \mathbf{G}_S^z, \quad (13$$

where signals P_p, P_p^*, $\mathbf{z}$ are Laplace transforms, and

$$\mathbf{z} = \begin{bmatrix} p_o \\ t_o \end{bmatrix} \tag{14}$$

$$\mathbf{G}_S^z = \left[G_S^{p_o},\, G_S^{t_o},\right] \tag{15}$$

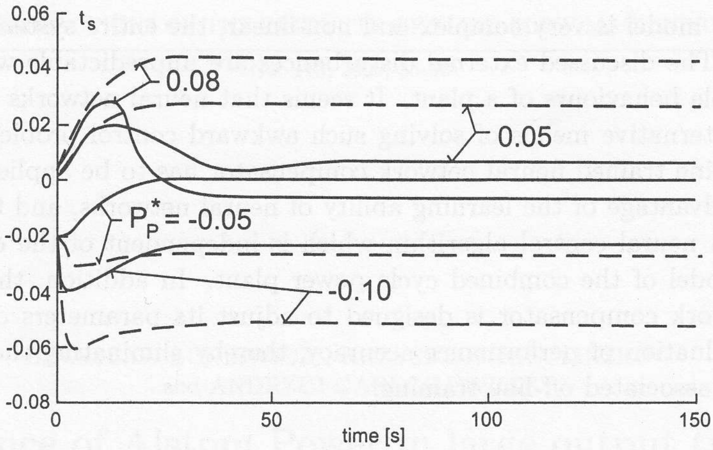

Figure 4. Response of gas turbine firing temperature to step change of power plant; ------- constant inlet guide vane position; - - - - inlet guide vane position control.

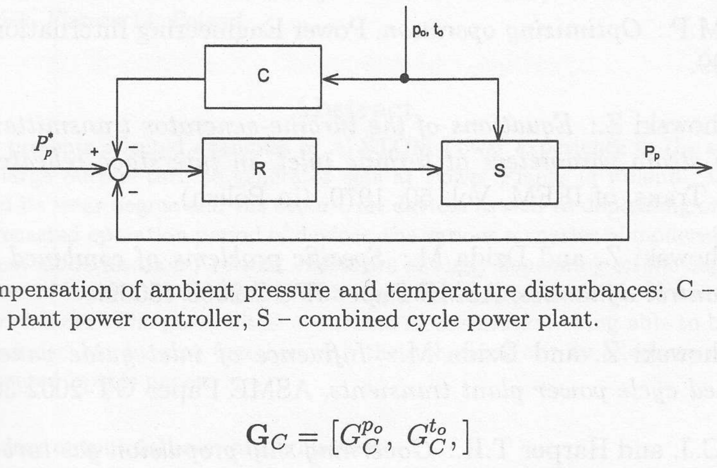

Figure 5. Compensation of ambient pressure and temperature disturbances: C – compensator, R – plant power controller, S – combined cycle power plant.

$$\mathbf{G}_C = \left[G_C^{p_o},\, G_C^{t_o}\right] \tag{16}$$

$G_S^{m_F}$ is power plant transfer function with regard to fuel flow rate, $G_S^{p_o}$, $G_S^{t_o}$ are power plant transfer functions with regard to corresponding ambient pressure and ambient temperature, $G_C^{p_o}$, $G_C^{t_o}$ are similar transfer functions of compensator.

Finally, to eliminate the dependence of combined cycle plant power on ambient pressure and temperature the transfer function matrix of disturbances compensator should be as follows:

$$\mathbf{G}_C = \left(G_R \cdot G_S^{m_F}\right)^{-1} \cdot \left[G_S^{p_o},\, G_S^{t_o}\right]. \tag{17}$$

The above relationship, (17), represents a linear concept of compensation of external disturbances. Moreover this assumes that combined cycle power plant transfer functions $G_S^{p_o}$ and $G_S^{t_o}$ are known. Unfortunately any combined cycle power plant model is very complex and non-linear, the entire system is very intertwined. The discussed external disturbances are unpredictable which causes unpredictable behaviours of a plant. It seems that neural networks can be perceived as alternative means of solving such awkward control problems. In this case an on-line trained neural network compensator has to be applied. The aim is to take advantage of the learning ability of neural networks, and to derive an autonomous neural control algorithm which is independent of the exact mathematical model of the combined cycle power plant. In addition, the suggested neural network compensator is designed to adjust its parameters on-line from a direct evaluation of performance accuracy, thereby eliminating the need for a trainer and associated off-line training.

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