Control-Oriented Modeling of the Energy-Production of a Synchronous Generator in a Nuclear Power Plant

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Abstract

A simple dynamic model of the synchronous generator in Paks Nuclear Power Plant (Hungary) is developed in this paper based on first engineering principles that is able to describe the time-varying active and reactive power output of the generator. These generators are required to take part in the reactive power support of the power grid following the demand of a central dispatch center, and also contribute to the frequency control of the grid. The developed model has been verified under the usual controlled operating conditions when the frequency and the active power are controlled.

Static and dynamic sensitivity analysis has been applied to determine the model parameters to be estimated. The model parameters have been estimated applying the asynchronous parallel pattern search method using real measured data from the nuclear power plant. The confidence regions in the parameter space have been analyzed by investigating the geometry of the estimation error function.

The developed model can serve as a basis for controlling the optimal energy production of the generator using both the active and reactive power components.

Keywords: Electrical energy generation, Active and reactive power, Synchronous generator, Dynamic modeling, Parameter estimation

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1. Introduction

A major portion of industrial energy distribution and transportation is performed in the form of electrical energy using large-scale electrical power grids. Both of the energy consumers and producers are connected to this grid that should be operated in a balanced way taking into account the time-varying power demand of the consumers that is difficult to predict. The properties of the consumers are modeled by various types of loads: (i) an resistive one, that represents, for example, heating devices, traditional bulbs, that require active (or resistive) power, (ii) an resistive one with serial inductance representing motors and rotating household appliances (washing machine, lawnmower etc.) and (iii) a capacitive input stage load for representing the simple nonlinear switching mode power supplies. The latter two types of loads need reactive power, that adds to the active one as a vector when the total power is computed.

The power plants, that are the energy sources, can also be of various types including nuclear power plants, wind and solar power plants, just to mention often discussed hypothetical future sources of electric energy(after terminating fossil fuel production). From the viewpoint of the power grid the electric power generation of these plants can be characterized by the operation of the electrical generators, the subject of our study. These power plants should be able not only to follow the time-varying active and reactive power demand of the consumers, but also keep the quality indicators (frequency, waveform, total harmonic distortion) of the grid [1]. This can be achieved by applying proper control methods based on dynamic models of the involved generators.

Reactive power is tightly related to bus voltages throughout a power network, and hence it has a significant effect on system security. Its importance is indicated by the fact that insufficient reactive power of the system may result in the voltage collapse. Therefore, it is widely accepted that the consumer of reactive power should pay for the reactive power support service and the producers of reactive power are remunerated [2]. The problem of controlling the reactive power production as a component of the effective integration of renewable energy sources into the power grid is analyzed and solved in [3] using the dynamic model of the generator of the plant. A simple dynamic model of permanent magnet synchronous generators is reported in [4], that is used to investigate their short-term transient behavior to investigate their direct interconnection to the grid.

The electrical energy generation by power plants using renewable energy (wind, solar, etc.) has attracted a great attention nowadays because of its practical importance. The modeling and analysis of the steady-state behavior for various operating conditions of a six phase synchronous generator used as a stand-alone electric energy source is presented in [5] in conjunction with a hydro power plant. The experimental investigation of the same generator is reported in [6].

Because of the specialities and great practical importance of synchronous generators in power plants, their modeling for control purposes is well investigated in the literature. Besides of the basic textbooks (see e.g. [7]) that develop general purpose dynamic models for SGs, there are several papers that describe the modeling and use the developed models for dynamic analysis and controller studies [8]. Two SG models are presented and analyzed in [8], that are validated using a 75 kVA salient-pole synchronous machine with damper windings. In [9] a new method of SG modeling is presented taking an infinite inner resistance into account, and a statistical technique for determining the parameters of the synchronous machine is also proposed.

It is well known that integrating distributed generation into electric power systems presents great challenges and opportunities at the same time [10], that does not only need suitable dynamic models for the involved synchronous generators, but also a dynamic model of the power grid with its consumers. Therefore, it is important to emphasize that control-oriented modeling of real industrial generators in power plants presents special requirements and challenges because of the frequent and unforeseen disturbances from the electrical network and the load changes caused by the switching between the high and low production operating mode of the power plant. An optimization study was presented in [11] with constraints for the excitation control in synchronous generators, that aims at damping oscillations in the grid and uses a simple dynamic model of the generators. Another control study of synchronous generators is reported in [12], that focuses on the regulation of the active and reactive power to a set point ordered by the wind farm control system, where also a simple dynamic model of the generators is utilized.

Nuclear power plants (NPPs) generate electrical power from nuclear energy, where the final stage of the power production includes a synchronous generator (SG) that is driven by a turbine. Although nuclear energy is not considered as a promising clean energy source on a world scale [13], the electrical energy produced by the Paks Nuclear Power Plant (Paks NPP) presents 40 % of the total electrical energy production in Hungary, thus its efficient and safe operation is vital. Although it is well known that nuclear power plants are operated mostly and efficiently such that their maximal power is produced, the generators of the Paks NPP are required to take part in the reactive power support of the power grid following the demand of a central dispatch center of Hungary. In addition, the operating nuclear power plant units also contribute to the frequency control of the grid by adjusting the nuclear power of the reactor itself. The above grid-wide control functions are partially supported by the operation of three main coupled control loops: the reactor power, turbine and generator controllers.

The refurbishment of the control system of this plant has already been started as part of its lifetime extension project. This gives the possibility to extend and improve the functionality of the present control system to be able to control both of the generated active and reactive power components effectively and simultaneously. Therefore, the aim of this paper is to propose a dynamic model of the SGs in the Paks NPP for control studies that is able to describe its dynamic (transient) behavior in the short term (1 sec - 1 hour) time range. Furthermore, an optimization-based method is also to be developed for estimating the model parameters from industrial measured data.

