3 XI 2003

INSTITUTE OF FLUID-FLOW MACHINERY
POLISH ACADEMY OF SCIENCES

TRANSACTIONS OF THE INSTITUTE OF FLUID-FLOW MACHINERY

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

WYDAWNICTWO IMP PAN

GDAŃSK 2003

TRANSACTIONS OF THE INSTITUTE OF FLUID-FLOW MACHINERY

Appears since 1960

Aims and Scope

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.

EDITORIAL COMMITTEE

EDITORIAL BOARD

INTERNATIONAL ADVISORY BOARD

EDITORIAL AND PUBLISHING OFFICE

IFFM Publishers (Wydawnictwo IMP), Institute of Fluid Flow Machinery, Fiszera 14, 80-952 Gdańsk, Poland, Tel.: +48(58)3411271 ext. 141, Fax: +48(58)3416144, E-mail: esli@imp.gda.pl http://www.imp.gda.pl/

Terms of subscription

Subscription order and payment should be directly sent to the Publishing Office

Warunki prenumeraty w Polsce

Wydawnictwo ukazuje się przeciętnie dwa lub trzy razy w roku. Cena numeru wynosi 20,- zł + 5,- zł koszty wysyłki. Zamówienia z określeniem okresu prenumeraty, nazwiskiem i adresem odbiorcy należy kierować bezpośrednio do Wydawcy (Wydawnictwo IMP, Instytut Maszyn Przepływowych PAN, ul. Gen. Fiszera 14, 80-952 Gdańsk). Osiągalne są również wydania poprzednie. Prenumerata jest również realizowana przez jednostki kolportażowe RUCH S.A. właściwe dla miejsca zamieszkania lub siedziby prenumeratora. W takim przypadku dostawa następuje w uzgodniony sposób.

ISSN 0079-3205

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 100$^{\text{th}}$ 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, 75-83

KRZYSZTOF BADYDA*, WOJCIECH BUJALSKI, JANUSZ LEWANDOWSKI and ANDRZEJ MILLER

Steam turbines identification based on archived process data

Institute of Heat Engineering, Warsaw University of Technology, 21/25 Nowowiejska Str., 00-650 Warsaw, Poland

Abstract

Nowadays, various programs for optimization and simulation of power systems are used. Mathematical model based on particular system element characteristics is a core of this type of programs. How accurate the modelling is depends on the accuracy of implemented characteristics. In the course of time, characteristics are subject to change (ageing process). Continuous correction of characteristics must be done to keep them up to date. Till now, characteristics have been built based on thermal measurements, performed by special companies and could not be corrected in the on-line mode. Today, most power plants are equipped with distributed control systems (DCS). These systems collect information for controlling, perform the control and archive the results of measurements. A large number of values are collected even during short system working time. These data can be easily used in different types of calculations. One of them is identification of characteristics. This type of data allows correcting characteristics in on-line mode.

Keywords: DCS; Identification; Modelling; Optimization

1 Preparing data for identification process

1.1 Algorithms of getting and archiving data from DCS

Knowing the method of getting and archiving data from DCS is a basic issue for a proper building identification algorithms. These types of systems are assigned for plant control. Choice of measured values, their location and precision are adapted to plant controlling. DCS system refreshes all values (read from the

*Corresponding author. E-mail address: badyda@itc.pw.edu.pl

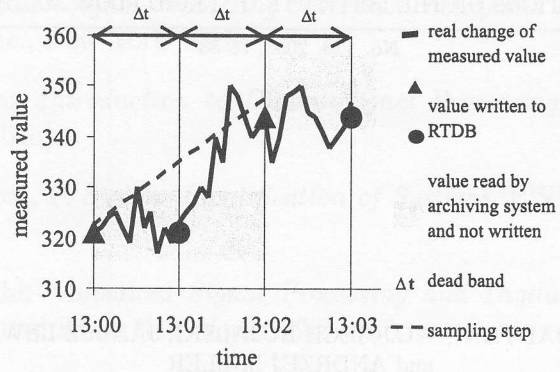

Figure 1. Scheme of writing data to the RTDB.

highway) once every second. These values are called "snapshots". Snapshots are written to the real time database (RTDB) with various frequencies. Archiving procedures check measurement values once every minute (which is a typical value), but not all of these values are written to the RTDB. There are algorithms responsible for limitation of data being written. Such an algorithm checks if the new value differs from the last one written to the RTDB by more than a predetermined value, called the dead band. Typical value of dead band is 1÷5%. Fig. 1 shows an idea of writing data to the RTDB. User can get a value from RTDB for any time. Such value is a linear interpolation between two adjacent points.

