# Dynamic Modeling of a Synchronous Generator Including Regulation

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***Abstract*—Synchronous machines are intensively used as generators due to their very good voltage and frequency regulation characteristics. To study the control of the generated active and reactive power it is necessary to have very accurate mathematical dynamic models to implement efficient simulations. This paper is focused on synchronous generator dynamic modeling for simulation and modeling of the power system. This article also deals with the examining of operation of control systems (especially excitation systems) of the synchronous generator (frequency and active power control, voltage and reactive power control).**

***Keywords*—synchronous generator modeling, frequency and active power control, voltage and reactive power control, excitation systems.**

## I. Introduction

Synchronous generators form the principal source of electric energy in power systems. The commercial birth of the synchronous generator can be dated to 1891, when the first alternate transmission of electricity from Lauffen to Frankfurt (Germany, length 175 km, 20 kV line) was realized. Many large loads are driven by synchronous motors. Synchronous compensators are used to compensate the reactive power and voltage control. These devices operate on the same principle and are collectively referred to as synchronous machines [1].

The basic operating state of each power system (and also of a synchronous generator) is its steady state (electrical and mechanical) of operating system quantities. Any change in system operating parameters leads to disturbing a steady state (equilibrium), resulting in a transient phenomenon. To describe the behavior of the synchronous machine in these conditions, it is important to determine its steady state, but also to characterize its dynamic behavior during transient conditions. Because of the transient conditions, regulation (the frequency and active power regulation, as well as the voltage and reactive power regulation) is an essential part of the power system [2].

## II. Mathematical Model of the Synchronous Generator and the Power System

The basic mathematical model of the synchronous generator (turbogenerator as well as hydrogenerator) is based on its design and consists of equations for stator voltages and rotor voltages. After applying dq0 transformation, a system of first order linear differential equations is obtained [1]-[12]:

$$\left[\frac{\mathrm{d}i}{\mathrm{d}t}\right] = -[N]^{-1}[M][i] + [N]^{-1}[u] = [A][i] + [B], \qquad (1)$$

where

$[M]$ is the matrix with constant coefficients, it contains parameters of the synchronous generator (resistances and inductive reactances) in ohms or per units bound to unknown currents,

$[N]$ is the matrix with constant coefficients, it contains parameters of the synchronous generator (inductances) in henrys or per units bound to time derivations of unknown currents,

$[u]$ is the matrix of input known quantities with constant coefficients, it contains the matrix of stator voltages and rotor voltages in volts or per units,

$[i]$ is the matrix of output unknown quantities, it is formed by the matrix of stator currents and rotor currents in amperes or per units,

$\left[\frac{\mathrm{d}i}{\mathrm{d}t}\right]$ is the matrix of time derivations of unknown rotor and stator currents in amperes or per units.

Among other elements, the voltage control in the power system is realized by excitation systems (by regulation of the field current, respectively field voltage) of the synchronous generator. As a result, the field voltage is required as a single input for the calculation (whether for the calculation of a steady state or transient phenomena). This can be achieved by expressing stator voltages (in the d-axis and q-axis) in the system (1) by an external load connected to terminals of the synchronous generator included in the matrices $[M]$ and $[N]$ [1].

If it is necessary to extend the mathematical model of the synchronous generator to other elements of the power system (in the d-axis and q-axis), it is necessary to extend the system (1) by submatrices corresponding to given elements of the power system. It is possible to model the element, respectively a part of the element of the power system (for example transformer, line, induction motor and so on) replaced by the series impedance (unknown quantities are currents in d-axis and q-axis flowing in a branch with the given element) or in the form of the shunt admittance (unknown quantities are voltages in d-axis and q-axis at the node in which the given element is connected) [1].

A simple linear model (1) of the synchronous generator and the power system does not include voltage and frequency regulation. The field voltage, which represents a single input to the system (1), is constant during the whole calculation. Also, the constant synchronous speed is considered in this model.

## III. Implementation of the Synchronous Generator Model in the Real Power System

In [2] the synchronous generator operating in island mode was modeled and the response of its excitation system to rapid load changes, in particular to rapid reactive power changes was examined. This analysis is based on the real measured data during the black start test representing the power supply of self-consumption of the Vojany thermal power plant from the Ružín pumped storage power plant. The single-line diagram of the examined real power system is presented in Fig. 1.

