A New Power Generating Units Dynamic Model

S. Glickman, R. Kulessky, G. Nudelman

The Israel Electric Corporation Ltd., Generation & Transmission Group, P.O. Box 10 Haifa 31000 Israel

Abstract: This paper presents a new power generating unit dynamic model that requires only one experiment for parameter identification. This model represents boiler pressure effects as a differentiating process with its subsequent identification through a new approach. In addition, a novel procedure is proposed for the model parameter correction in case that the identification test is not sufficiently informative. This dynamic model is developed in the vicinity of the steady-state operation mode and can be used for load-frequency control tuning or its redesign, for Automatic Generation Control purposes, as well as a base for real-time simulators for dispatcher training. The modeling of 575MW power units of the IEC (Israel) is fulfilled through implementation of this model yielding sufficiently good results.

Keywords: Boiler-turbine models, Transfer function identification, Power system modeling

1. INTRODUCTION

We consider a Load-Frequency Control Unit Model (LFCUM) of a steam generation unit [3] that models unit load responses to net-frequency deviations and to load set point changes in vicinity of steady-state mode. Such dynamic model is needed first for the analysis of the “primary grid – frequency control”. Actually, the LFCUM is required to keep the dynamic response quality [11] by tuning of Unit Coordinated Control which influences directly on this response in the vicinity of ±(5-10)% of the steady–state mode parameters. This problem is especially urgent for networks with limited energy reserve in particular for the Israeli networks. Furthermore, LFCUM is needed for adequate description of the power unit’s required by the Automatic Generation Control (AGC) [5]. In addition, such LFCUM may also be used as a part of a real time simulator for operation staff and dispatcher training.

General nonlinear models for steam generation plant (see, for example, [1,4,9]) are related to physical and construction data. Obtaining of these data needed for accurate model calculation may be problematic for some working units. Actually, these models are often applied as a basis for developing corresponding LFCUM through identification technique [2,10,12]. Based on this approach, the LFCUM is developed in [3] according to the following principles:

- The LFCUM identification requires three relatively simple experiments.
- A transfer function identification method is used providing the model order reduction as a part of its own identification procedure. This identification is based on a test exited by a deterministic signal, which is used instead of the pseudo-random binary sequence (PRBS) excitation [2,12].
- The developed LFCUM structure includes only inertia and integrating links, which can be accurately identified by the proposed method.

There are several reasons to improve the LFCUM as developed in [3]. First, usage of this LFCUM requires identification of its parameters for every new operation point set, in vicinity of which this model is identified. Because this identification requires three experiments, the full model creation (for full load range) can be time- and cost consuming. So it is reasonable to develop LFCUM based on only one experiment. Such LFCUM is proposed in this paper by representing boiler pressure effects as a differentiating process. Another problem relates to the identification method [3,8]. This method is successful if frequency response (FR) data is enough informative for the transfer function (TF) identification. Frequency interval \((\omega_{\text{min}}, \omega_{\text{max}})\) in which FR is identified depends on signal to noise ratio. So this interval can be reduced because of this ratio decreasing what will cause a loss of the identification accuracy. There are two ways to overcome this problem: either \(\omega_{\text{min}}\) decreasing without filtering the noised data or \(\omega_{\text{max}}\) increasing through this data filter. This paper modifies the method [3,8] in the frame of the second way.

Additional problem of the approach [3] may arise due to limited performances of an identification experiment. For example, a load set point change has a limited rate for a working unit. If FR will be identified using such test signal, the identified FR may be not enough informative to represent adequately a process in the high frequency domain. It means that the identified TF does not give the adequate representation of fast processes. At the same time, net frequency abrupt deviation can lead to fast load changes. On the other hand, the above-identified TF can not adequately represent these load changes. On the other hand, the real load response caused by this abrupt deviation can be used for correction of the above identified TF. This paper presents a corresponding approach for this correction.

The behavior of LFCUM described here represents the basic dynamics of a 575MW unit at the Rutenberg Power Station (Israel).

2. MODEL DEVELOPMENT

2.1. Steam Generator Structure

For load-frequency control purposes, LFCUM is required to represent load and throttle pressure behavior. So, a model of boiler pressure effects has to be developed in the first instance.