1.2 Selecting data for identification process

Data collected for identification process have to be verified. The first step of verification process is to check if the values for individual measurements lie within technically accepted range. Finding steady state is a very important step in selecting data. Characteristics being considered are true for steady state. Steady state doesn't exist in reality, therefore it is necessary to define a state where changes are so small that they do not considerably affect the model precision [1]. There are many different criteria to define it, e.g. maximum deviation during measurements, maximum standard deviation, or maximum number of overflows. It is difficult to decide what is the best method for any specific case and what the defining limits for a chosen method are. It needs a lot of experience in modelling and thorough knowledge about the system being modelled. It is important for identification to consider if values are taken as temporary or average values and if this is the case, what the averaging time is. Temporary values transfer oscillation of measurements associated with process dynamics. This flaw can by removed

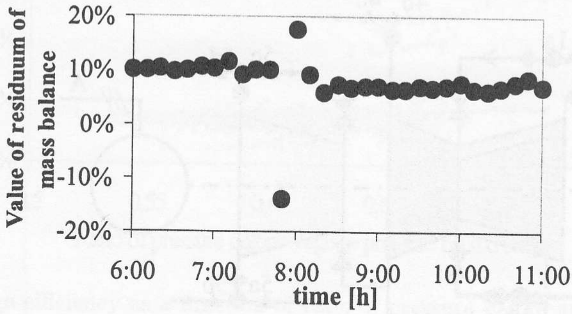

Figure 2. Residuum of mass balance of steam turbine based on temporary values, as percentage of supplied steam flow.

by averaging. Longer averaging time gives better smoothing of deviations, but it also smoothes changes of load. That is why the length of the averaging time should be about 2÷5 min for steam turbines.

One of the methods for removing incorrect values from database, which is used in the identification process, is a verification of primary balances, e.g. mass balance. Example of mass balance variation for steam turbine is shown in Fig. 2.

If there exists a proper set of measurements, equalizing calculations can be performed, which increase precision of obtained results [2, 3].

1.3 Preparing data for testing proposed methods

Database including proper measurement values has been built to verify proposed methods. Data sampled once a minute during a month have been collected. Records longer than 5 minutes have been chosen and successive electric outputs must differ by more than 1%. Data from unsteady state have been removed, too. As a result, the number of records has been reduced from 43000 to 1400.

2 Mathematical model

Models of steam turbines can be divided into two groups:

- full model;
- approximate model.

Full model is based on efficiency and steam flow capacity characteristics. Approximate model is an input-output type, with directly connected input and output data, using simple approximation [4].

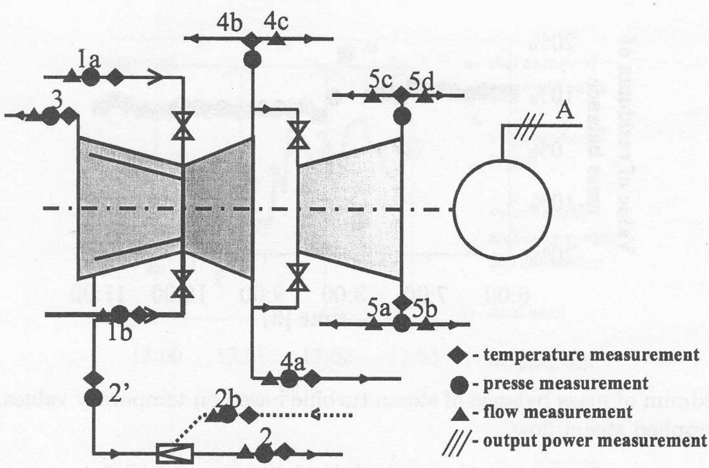

Figure 3. Simplified diagram of a turbine being identified, together with measuring points.

2.1.1 Object of identification

The object of identification is an extraction backpressure turbine working in one of the biggest CHP plants. Simplified diagram of this turbine, together with measuring points, is shown in Fig. 3. For modelling purposes, the turbine can be divided into four groups of stages, separated by extractions. Fig. 3 shows that measurements before the first stage and the last (fourth) stage are performed before valves and, consequently, a complete mathematical model for these stages cannot be identified. It is considered using simplified model for these stages.