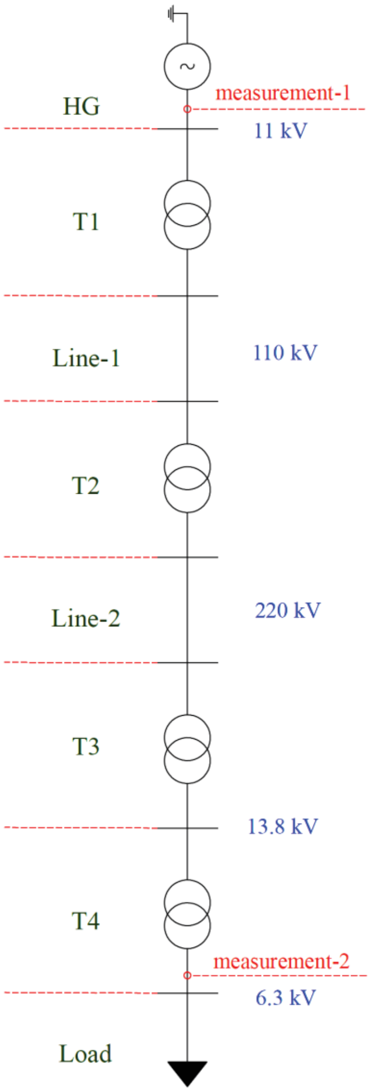


Fig. 1. Single-line diagram of the examined real power system [2].

There were two measurements provided during the test. First one was the measurement-1 of one period (0.02 seconds) RMS values and angles of voltages and currents at the generator terminals and second one was the measurement-2 of one period RMS values and angles of voltages and currents at the 6.3 kV terminals of the transformer T4. The test has been started with the HG (in the Ružín pumped storage power plant) start-up at no-load conditions. Consequently, the transformer T1, Line-1, transformer T2, Line-2 and transformer T3 and T4 were connected to the generator step by step to create the network to an important load (self-consumption of the Vojany thermal power plant). After the network creation the start-up of few motors were provided [2].

TABLE I presents the rated voltage and rated power of the hydrogenerator (HG) and transformers (T1, T2, T3, T4) of the examined real power system. The mathematical model of the synchronous generator and the power system in island operation was created according to [1]. The model of transformers (T1, T2, T3, T4) was created as a T-section and the model of power lines was created as a Π-section. The model of the load was represented by one series branch and by one shunt admittance [2].

TABLE I
Rated Power and Rated Voltage of the Synchronous Generator and Transformers of the Examined Real Power System

| Element of the power system | HG | T1 | T2 | T3 | T4 |
|---|---|---|---|---|---|
| Rated power (MVA) | 35 | 40 | 200 | 125 | 25 |
| Rated voltage (kV) | 11 | 10.5/121 | 230/121 | 242/13.8 | 13.8/6.3 |

In [2] were three different events simulated and examined:

- Line-2 connection to T2 during the network creation.
- Starting of 1 250 kW induction machine supplied from T4.
- Starting of 1 600 kW induction machine supplied from T4.

Measured RMS values and angles of voltages and currents at generator terminals and at load (realized during the real test) were used for one period impedance change at both places. Based on the solution of the equation (1) the field voltage was computed to achieve simulated voltage at the generator terminals be the same as the measured one. In the case of the induction motors connection two approaches were provided. The first one was the computation of the field voltage (and field current) based on the impedance change directly on the generator terminals (model of the generator without the rest of the network). The second approach was the computation of the field voltage (and field current) based on the impedance change at the 6.3 kV terminals of the transformer T4. The comparison of the results reached by the both approaches was used for the network model verification [2].

The simulated and measured voltage and current at generator terminals and computed field voltage after 1 250 kW induction motor connection are shown in Fig. 2. The starting of such motor leads to the voltage dip which level depends on the actual short-circuit power. In the case of island operation, the network was supplied only from the hydrogenerator, the RMS voltage value felt down to approximately 80 % of initial value. The regulation operation is clear from the field voltage course. It is clear from the beginning of the event, that the voltage regulation evaluated the situation of the sudden voltage dip as a fault (such as a short-circuit) and kept the excitation to zero. After about 100 ms, the voltage regulator began to excite and increased the voltage to the required value. It is clear from the course of current at generator terminals that the generator was operating in the underexcited mode. The starting of the induction motor represents the reactive power consumption, so during the motor start-up the generator was less underexcited (the current decreased at the generator terminals) [2].