2. The synchronous generator model

In this section a state space model of a synchronous generator is presented. The model development is largely based on [7], but the special circumstances of the generator operation in the considered NPP have also been taken into account. It is important to note, however, that large industrial synchronous generators operating in other (e.g. hydro, gas or coal powered) types of power plant have similar operating conditions and grid requirements, therefore the resulting dynamic model is also applicable there.

Only the basic steps of the model development and the resulting model equations are described here using the notation list found in the Appendix. The detailed derivation together with the results of the model analysis can be found in [14], [15].

2.1. System description and operating conditions

The Paks NPP, where the investigated generators work, is located in Hungary, and operates four pressurized water (VVER-440/213 type) reactors with a total nominal electrical power of 2000 MW. Each reactor is equipped with two turbine-generator units that work in parallel. The turbo generator, the subject of our study, is a specific SG with a special cooling system.

There are two main control loops operating at each turbine-generator unit. One PI controller regulates the angular velocity by manipulating the mass flow of the steam to the turbine, i.e. the mechanical torque. The other PI controller keeps the active power by manipulating the exciter voltage. Similarly to other power plants, both active and reactive components of the generated power depend on consumer needs and on their own operability criteria. This consumer generated time-varying load is the major disturbance that should be taken care of by the generator controller.

The final aim of our study is to design a controller that controls reactive power so that its generation follows an externally given trajectory while the quality of the control of active power remains (nearly) unchanged.

2.2. The engineering model

For constructing the SG model, the following modeling assumptions are made:

- a symmetrical tri-phase stator winding system is assumed,
- one field winding is considered to be in the machine,
- there are two amortisseur or damper windings in the machine,
- all of the windings are magnetically coupled,
- the flux linkage of the winding is a function of rotor position,
- the copper loss and the slots in the machine can be neglected,
- the spatial distribution of the stator fluxes and apertures wave are considered to be sinusoidal,
- stator and rotor permeability are assumed to be infinite.

It is also assumed that all the losses due to wiring, saturation, and slots can be neglected.

The engineering model consists of three parts: the electrical, mechanical and controller parts respectively. The detailed derivation can be found in [15], while the notation list is given in the Appendix.

2.3. Electrical part of the model

The voltage equations of the generator can be expressed in a simplified matrix form as

$$\mathbf{v_{dFDqQ}} = -\mathbf{R_{RS\omega}}\mathbf{i_{dFDqQ}} - \mathbf{L}\dot{\mathbf{i}}_{\mathbf{dFDqQ}}, \tag{1}$$

where $\mathbf{v_{dFDqQ}} = \begin{bmatrix} v_d & -v_F & v_D = 0 & v_q & v_Q = 0 \end{bmatrix}^{\mathbf{T}}$ and $\mathbf{i_{dFDqQ}} = \begin{bmatrix} i_d & i_F & i_D & i_q & i_Q \end{bmatrix}^{\mathbf{T}}$, while $\mathbf{R_{RS\omega}}$ and $\mathbf{L}$ are given by the following expressions

$$\begin{aligned}
\mathbf{R_{RS\omega}} &= \begin{bmatrix} r & 0 & 0 & \omega L_q & \omega k M_Q \\ 0 & r_F & 0 & 0 & 0 \\ 0 & 0 & r_D & 0 & 0 \\ -\omega L_d & -\omega k M_F & -\omega k M_D & r & 0 \\ 0 & 0 & 0 & 0 & r_Q \end{bmatrix} \\
\mathbf{L} &= \begin{bmatrix} L_d & kM_F & kM_D & 0 & 0 \\ kM_F & L_F & M_R & 0 & 0 \\ kM_D & M_R & L_D & 0 & 0 \\ 0 & 0 & 0 & L_q & kM_Q \\ 0 & 0 & 0 & kM_Q & L_Q \end{bmatrix}.
\end{aligned}$$

The simplified equivalent circuit of the model is shown in Fig. 1.

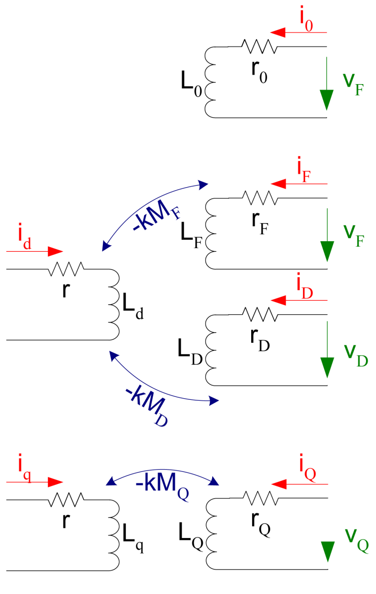

Figure 1: The simplified equivalent circuit of the transformed stator and rotor circuits

The state space model for the currents is obtained by expressing $\dot{\mathbf{i}}_{\mathbf{dFDqQ}}$ from (1), as

$$\frac{d}{dt}\mathbf{i}_{\mathbf{dFDqQ}} = -\mathbf{L}^{-1} \cdot \mathbf{R}_{\mathbf{RS}\omega} \cdot \mathbf{i}_{\mathbf{dFDqQ}} - \mathbf{L}^{-1} \cdot \mathbf{v}_{\mathbf{dFDqQ}} \tag{2}$$

2.4. Mechanical part of the model

The total torque accelerating the generator can be expressed as

$$T_{Acc} = T_{Mech} - T_{Electr} - T_{Dump},$$

where T_{Mech} stands for the mechanical torque and T_{Electr} is the electrical torque. It is often convenient to write the damping torque as $T_{Dump} = D\omega$, where D is a damping constant.

