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Effective estimation of angular speed of synchronous generator based on stator voltage measurement

Michał Lewandowski[a,*], Łukasz Majka[a], Aleksandra Świetlicka[b]

[a] Silesian University of Technology, Faculty of Electrical Engineering, ul. Akademicka 10, 44-100 Gliwice, Poland
[b] Poznan University of Technology, Institute of Automation and Robotics, ul. Piotrowo 3A, 60-965 Poznań, Poland

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ABSTRACT

Estimation of the parameters of the power generators are important part of a power system modeling and simulation. A reliable estimation of a synchronous generator parameters can be done using waveforms measured directly on the terminals of the machine. The waveforms are recorded during a carefully chosen disturbance tests of the generating unit. One of the quantities necessary to determine the generator parameters is the deviation of the generator angular speed. However, because of the safety reasons, it is very difficult to get access to the direct measurement of this quantity on a operating generating unit. Angular speed estimation based on a generator stator voltage seems to be an alternative solution to the problem.

The aim of the paper is to find a computationally efficient and accurate method of indirect angular speed estimation of a synchronous generator which is based on the recording of its stator voltage during a load rejection test. The algorithms evaluated in the paper are based on Prony's estimator, zero-crossing detection, least-square data fitting and layer recurrent neural network. Paper contains literature survey, mathematical model of the considered generator, analysis of its stator voltage recorded in a power plant, description of the selected algorithms and results of the algorithms estimation using a signal with known frequency variation. Performed algorithms evaluation allows to choose the best solution in terms of accuracy and computational effort.

1. Introduction

Modeling of the dynamics of a power system, especially under emergency conditions, requires a reliable mathematical representation of generating units operating in the system. In Fig. 1 a simplified diagram of a generating unit is shown. The generating unit consists of three main blocks: a steam turbine, a power generator and an excitation system. The steam turbine, the generator and the excitation system are mechanically connected with a shaft rotating with angular speed ω.

These elements are characterized by a complex mathematical models and a large number of degrees of freedom resulting from, among others, numerous control systems [1–3]. In the literature, one can find papers focused on the methodology of efficient and reliable determination of parameters of the models describing the generating unit [1,2,4,5]. In many of these methods, dynamic waveforms of selected generating unit quantities are recorded during appropriately chosen disturbance tests. These waveforms are the basis for determining the parameters of particular components of the generating unit mathematical model. Among the recorded waveforms, one can distinguish signals which are directly related to electrical quantities such as voltages and currents of the stator and rotor circuits, as well as non-electrical signals, such as the deviation of the angular speed of the machine or the flow of a steam through the turbine. The reliability of the recorded data is very important for the accuracy of the estimated parameters of the generator mathematical model.

The angular speed of the generator and its deviation are used in electromechanical equations describing the machine in its transient states. These signals contain important information about the behavior of the generating unit during changes of its active load. In the paper, the load rejection test is considered. In this case, the angular speed deviation signal represents the reaction of the turbine and its governor (operating in the automatic mode) to the disturbance made in the electrical part of the generating unit. The change consist in opening a main circuit breaker at non-zero initial active and reactive power load. During this test, usually a small change in the angular speed of the generator is observed (from 1% to 3%) [6,7]. It is very difficult to record such a small change with an appropriate resolution, especially if the measurement is done by an external measuring systems. Accurate speed sensors (encoders) installed in the turbine governor are usually not available for external recorders, due to their critical importance for

* Corresponding author.
E-mail addresses: michal.lewandowski@polsl.pl (M. Lewandowski), lukasz.majka@polsl.pl (Ł. Majka), aleksandra.swietlicka@put.poznan.pl (A. Świetlicka).