Fig. 3 shows the simulated currents at generator terminals ($i_d$ in d-axis, $i_q$ in d-axis), amortisseur currents, and computed field current in the case of 1 250 kW induction motor connection mentioned above. Due to generation of the currents in amortisseur windings ($i_{1d}$ and $i_{1q}$) the falling of the voltage was slowed down [2].

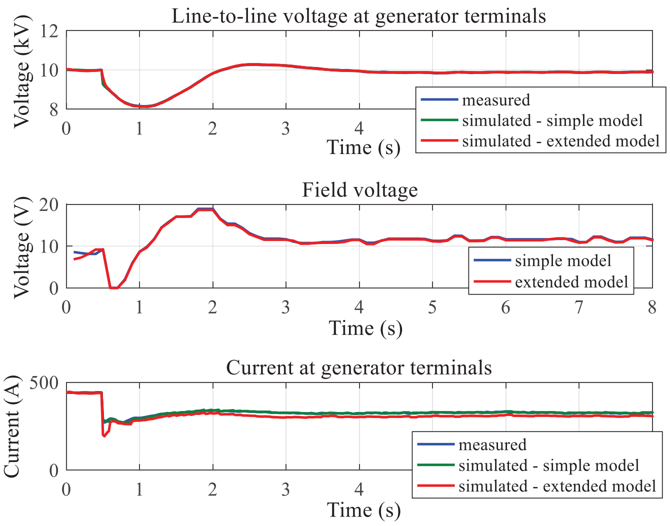


Fig. 2. Simulated and measured voltage and current at generator terminals and computed field voltage after 1 250 kW induction motor connection [2].

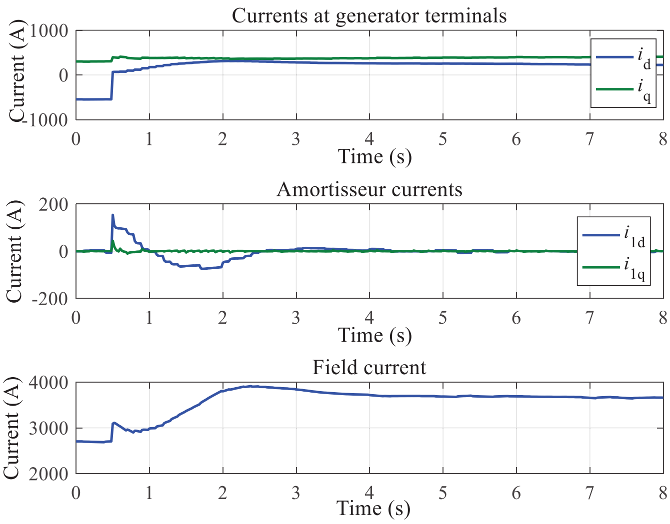


Fig. 3. Simulated currents at generator terminals, amortisseur currents, and computed field current after 1 250 kW induction motor connection [2].

In the case of modeling the examined real power system in a simplified or extended way (using a simple network model consisting only of the model of the generator and the impedance at its terminals, respectively using the extended model including transformers and power lines between generator terminals and induction motors), almost identical voltage and current time courses were obtained, what is indicating the correctness of the network model between generator terminals and induction motors, as well as the suitability of using of both models [2].

## IV. Conclusion

Described methodology in this paper does not follow standard procedures [13]-[15] for modelling excitation systems of synchronous generators and is based on the analytical solution of the differential equations. The purpose of the generator's field voltage and current courses calculation based on known RMS values and angles of voltages and currents at generator terminals (in the case of different events, for example switching on or switching off the lines or the load) is to obtain relevant information for modeling the excitation system of the synchronous generator. Such approach is suitable mainly in the case of missing of key information about modeled excitation system, such as its type, transfer function, values of constants Research mentioned in this article is necessary for the appropriate excitation system model finding in the next step, whether in the form of transfer functions or in the form of the mathematical function or algorithm [2].

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