2.1.2 Identification of efficiency characteristic

General form of efficiency characteristic of a group of steam turbine stages can be written as [1]:

$$\eta_{i(a,b)} = \eta_{io(a,b)} + 5 \cdot \vartheta \cdot \eta_{io(a,b)} + \vartheta \cdot \eta_{io(a,b)} \cdot \left(\left(\frac{(\pi_o)}{\left(\frac{p_b}{p_a}\right)} \right)^4 + 4 \cdot \left(\frac{(\pi_o)}{\left(\frac{p_b}{p_a}\right)} \right)^{-1} \right) \quad (1)$$

$\eta_{io(a,b)}$ – nominal efficiency, π_o – nominal pressure ratio, p_a – pressure before the group of stages, p_b – pressure behind group of stages, ϑ – coefficient.

Therefore, it is possible to write this characteristic in the following form:

$$\eta_{i(a,b)} = a + 5 \cdot b + b \cdot \left(\left(\frac{(c)}{(\pi)} \right)^4 + 4 \cdot \left(\frac{(c)}{(\pi)} \right)^{-1} \right) \quad (2)$$

where $a = \eta_{io(a,b)}$, $b = \vartheta \cdot \eta_{io(a,b)}$, $c = \pi_o$ are identification coefficients.

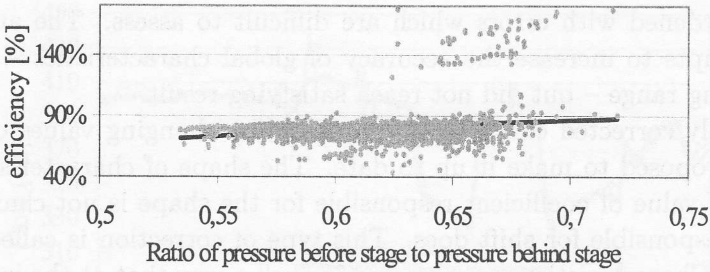

Figure 4. Group stage efficiency as a function of ratio of pressure before and behind the stage, based on the measurements from DCS for the third group of turbine stages for one year, sampled every two hours.

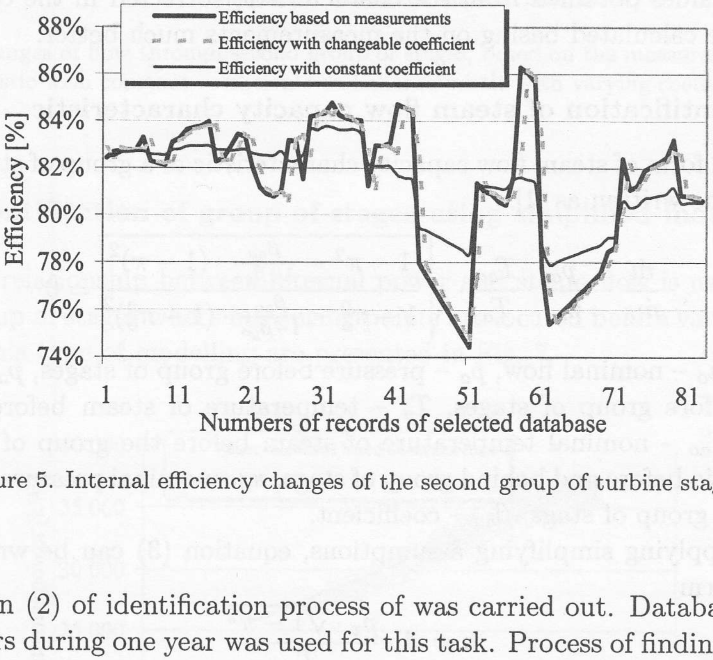

Figure 5. Internal efficiency changes of the second group of turbine stages.

Equation (2) of identification process of was carried out. Database sampled every 2 hours during one year was used for this task. Process of finding the values of coefficients was based on minimizing the sum of squares of differences between measured and calculated values.

Efficiency of group stages depends on the ratio of pressure before and behind the stage. Example of this type of dependence, calculated on the basis of measurements (points) and obtained characteristic (line), is shown in Fig. 4.

Results of identification presented here were tested on the selected database (see chapter 1.3). Results of tests are presented in Fig. 5.