Since $\dot{\omega} = \frac{T_{Acc}}{\tau_j}$, the time derivative of the angular velocity is

$$\dot{\omega} = -\frac{L_d i_q}{3\tau_j} i_d + \frac{-kM_F i_q}{3\tau_j} i_F + \frac{-kM_D i_q}{3\tau_j} i_D + \frac{L_q i_d}{3\tau_j} i_q + \frac{kM_Q i_d}{3\tau_j} i_Q + \frac{-D}{\tau_j}\omega + \frac{T_{Mech}}{\tau_j}. \tag{3}$$

Note, that (3) can be used as a supplementary state equation for state space model (2).

The torque angle (δ) of the SG is

$$\delta = \delta_0 + \int_{t_0}^{t} (\omega - \omega_r) dt, \tag{4}$$

which can be differentiated to obtain $\dot{\delta}$ in per unit notation

$$\dot{\delta} = \omega - 1, \tag{5}$$

so the torque angle (δ) can also be regarded as a state variable in the model (2), (3) and (5).

Altogether, there are seven state variables: i_d, i_F, i_D, i_q, i_Q, ω and δ. Input variables (i.e. manipulable inputs and disturbances) are T_{Mech}, v_F, v_d and v_q. Observe, that state equations (2), (3) and (5) *are bi-linear in the state variables* since matrix $\mathbf{R}_{\mathbf{RS}\omega}$ in (2) is a linear function of ω.

2.5. Output equations of the model

The output active power equation can be written in the following form:

$$p_{out} = v_d i_d + v_q i_q + v_0 i_0 \tag{6}$$

Assuming steady state conditions for the stationary components ($v_0 = i_0 = 0$), (6) simplifies to

$$p_{out} = v_d i_d + v_q i_q, \tag{7}$$

and the reactive power is

$$q_{out} = v_d i_q - v_q i_d. \tag{8}$$

Equations (7-8) are the *output equations* of the generator's state space model. It is important to note, that these equations *are bi-linear in the state and input variables.* In order to facilitate the subsequent model parameter estimation, an additional measurable output, the stator current i_{out} is introduced as

$$i_{out} = \sqrt{i_d^2 + i_q^2} \tag{9}$$

2.6. Controllers

Control schemes of synchronous machines are commonly based on a nonlinear model with two classical PI controllers that ensure stability of the equilibrium point under small perturbations [16].

One controlled output is the active power (p_{out}) with the manipulated input being the exciter voltage (v_F), while the angular velocity (ω) is controlled by manipulating the mechanical torque T_{Mech} (indirectly through the steam flow rate to the turbine).

As each PI controller has two parameters, our model includes the parameters of the *exciter voltage controller* (P and I), and that of the *angular velocity controller* (P_ω and I_ω).

3. Model analysis

A preliminary analysis of the dynamic properties (i.e. stability and disturbance rejection properties) was first analyzed in order to verify our model against engineering intuition.

Thereafter parameter sensitivity analysis has been performed as a preparatory step for model parameter estimation.

3.1. Dynamical analysis

The above model (Eqs. (2), (3), (5), (6), (8)) has been verified by simulation against engineering intuition using parameter values of a similar generator taken from the literature [7]. The stability of the open loop model, as well as disturbance rejection and reference tracking properties of the partially controlled model (i.e. the model with only the angular velocity controller) have also been investigated.

Local stability analysis of the SG model has been performed around its physically meaningful equilibrium point, and it was found that the model is locally asymptotically stable. Details can be found in [15], [17].

The disturbance rejection properties of the model have been investigated in such a way that a single SM was connected to an infinite bus that models the electrical network. The simulation analysis showed that the SG has good disturbance rejective properties against load disturbance from the electrical network (see [15] and [17]).

3.2. Sensitivity analysis

The developed model has 23 parameters, 19 of them belong closely to the SG, the remaining four characterize the controllers. This number is too high for any engineering parameter estimation method that can handle dynamic models nonlinear in its parameters. Therefore, the need arises to select those "influential" parameters for parameter estimation that effect significantly the dynamic response of the SG, and thus the measured data may have sufficient information for their estimation.

Simple ways of parametric sensitivity analysis were therefore carried out to determine the parameters that can be reliably estimated using both preliminary and estimation error based sensitivities.

The preliminary sensitivity analysis. was used to pre-select those parameters that have no or negligible influence on the model outputs. Here we performed dynamic simulations with the nominal values of the parameters, and by changing them one-by-one 10% up and down from their nominal values, we repeated the simulations and observed the differences in the output. This way we have concluded that the model output is not sensitive to the inductances l_d, l_q, l_D, l_Q, L_{MD}, L_{MQ}, and L_Q therefore they could be excluded from the set of the parameters to be estimated, and their value was fixed to ensure the stability of the model.

On the other hand, the preliminary sensitivity analysis revealed two model parameters, the inductances L_{AD} and L_D, that affect critically the stability of the closed loop model. There was only a very narrow region in their physically meaningful domain, where the stability of the model could be guaranteed. Therefore, these parameters were also excluded from the set of parameters to be estimated.

For the detailed preliminary sensitivity analysis results we refer to our earlier conference paper [17].

Sensitivity of the estimation error function. Further parameters from the set of less influencing ones, including the resistances r_D and r_Q, have also been excluded from the set of parameters to be estimated based on the analysis of the sensitivity of the estimation error function (see later in subsection 4.2) with respect to them.

4. Parameter estimation

The developed model (Eqs. (2), (3), (5), (6), (8)) together with the model equations of the two considered PI controllers have been used for estimating its parameters using measured data from the Paks NPP obtained from load changing transients. The model is nonlinear in its parameters, therefore a special, optimization-based parameter estimation have been used that minimized the estimation error.

4.1. Base and normalized quantities

The first step in parameter estimation is to choose the normalized (p.u.) values of the considered SG in the Paks NPP. For this, the nominal (original) operating values of the SG were recorded which are as follows. The apparent energy is 259 MVA, the $\cos\varphi$ is 0.85, voltage is 15.75 kV, current is 9490 A, frequency is 50 Hz, excitation current is 1450 A, excitation voltage is 435 V.