The nonlinear equation [4] relates the steam flow \(S_F\) to the throttle pressures \(P_T\) and the control valve area \(C_v\):
Expanding the right hand side (1) into the Taylor series around an operating point \((C_{v_0}, P_{r_0}, S_{f_0})\) we derive the linear equation about deviations \((\Delta C_P, \Delta P_r, \Delta S_f)\):

\[
\Delta S_f = k}\Delta C_P - P_{r_0} + \Delta P_r \cdot C_{v_0}
\]

where \(k = \frac{S_{f_0}}{C_{v_0}P_{r_0}}\).

Assume that the boiler pressure effect model is described by the following equation in the Laplace transform form:

\[
\Delta P_r = W_{bl}(s) \cdot \Delta C_T(s)
\]

(3)

We consider that (3) presents this effect for a throttle pressure process operating in a closed control loop. In this operation the throttle pressure set point is taken constant. Substituting (3) into (2) and using the Laplace transform we arrive at the following incremental equation:

\[
\Delta S_f = (kP_{r_0} + kC_{v_0}W_{bl}(s))\Delta C_T(s)
\]

As it follows from physical considerations, the transfer function \(W_{bl}(s)\) possesses properties of a differentiating dynamic link. It is determined here as a link the transfer function of which has one zero in the origin of \(s\)-plane. This implies that a dynamic differentiating link can be represented as a series connection of a pure differentiating link with the transfer function \(s\) and a low-pass filter of arbitrary order.

\[
\Delta S_f\text{ is estimated by the similar equation}
\]

\[
\Delta S_f = (kP_{r_0} + kC_{v_0}W_{bl}(s))\Delta C_T(s)
\]

(5)

where \(W_{bl}(s)\), a turbine-generator transfer function, has to be identified.

### 2.2. Turbine-Generator Structure

The turbine-generator model [4] is described in terms of deviations of the mechanical power \(\Delta P_m\) and the steam flow \(\Delta S_f\) by the linear equation:

\[
\Delta P_m = W_{tg}(s) \cdot \Delta S_f(s)
\]

(6)

\(\Delta S_f\) is estimated similarly:

\[
\Delta S_f = \hat{W}_{tg}(s) \cdot \Delta S_f(s)
\]

(7)

where \(\hat{W}_{tg}(s)\), a turbine-generator transfer function, has to be identified.

### 2.3. Load-Frequency Control System (LFC) Structure

For two identical 575MW units, No.1, 2 (Rutenberg PS) the LFC is presented by the following equations. The governor as an electro-hydraulic servo is described by the saturation nonlinear function \(\varphi_t\) relating the load-frequency controller output \(C_t\) and the feed-forward \(C_f\) from the network frequency deviations \(\Delta F_n(t)\) to the control valve \(C_v\) position:

\[
\Delta C_t = \varphi_t(C_v, C_f, HL, LL)
\]

(8)

where \(HL, LL\) are high- and low- limits of \(C_v\) position.

The load controller with transfer function \(W_L(s)\) forms the first component of control valves position demand \(C_v^l\):

\[
\Delta C_t = W_L(s) \cdot \varepsilon_L(s)
\]

(9)

The error load \(\varepsilon_L\) is calculated here as follows:

\[
\varepsilon_L = \Delta L_{sw} - \Delta P_r + c \cdot J \cdot F_{sw} \cdot \frac{d\Delta F_n}{dt} + e_f - k \cdot \Delta P_r
\]

(10)

where: \(L_{sw}\) is load set point; \(P_r\) is actual electric power measured on the generator’s terminals; \(J, c\) are the inertia constant of a power unit and a proportional gain, respectively; \(F_{sw}\) is an operating point of the Taylor series expansion for the net frequency function \(F_n(t); k\) is a gain.