The above figure shows that values calculated basing on the efficiency characteristic hardly reflect values based on the measurements. One of the causes of errors is the fact that measuring instruments are located away from the turbines. It is important to remember that values calculated basing on the measurements are also burdened with errors which are difficult to assess. The authors made many attempts to increase the accuracy of global characteristics – relevant for full operating range – but did not reach satisfying result.

Currently corrected characteristic process (by changing values of the coefficients) is proposed to make it up to date. The shape of characteristic does not change (the value of coefficient responsible for the shape is not changed), while the value responsible for shift does. This type of correction is called an on-line correction. Characteristics are corrected in such a way that at the instant i coefficients calculated at the instant $i-1$ are used, and after having used a coefficient calculated at the instant i, a new coefficient for the instant $i+1$ is calculated. Results of this modelling, using the database described before, are shown in Fig. 6. Efficiency values obtained from the characteristic corrected in the on-line mode reflect those calculated basing on the measurements much better.

2.1.3 Identification of steam flow capacity characteristic

General form of steam flow capacity characteristic of a group of steam turbine stages can be written as [1]:

$$\frac{\dot{m}}{\dot{m}_o} - \frac{p_a}{p_{ao}} \cdot \frac{T_{ao}}{T_a} \cdot \sqrt{\frac{1-\pi^2-\frac{\beta_{go}}{1-\beta_{go}}\cdot(1-\pi)^2}{1-\pi_o^2-\frac{\beta_{go}}{1-\beta_{go}}\cdot(1-\pi_o^2)^2}} = 0 \tag{3}$$

$\dot{m}$ – flow, $\dot{m}_o$ – nominal flow, p_a – pressure before group of stages, p_{ao} – nominal pressure before group of stages, T_a – temperature of steam before the group of stages, T_{ao} – nominal temperature of steam before the group of stages, π – pressure ratio before and behind group of stags, π_o – nominal pressure ratio before and behind group of stags, β_{go} – coefficient.

After applying simplifying assumptions, equation (3) can be written in the following form:

$$\dot{m} = A \cdot \frac{p_x \cdot \sqrt{1-\pi^2}}{T_x} \tag{4}$$

where: $A = \frac{T_{x\,o}}{p_{x\,o}} \cdot \sqrt{\frac{1}{1-\pi_o^2}} \cdot \dot{m}$

Identification of steam flow capacity characteristic process was made in the same way as for the identification of efficiency of groups of stages. Calculations were performed basing on data collected during one year, sampled every two hours. A criterion to find coefficients was to minimize the sum of squares of the differences between calculated value and measured one. Fig. 6 shows the results of calculations.

There are relatively big temporary changes of characteristic with varying coefficients in both cases: efficiency and steam flow capacity. Adding limitations for coefficient changes in one step can smooth it.

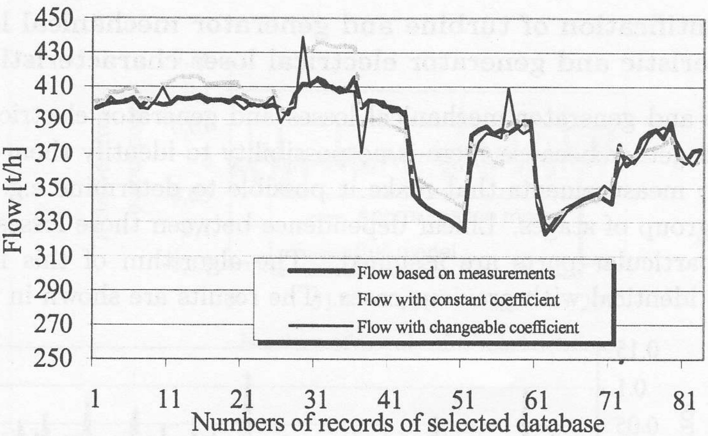

Figure 6. Changes of flow through second group of stages, based on the measurements, characteristic with constant coefficients and characteristic with varying coefficients.

2.1.4 Identification of group of stages using simplified model

Simple relationship between internal power and steam flow is used for modelling a group of stages where measuring points are located before valves. Typical results of this type of modelling are presented in Fig. 7.