The base quantities were determined from the stator measured steady state value of the rated power $S_B = 259$ MVA$/3 = 86.333$ MVA, the output voltage $V_B = 15.75$ kV$/\sqrt{3} = 8.874$ kV, the output current $I_B = 9729$ A, and the angular velocity $\omega_B = 2\pi f$ rad/s, where the subscript B refers to the base value of quantities. Using the base quantities, we can calculate the base units for time, resistance and inductance, that are $t_B = 1/(2\pi 50 \text{ Hz}) = 3.183$ ms, $R_B = V_B/I_B = 0.912\Omega$ and $L_B = V_B/(I_B/t_B) = 2.90$ mH.

From the measured rotor signals we can calculate the rotor base current and voltage values, that are $I_{FB} = -454.625A$ and $V_{FB} = -189900V$. Using the above rotor base values, the base units for resistance ($R_{FB} = V_{FB}/I_{FB}$), inductance ($L_{FB} = V_{FB}/(I_{FB}/t_{FB})$) can be easily obtained. The normalized quantities are obtained from the original ones by dividing them with the base quantities.

4.2. The measured signals and the estimation error function

There are six measured signals available from the generator: the active power (p_{out}), reactive power (q_{out}), angular velocity (ω), exciter voltage and current (v_F and i_F), and the stator current (i_{out}). The vector of measured signals is:

$$\mathbf{d} = \left[\begin{array}{cccccc} p_{out} & q_{out} & \omega & v_F & i_F & i_{out} \end{array} \right]^{\mathbf{T}} .$$

Note that p_{out}, q_{out} and i_{out} are output variables, i_F and ω are state variables, and v_F is an input variable of the state space model (Eqs. (2), (3), (5), (6), (8)).

A six hour long measurement record has been used to estimate the parameters of the SG. Unfortunately, the quality of the measured exciter voltage and current (v_F and i_F), and that of the output current (i_{out}) signals were poor compared to the other signals, as their measurement record consisted of about 10 samples in the measurement period. In order to achieve sufficient excitation of the system that is needed for parameter estimation, we have used a measurement record containing of a load changing transient that is ***not*** a usual operation course of the power plant unit. This ensures that the measured data carry enough information for the parameters in the dynamic model so that they could be reliably estimated.

The estimation error. Having the measured signals $\mathbf{d}$ and their counterparts computed by the model $\tilde{\mathbf{d}}$, the estimation error can be defined as the mean-square deviation for these signals. However, because of the above mentioned signal quality problems, the estimation error has been calculated only in a ten minute neighborhood of the measured values of v_F, i_F and i_{out}.

Furthermore, the huge domain width of the signal values in the deviations (that can be as large as from $1.696 \cdot 10^{-5}$ to 1361.5) requires a normalization to transform each to the range of 1. The constant vector $\mathbf{n}$ was used for this purpose, the value of which is seen in the third column of Table 1.

Finally we recall, that the intended use of the model is to control the active and the reactive power, therefore we want the model to reproduce

i	Signal	n_i	w_i
1	p_{out}	0.02152	0.5
2	q_{out}	$1.6348 \cdot 10^{-3}$	1.0
3	ω	58979.45	0.5
4	v_F	1971.391	0.2
5	i_F	$7.345 \cdot 10^{-4}$	0.2
6	i_{out}	$2.0445 \cdot 10^{-3}$	0.2

Table 1: Measured signals with their normalizing factors and weights

these signals in the best quality. Therefore, a signal weight vector **w** has been introduced, with the weights seen in the last column of Table 1.

With the above, the error function V is calculated form **d**, **n** and **w** as

$$V = \sum_{t=1}^{N} \left(\sum_{i=1}^{6} w_i \cdot n_i \cdot (d_i(t) - \tilde{d}_i(t))^2 \right), \tag{10}$$

where N is the number of measurement points, and

$$\tilde{d} = \left[\begin{array}{cccccc} \tilde{p}_{out} & \tilde{q}_{out} & \tilde{\omega} & \tilde{v}_F & \tilde{i}_F & \tilde{i}_{out} \end{array} \right]^T$$

is the vector of simulated signals.

4.3. Generator parameters and initial values

As we have seen before, the developed model has 23 parameters that are collected in Table 2.

The initial parameters of the generator in the Paks NPP were taken from the literature [7], where the parameters for a similar generator were given, but some initial parameters are the known engineering parameters of the actual SG. In some cases, however, slight modifications of the parameters taken from the literature were made during the preliminary simulation experiments dedicated for the parameter sensitivity analysis. All nominal parameters have been normalized, i.e. transformed to p.u. The resulting values can be seen in the second column of Table 2.

Besides the model parameters and their nominal value that belong closely to the SG, the parameters (P_ω and I_ω) of the angular velocity controller (turbine speed controller), and that of the exciter voltage controller (P and I) are also given in Table 2.

The results of the sensitivity analysis (see in sub-section 3.2 before) are also indicated in the third column of Table 2 with a "y" answer to the "est.?" (i.e." estimated?") question.

Based on the above sensitivity analysis results, the parameters to be estimated are: L_F, r_F, r, L_d, L_q, L_{AQ}, D, P, I. *The value of all the other parameters was set fixed to its nominal value shown in Table 2.* Finally, some initial values in the state equations were calculated. The measured value of the exciter voltage is $v_F(t=0) = 0.001645$. From this, we can calculate the initial value of δ and obtain the d and q components of the network voltage: $v_d(t=0) = -1.3585$, $v_q(t=0) = 0.46$.