Fig.1 illustrates unit 575MW responses in the mode, which is equivalent to \(\tau = (118.0)\text{ Hz} t\). As one can see, the unit load is increased on 30MW during 8sec when \(MW/minRHL \approx 40\). Such fast response is mainly caused by \(C_f\). Both 575MW units are tuned identically.
If the load set point rate was not wide enough, the identified problem is overcome in the following way. Usually, transfer functions of power station processes are of problematic in the case of an unknown TF order. In [3,8] this is computed as the ratio \( W_{k}(s) = \Delta P_{k}(s) / \Delta S_{k}(s) \), \( k = 1, 2, 3, \ldots \) be the \( k \)-level TF where \( \Delta S_{k}(t) \) is the steam flow estimate after the power unit simulation with the \((k-1)\)-level TF of this turbine-generator. We assume that \( \Delta S_{1} = \Delta S_{F} \).

There are two methods to provide the required accuracy: either \( \omega_{max} \) decreasing or max \( \omega \), which can cause a decrease in the identification accuracy measured by [8]

3.3. Theorem 1

The boiler transfer function \( W_{BL}(s) \) is calculated as the ratio \( W_{BL}(s) = \Delta P_{k}(s) / \Delta C_{F} \) using the data (13). Recall that \( W_{BL}(s) \) is described as a differentiating link.

Let us assume that FR is identified in frequency interval \( [0, \omega_{max}] \). Due to the dependence of \( \omega_{max} \) on the noise level, this interval can be reduced (see Theorem in [3]). Then FR is identified within a more narrow frequency interval, which can cause a decrease in the identification accuracy.

\[
\lim_{k \to \infty} W_{TG}(s) = W_{TG}(s)
\]

4. BOILER IDENTIFICATION

The boiler transfer function \( W_{BL}(s) \) is calculated as the ratio \( W_{BL}(s) = \Delta P_{k}(s) / \Delta C_{F} \) using the data (13). Recall that \( W_{BL}(s) \) is described as a differentiating link.

Let us assume that FR is identified in frequency interval \( [0, \omega_{max}] \). Due to the dependence of \( \omega_{max} \) on the noise level, this interval can be reduced (see Theorem in [3]). Then FR is identified within a more narrow frequency interval, which can cause a decrease in the identification accuracy measured by [8]

\[
R = M\{ (m_{s}(t) - \hat{h}(t))^2 \}
\]

where:

\( M\{ \bullet \} \) is the expected value of the bracketed function;

\( m_{s}(t) \) is the expected value of the process output;

\( \hat{h}(t) \) is the process model output.

There are two ways to provide the required accuracy: either \( \omega_{max} \) decreasing or \( \omega_{max} \) increasing. The theorem below applied to the second way can be proved.

4.1. Theorem 2

Let the initial data used for identification be the output \( h(t) \) and the input \( u(t) \) signals of the process. Suppose that \( h(t) = m_{s}(t) + h^{0}(t) \), where \( h^{0}(t) \) is an independent stationary random signal with zero mean value and spectral density function \( H^{+}(i\omega) \); \( u(t) \) is a deterministic function. Further, \( m_{s}(t) = u(t) = 0 \) for \( t \leq 0 \) and \( m_{s}(t) = h_{0} \), \( u(t) = u_{0} \) for \( t \geq T \), where \( T \) is the recovery time of a time response.

Let the above initial data be filtered by the link

\[
F(s) = (\sigma \cdot s + 1)^{-1}
\]

Then the new data are defined:

\[
h_{i}(i\omega, \sigma) = h(i\omega)F(i\omega)
\]

\[
u_{i}(i\omega, \sigma) = u(i\omega)F(i\omega)
\]

The following functions are introduced now:
\[ e_s(t) = h_0 - h_1(t, \sigma) \]
\[ e_u(t) = u_0 - u_1(t, \sigma) \]  
(18)

Let \( m_0(t, \sigma) = h_0 \) and \( u_1(t) = u_0 \) for \( t \geq T \) where \( m_0(t, \sigma) \) is the expected value of \( h_0(t, \sigma) \).

In accordance with the Theorem [8], the frequency response of the process model \( \tilde{W}(i\omega) \) is calculated as the ratio

\[ \tilde{W}(i\omega) = \frac{e_s(i\omega)}{e_u(i\omega)} \]  
where \( \omega \in [0, \omega_{\text{max}}(\sigma)] \).