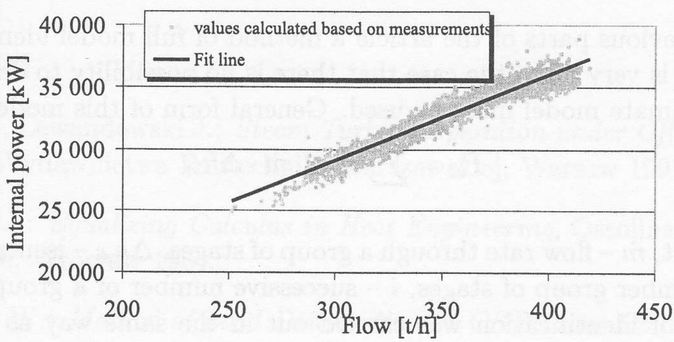

Figure 7. Relationship between internal power and steam flow for the first group of turbine stages.

The results are of the same accuracy as previous ones, for a full model. Correction for characteristic accuracy was used for this type of modelling, too. The result of this type of approach is the same as in previous cases.

2.1.5 Identification of turbine and generator mechanical losses characteristic and generator electrical loses characteristic

Turbine and generator mechanical losses and generator electrical losses are considered together because there is no possibility to identify them separately – there are no measurements that make it possible to determine e.g. mechanical power of a group of stages. Linear dependence between those losses and output power for particular parts are assumed. The algorithm of this identification process was identical with previous cases. The results are shown in Fig. 8.

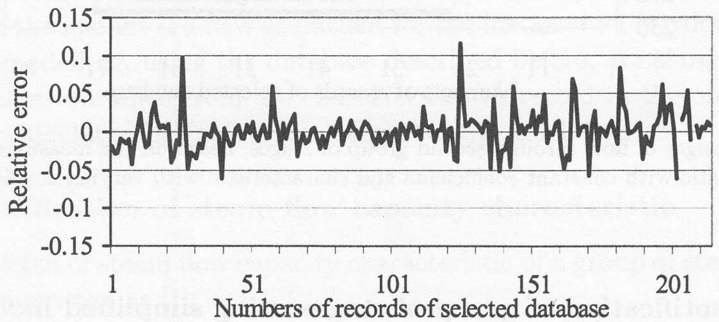

Figure 8. Relative output power error.

2.1.6 Approximate model

In the previous parts of the article a method of full model identification was presented. It is very often the case that there is no possibility to do this. In such cases approximate model must be used. General form of this model is:

$$P_{el} = \sum a_i^n a_i \cdot \dot{m} \cdot \Delta h_{si} \tag{5}$$

where:

a_i – coefficient, $\dot{m}$ – flow rate through a group of stages, Δh_{si} – isentropic enthalpy drop, n – number group of stages, i – successive number of a group of stages. The process of identification was carried out in the same way as described for the full model. The results of calculations are shown in Fig. 9. Full model and approximate model have similar precision, but approximate model does not have so big temporary deviation.

3 Summary

Methods and algorithms necessary to build characteristics based on data taken from the DCS are presented. The results show that the precision of mea-

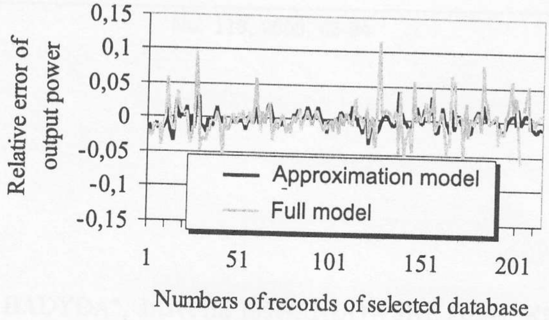

Figure 9. Relative error of the output power calculated basing on full and approximate model.

surements in DCS systems is very low. It is not possible to build sufficiently precise global characteristic, describing operation of the modelled system for the full operating range. Using the on-line correction of characteristic coefficient, gives quite good results. This method of modelling is proper, especially for processes without switching on/off devices in the system, because model calibration is made under the same conditions as the modelling process.

Received 5 May 2003

References

[1] Miller A., Lewandowski J.: *Steam Turbine Operation under Off-Design Conditions*, Wydawnictwa Politechniki Warszawskiej, Warsaw 1992.

[2] Szargut, J.: *Equalizing Calculus in Heat Engineering*, Ossolińskich Publishing House, Wrocław 1984.

[3] Bujalski, W.: *Method of Load Distribution in CHP Plant Controlled by distributed control systems (DCS)*, Ph.D. Thesis, Warsaw University of Technology, Warsaw 2002.

[4] Badyda K.: *Problems of Mathematical Modelling of Power Installations*, Oficyna Wydawnicza Politechniki Warszawskiej, Warsaw 2001.