4.4. The parameter estimation method

With the above classification of parameters, the appropriately designed estimation error (10) can be regarded as a function of parameters to be estimated, i.e. $V(L_F, r_F, r, L_d, L_q, L_{AQ}, D, P, I)$ given the value of the measured signals. A commonly accepted way of estimating the parameters is to minimize this estimation error function, that is

$$\min_{L_F, r_F, r, L_d, L_q, L_{AQ}, D, P, I} V(L_F, r_F, r, L_d, L_q, L_{AQ}, D, P, I) \tag{11}$$

and take the minimizer as an estimate.

Error function minimization. Minimization of the estimation error function has been performed using the Asynchronous Parallel Pattern Search (APPS) method. APPS is a variation of parallel pattern search that uses parallel resources more efficiently by eliminating synchronization [18]. The optimization problem is solvable with APPS method without explicit derivative information. Note that one has to start APPS method from different starting points because APPS method is a local optimization method.

The dimension of the parameter space is nine with the parameters collected in Table 3 together with their search space, the constrains of which is given in the last column. The resulting estimated parameters are also shown in the table.

4.5. The quality of the estimated parameters

The quality of the estimated parameters has been examined from the shape of the estimation error function as functions of the parameters in the neighborhood of its minimum that belongs to the estimated values. The

Parameter	initial value (p.u.)	est.? (y/n)	estimated value (p.u.)	confidence (%) (for 90%)
L_{AD}	1.550	n	-	-
L_D	1.605	n	-	-
L_F	1.65	y	1.651	3
r_F	$7.4 \cdot 10^{-4}$	y	$6.305 \cdot 10^{-4}$	3
r	$1.096 \cdot 10^{-3}$	y	$1.09 \cdot 10^{-3}$	4.9
L_d	1.7	y	2.1	2.9
L_q	1.64	y	1.526	1.2
L_Q	1.526	n	-	-
L_{AQ}	1.49	y	1.527	4.8
l_d	0.150	n	-	-
l_q	0.150	n	-	-
l_F	0.101	n	-	-
l_D	0.055	n	-	-
l_Q	0.036	n	-	-
L_{MD}	0.02838	n	-	-
L_{MQ}	0.2836	n	-	-
r_D	0.0131	n	-	-
r_Q	0.054	n	-	-
D	2.004	y	2.004	2.5
P	0.05	y	0.0515	20
I	0.1	y	0.0021	14
P_ω	$1.096 \cdot 10^{-3}$	n	-	-
I_ω	$1.096 \cdot 10^{-5}$	n	-	-

Table 2: Model parameters

Parameter	Estimated value (p.u.)	Confidence (90%)	Domain (%)
L_F	1.651	3%	±10%
r_F	$6.305\ 10^{-4}$	3%	±40%
r	$1.090\ 10^{-3}$	4.9%	±20%
L_d	2.1	2.9%	±20%
L_q	1.526	1.2%	±15%
L_{AQ}	1.527	4.8%	±15%
D	2.004	2.5%	±45%
P	0.0515	20%	±30%
I	0.0021	14%	±30%

Table 3: Parameter estimation data

error function was plotted against two parameters with all the others fixed at their estimated values in Figs. 2, 3, 4 and 5. The dots denote the set of points where the error had been evaluated. The surface representing the error function has been fit on these points.

The confidence regions. As the parameter estimation was based on optimization, no statistical properties of the estimation (e.g. covariance matrix, or confidence regions) could be obtained. However, a good approximation of the confidence region in the parameter space can be obtained by computing the $(1 + \alpha) \cdot V_{min}$ level set of the estimation error function, where V_{min} is its minimum value, and $(1 - \alpha) \cdot 100$ is the confidence level [19]. With this, a conservative approximation of the individual confidence intervals of the parameters can be obtained by projecting the confidence region to the one-dimensional parameter sub-space. The obtained approximate individual confidence intervals are also collected in Table 3 at the 90% confidence level (i.e. $\alpha = 0.1$).

It is important to note that the confidence regions carry information about the information content of the measured data that were used for the parameter estimation, i.e. about the excitation of the system. In the case of sufficient excitation (i.e. good quality data) these regions are of elliptical shape.

Fig. 2 shows the estimation error as a function of the parameters L_F and r_F, together with its level sets, and the 95% and 90% confidence regions.

Note that these regions have an exotic shape, and the individual confidence intervals for L_F and r_F were determined so wide that the resulting rectangle completely covers the confidence region. In Figs. 2, 3, 4 and 5 the dark blue color represents the 90% confidence region and the blue color shows the 80% region. The bottom subfigures of Figs. 2 and 4 show the 95% and the 90% confidence regions.

The confidence interval of L_d and L_q is small which means that the estimation is sharp, as it is apparent in Fig. 4.

4.6. The quality of the fit

The quality of the SG model with its estimated parameters can be evaluated in the space of the output and state variables as signals, too. As the final aim of our study is to design controllers that control both the active and the reactive power, the quality of the obtained model is evaluated by comparing these measured signals with their simulated counterparts provided by the model.

The simulation results are shown in Fig. 6, where the active (p_{out}), reactive (q_{out}) power and the torque angle (δ) are shown. It is apparent that the model has an excellent fit with both the measured active and reactive power signal.

Note that the torque angle is a non-measured state variable that provides an insight on how the active power controller operates during a load changing transient. The controller had to decrease the exciter voltage in such a great extent so that the simulated reactive power signal could follow the measured signal. This is the reason of the undesired large variation of the torque angle.

5. Conclusion and further work

A dynamic model of a large industrial synchronous generator commonly applied in power plants is developed in this paper based on first engineering principles that is able to describe the time-varying active and reactive power output of the generator. The model is based on first engineering principles that describes the mechanical phenomena together with the electrical model.

The developed model has been verified under the usual controlled operating conditions in Paks Nuclear Power Plant (Hungary) when the angular velocity and the active power are controlled. A sensitivity analysis of the estimation error has been applied to determine the model parameters to be estimated out of the possible 23 model parameters.