Then

\[ \omega_{\text{max}}(\sigma) > \omega_{\text{max}}(0), \sigma > 0 \]  
(20)

**Remark**

One can assure that increasing \( \omega_{\text{max}} \) does not necessarily cause a rise of the identification accuracy measured by (16). So in parallel with \( \omega_{\text{max}} \) changing, values of \( R(\omega_{\text{max}}) \) have to be checked.

### 5. IDENTIFICATION RESULTS

Two identical 575MW units, No.1, 2 (Rutenberg PS) were used in identification and validation experiments. The main goal was to check the accuracy of the unit’s dynamic representation by the presented model on the vicinity of the boundaries around the steady-state mode. The CSTP [6,7] was used for all identification.

The steady-state operating point around which the unit No.1 was linearized is:

\[ (P_{g0}, S_{g0}, P_{v0}, C_{v0}) = 174.4\text{Atm}, 1530 / h, 510\text{MW}, 80\% \]  
(21)

The identification data (13) was obtained in response to the load set point \( \Delta P_L \) (Fig.4, a).

5.1. Boiler identification of the power unit No.1

Three identified transfer functions of the unit No.1 boiler are given below together with filter parameters \( \sigma [\text{sec}] \), see Theorem 2:

\[ \tilde{W}_{ac}(s) = \frac{3740s^2 + 22s}{2657s^3 + 2458s^2 + 311s + 1}, \quad \sigma = 1, \]  
(23)

\[ \tilde{W}_{ac}(s) = \frac{-0.51s^3 + 20.3s}{223s^3 + 2322s^2 + 60s + 1}, \quad \sigma = 100, \]  
(24)

\[ \tilde{W}_{ac}(s) = \frac{-156s^3 + 20s}{0.96s^3 + 23s^2 + 44.8s + 1}, \quad \sigma = 120 \]  
(25)

Identification results involve also a comparison between time responses of processes and their identified models (Fig.3). As one can see from these figures, the best boiler model is described by (24) and the optimal filter is defined by \( \sigma = 100\text{sec} \). We emphasize that a change of \( \sigma \) from 100sec to 120sec totally change the character of the results (compare Fig3b,c). This phenomenon is explained as follows:

According to Theorem 2 the following conditions have to be fulfilled: \( m_0(t, \sigma) = h_0 \) and \( u_1(t) = u_0 \) for \( t \geq T \). Because the data length are bounded by \( T (T=370\text{sec}, \text{Fig.3}), \) there exists a certain \( \sigma \) (namely \( \sigma > 100\text{sec} \)) which causes violating these conditions and deteriorating identification results.

We note that (24) can be represented as a series connection of the differentiating link \( 20.3s \) and the filter \(-0.028s + 1)/(223s^3 + 2322s^2 + 60s + 1) \).

Fig.3. Plot of simulated and measured throttle pressure responses: a) \( \sigma = 1\text{sec} \); b) \( \sigma = 100\text{sec} \); c) \( \sigma = 120\text{sec} \)

5.2. Turbine-generator identification

The first-level TF of the turbine-generator of the power unit No.1 identified by using CSTP is as follows:

\[ \tilde{W}_{T_G}(s) = \frac{0.32}{24.1s + 1} \]  
(26)

The steam flow estimate satisfies the linear equation (2) around the operating point (21):

\[ \Delta S = 5.3C_v + 2.4\Delta P_y \]  
(27)

By usage of (24), (26), (27) time responses of the closed LFCUM to the load set point \( \Delta L_{sp} \) (Fig.4, a) were simulated (Fig.4). As one can see, there is a sufficiently good match between the model responses and real responses of unit No.1.
In this identification experiment, the load up extends over 300sec. At the same time, abrupt net frequency deviations cause faster responses of duration 10-20sec. So, the model (26) can not adequately describe the load process in the high frequency domain and it has to be corrected.

The 2nd- and 3rd-level models for turbine-generator of unit No.1 are identified following Theorem 1. The data acquired from an interruption caused by 218MW unit at Eshkol PS tripping.