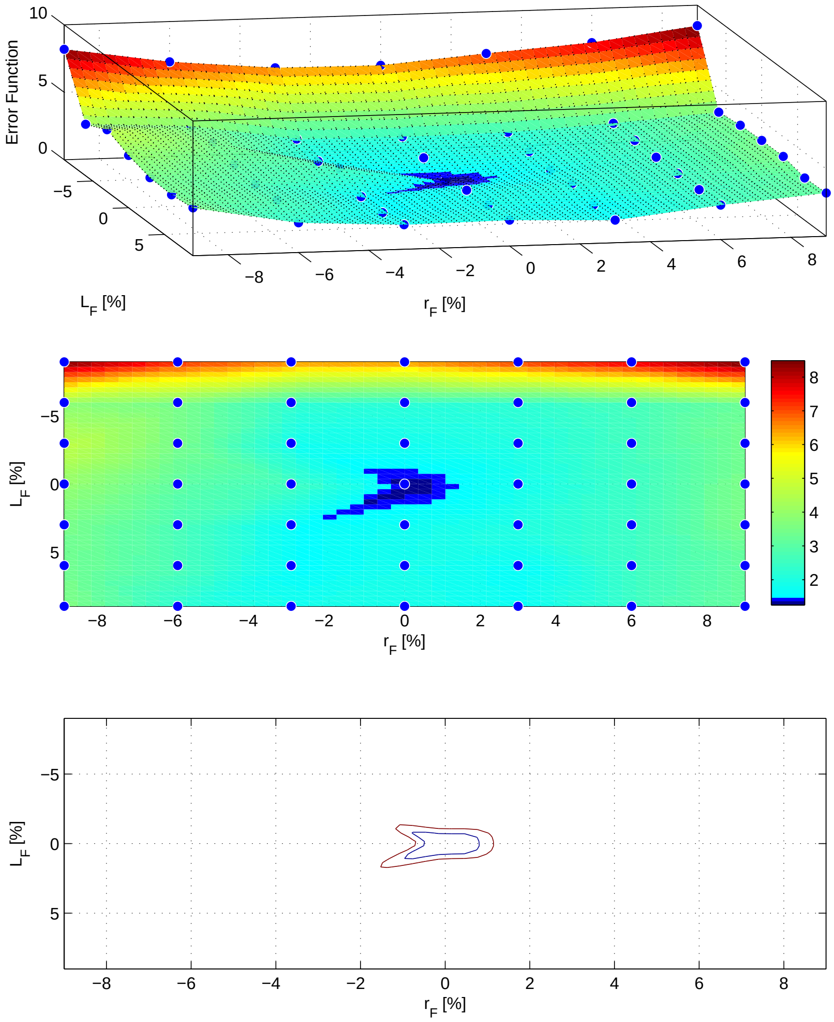

Figure 2: The value of the error function vs. ±9% changing of L_F and r_F and the confidence interval of L_F and r_F parameters

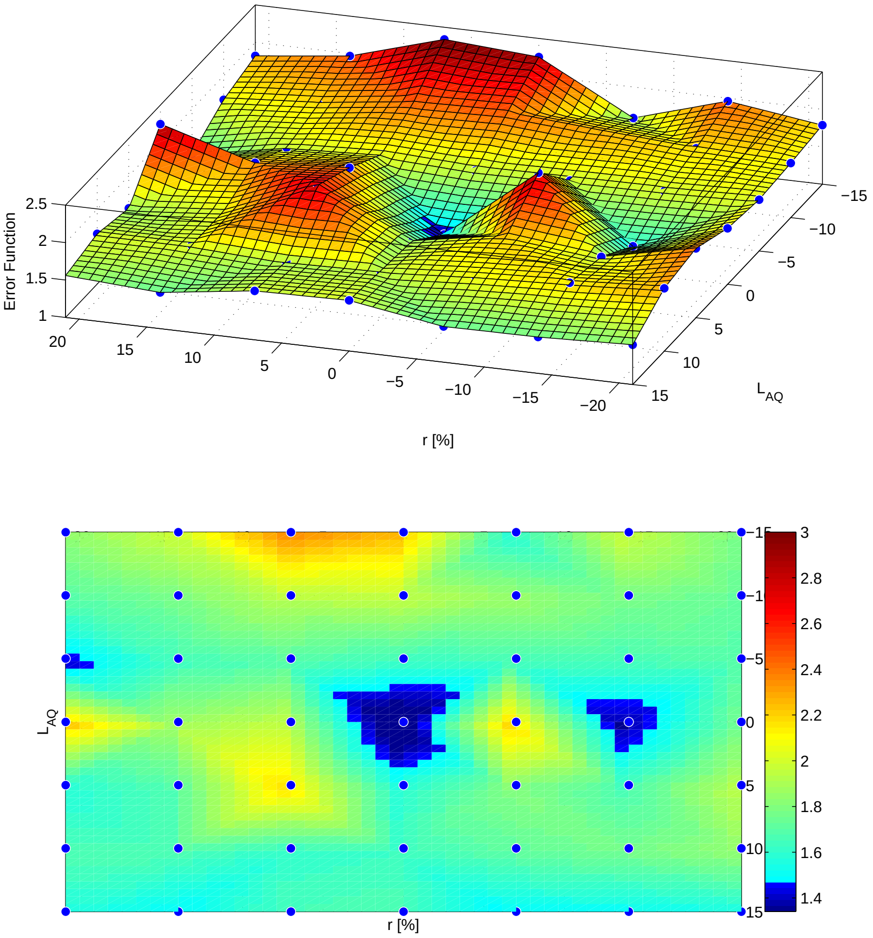

Figure 3: The value of the error function vs. ±21% changing of r and ±15% changing of L_{AQ} parameters

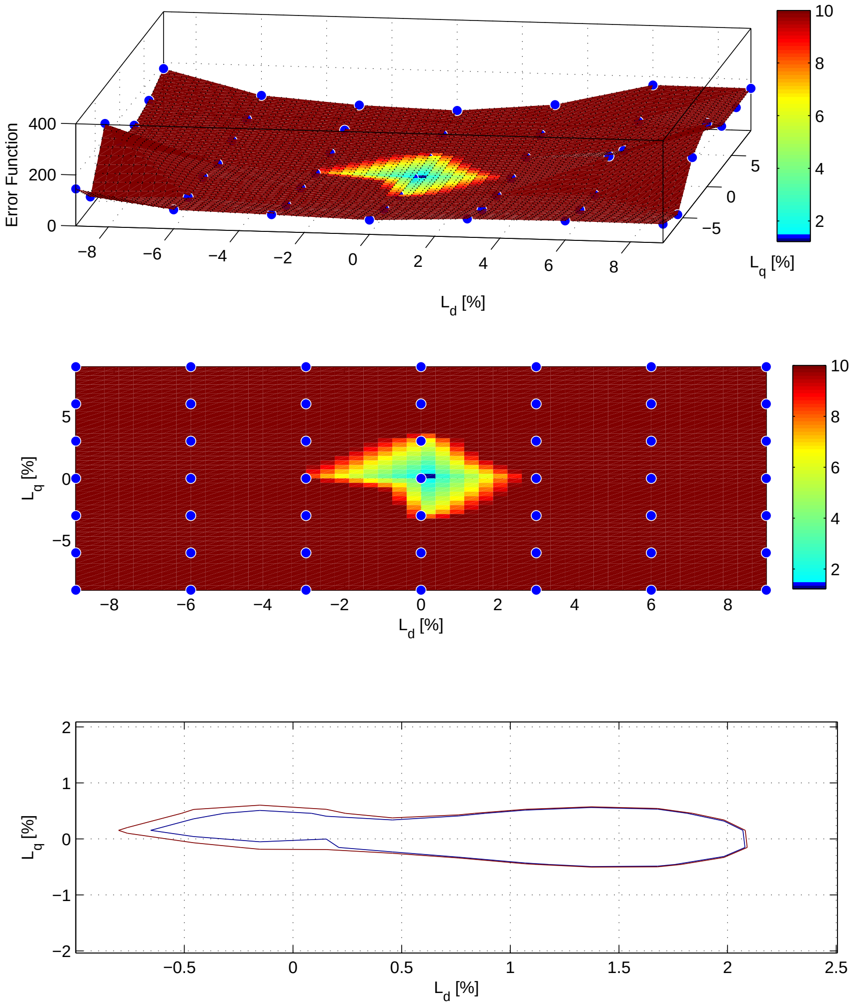

Figure 4: The value of the error function vs. ±9% changing of L_d and ±9% changing of L_q parameters