The following transfer functions are identified:

$$\hat{\mathcal{W}}_{\nu_1}(s) = \frac{0.46}{5.32s + 1}$$  \hspace{1cm} (28)

$$\hat{\mathcal{W}}_{\nu_2}(s) = \frac{0.37}{8.1s^2 + 4.7s + 1}$$  \hspace{1cm} (29)

The transfer function $\hat{\mathcal{W}}_{\nu_2}(s)$ identified by the “slow data” (13) can not accurately reproduce the fast components of this unit response. Usage of $\hat{\mathcal{W}}_{\nu_1}(s)$ increases the prediction accuracy (see validation results below).

6. VALIDATION RESULTS

The identified model was validated by simulation of units No.1-2 at Rutenberg PS behavior in regimes of net frequency abrupt deviations. This validation is fulfilled by usage of the third-level model for turbine-generator. The functions (24), (27), (29) were used without changes in validation tests. Two of them are exemplified in Fig.5, 6.

The time responses (Fig.5) show the behavior of units No.1 to a grid frequency drop (Fig5b) caused by 575MW unit at Maor David PS tripping. Fig.6 illustrates the behavior of units No.2 to a grid frequency deviations (Fig6b) caused by 218MW unit at Eshkol PS tripping.

As one can see from Fig.5, 6 the identified model represents dynamic response of Rutenberg PS units No.1, 2 with sufficient accuracy.
7. CONCLUSIONS

The simplified generating unit model oriented towards load-frequency control and a method for its identification are presented. The purpose of this model development is to obtain the best possible accuracy of unit load and of throttle pressure simulation which are the most important variables for the analysis of the behavior of the load frequency control system. In the general case, the developed model requires only one identification experiment, which is achieved through representing boiler pressure effects as a differentiating process. The identified model can be corrected by the developed procedure using data of unit behavior in normal working regimes. The presented modification of the identification method extends transfer function bandwidth. In addition, noise effects are also reduced. The developed model can be used for redesign or tuning of load-frequency control system, for AGC control purposes as well as building or setting up a real-time simulator for dispatcher training. The modeling for 575MW power units of the IEC is fulfilled by implementation of the proposed model and its identification approach yielding sufficiently accurate results.

8. ACKNOWLEDGMENT

The authors wish to thank D. Kohn and M. Bachar for their help in planning and executing this work at the Israel Electric Corporation.

9. REFERENCES


10. BIOGRAPHIES

Steve Glickman was born in the United States in 1947. He received his M.S. and Ph.D. degrees, all in Electrical Engineering, from the Ural Polytechnic Institute (UPI), Russia, in 1959 and 1967. He received his Dr.Sc degree in Electrical Engineering from the Moscow Energy Institute in 1988. Up to 1991 he had worked in Russia: the Ural Turbine Plant (1959-61), Electro-Project Institute (1961-67), the UPI (1967-91). Since 1989 he is a full professor at the UPI. After immigrating to Israel he began working as a senior controls specialist in the control system department of the Israel Electric Corporation, where he has worked until the present. His research interests are digital control systems optimization, process identification, variable bandwidth control, amplitude quantization theory.

Roland Kulessky was born in Russia in 1937. He received his M.S. and Ph.D. degrees, all in Electrical Engineering, from the Ural Polytechnic Institute (UPI), Russia, in 1959 and 1967. He received his Dr.Sc degree in Electrical Engineering from the Moscow Energy Institute in 1988. Up to 1991 he had worked in Russia: the Ural Turbine Plant (1959-61), Electro-Project Institute (1961-67), the UPI (1967-91). Since 1989 he is a full professor at the UPI. After immigrating to Israel he began working as a senior controls specialist in the control system department of the Israel Electric Corporation, where he has worked until the present. His research interests are digital control systems optimization, process identification, variable bandwidth control, amplitude quantization theory.

Gregory Nudeman was born in Russia in 1958. He received his M.S. degree in Control System Engineering from the Moscow Institute of Railway Engineering in 1980. Up to 1991 he had worked in Russia as a Control Field Engineer at the Start Up Company (1981-1991). There he dealt mainly with optimization of power unit control systems configuration and their performance optimization in their main regimes. From 1992 he has worked in Israel as a controls engineer at the Haifa Power Station of the Israel Electric Corporation. His research interests are thermal power process identification, load – frequency coordination control, industrial control system tuning, auto-tuning problems.