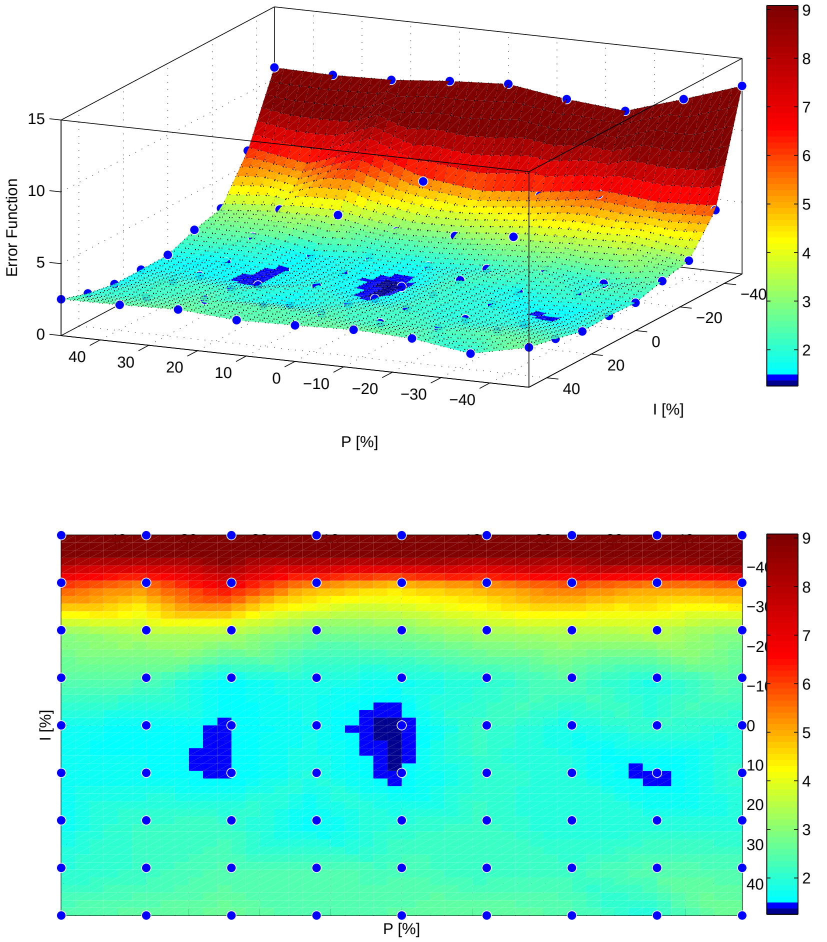

Figure 5: The value of the error function vs. ±45% changing of P and I

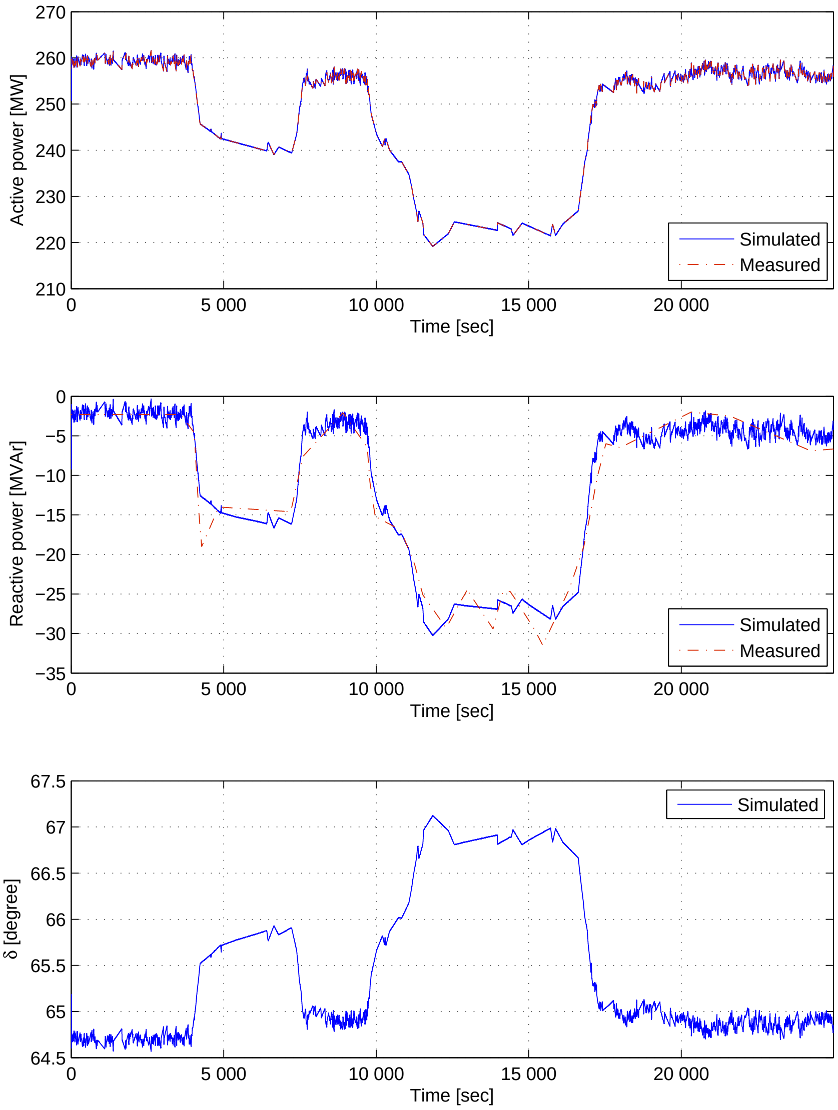

Figure 6: The simulated and measured active and reactive power, and the simulated torque angle

The selected model parameters have been estimated by using measured data of a sufficiently exciting load changing transient from an industrial generator operating in the Paks Nuclear Power Plant in Hungary applying the asynchronous parallel pattern search method that minimizes the estimation error as a function of the parameters. The confidence regions in the parameter space have been analyzed by investigating the geometry of the estimation error function. The quality of the model has been evaluated by the fit in the active and reactive power, and a good fit could be achieved.

Further work is directed towards designing a multiple-input multiple-output controller that does not only control the rotation speed and the active power, but can follow the externally given trajectory of the reactive power demand, as well. This fits well into the recent trends in electrical energy market where it is more widely accepted that consumers pay for the reactive power support service.

6. Appendix

Abbreviations	
APPS	Asynchronous Parallel Pattern Search
NPP	Nuclear power plant
p.u.	Per Unit, Base quantities
SG	Synchronous generator
SM	Synchronous machine
Symbols	
$\mathbf{a}_{\%}$	The boundaries of the parameter space
$\mathbf{d}$ and $\tilde{\mathbf{d}}$	The measured and simulated signals
D	Damping constant
H	Inertia constant
i_d and i_q	Stator voltage, d and q component
i_D and i_Q	Currents of amortisseur winding
i_{out}	Stator current
$k = \sqrt{3/2}$	
$L_{AD} = kM_D$	Amortisseur winding linkage induct.
$L_{AF} = kM_F$	Field linkage inductance
$L_{AQ} = kM_Q$	Amortisseur winding linkage induct.
L_{AD} and L_{AQ}	Mutual inductances
L_d and L_q	d and q component of stator inductance

L_D and L_Q	Inductances of amortisseur winding
l_d and l_q	Linkage inductances
l_F, l_D and l_Q	Linkage inductances
L_{FB}	Rotor inductance, base
L_{MD} and L_{MQ}	Mutual inductances
M_D, M_Q and M_F	Mutual inductances
$\mathbf{n}$	Signal normalization vector
r	Stator resistance
R_B and L_B	Resistance and inductance, base
r_F, r_D and r_Q	Rotor resistances
R_{FB}	Rotor base resistance
P, I, P_ω, I_ω	PI controller parameters
p_{out}	Active power
q_{out}	Reactive power
S_B	Rated power, base quantity
t_B	Time, base
T_{Dump}	Damping torque
T_{Electr}	Electrical torque
T_{Mech}	Mechanical torque
V_B and I_B	Stator voltage and current, base
v_d and v_q	Stator voltage, d and q component
v_F and i_F	Exciter voltage and current
V_{FB} and I_{FB}	Rotor voltage and current, base
$\mathbf{w}$	Signal weight vector
δ	Torque angle
ω	Angular velocity
ω_e	Angular velocity, base
$\tau_j = 2H\omega_B$	

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We acknowledge the financial support of this work by the Hungarian State and the European Union under the TAMOP-4.2.1/B-09/1/KONV-2010-0003 project. This work was also supported in part by the Hungarian Research Fund through grant 83440.

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