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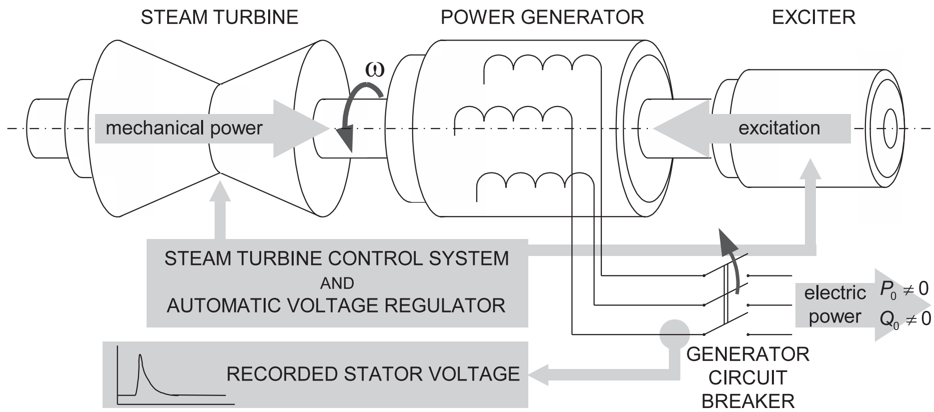

Fig. 1. Simplified diagram of the generating unit.

turbine safety. Visible parts of the turbine shaft are difficult to access, because they are usually thoroughly masked for safety reasons and they are constantly lubricated, which is the next problem in the angular speed measurement. Finally, any attempt of installation of an additional measuring system usually requires disconnection of the whole turbine set, which is unacceptable in most cases.

The problem is also connected with the occurrence of torsional vibrations of the shaft. Fortunately, during the load rejection test, the deviation of the angular speed of the generator can be reliably determined using the measurement of a stator voltage of the machine. The signal of the stator voltage is easy to access and measure and, due to its large amplitude, resistant to external disturbances.

The aim of the paper is to find a computationally efficient and accurate method of estimation of the generator stator voltage frequency deviation. This signal is directly associated with the deviation of the angular speed of the machine rotor due to the ceasing of the power system influence after opening of the circuit breaker (there is no rotor movement relative to the axis of the rotating field). The computational efficiency of the method is important, because the algorithm will be used as a part of a complex mathematical model of the generating unit [1], and thus it should be as fast as possible to not slow down the simulation process.

2. Angular speed estimation in the mathematical model of the generator

The mathematical model of the considered generating unit contains three main elements (Fig. 2): the model of the synchronous generator, the model of the electro-machine excitation system with a voltage regulator and the model of the steam turbine with its speed governor. The steam turbine drives a power generator with a predetermined angular speed ω which converts mechanical power to electrical active power P. At the same time the electro-machine excitation system uses the field voltage E_{fd} to control the flow of the reactive power Q from a generator to a power system.

Each element of the generating unit model is described by a set of parameters which are provided by the producer of the generator or have to be estimated. The process of the parameters estimation is based on the appropriately chosen measurement tests of the generator under different operating conditions. A more detailed description of the model shown in Fig. 2 can be found in [2,8,9]. The description of the model comprises of linear and nonlinear algebraic equations and differential equations, which are solved in the Matlab environment [10]. Solvers dealing with state equations can be applied or others that can deal with differential algebraic equations. Alternatively, solvers that are based on external libraries can be also applied [11]. For the purpose of the simulations concerning the discussed study, the model equations have been formulated in the Simulink environment [10]. The *ode45* solver (applying explicit Runge-Kutta formulae of orders 4 and 5) has been applied to handle the differential equations. In the further part of this paper, only the details relevant to the topic of the publication will be discussed.

The dynamical models of synchronous generators available in the literature can be divided into two groups: the XT type models and the RL type models. The XT type models are described using standard parameters (reactances and time constants) [1,2]. In description of the RL type models, resistances and inductances of electrical circuits are used [6]. A common feature of both models is the location of their equivalent circuits in the rotating d-q-0 coordinate system. The electrodynamic state of the synchronous generator is described by the equations of electromagnetic state [2]. The mechanical motion equations, where the signal of angular speed deviation is one of the main variables, supplement the equations of electromagnetic state. These equations, in relative values, can be written as:

$$\frac{\mathrm{d}(\Delta\omega)}{\mathrm{d}t} = \frac{1}{T_m}\left(\frac{P_m}{\omega} - M_e\right), \tag{1}$$

$$\frac{\mathrm{d}\delta}{\mathrm{d}t} = \omega_n \Delta\omega, \tag{2}$$

$$\Delta\omega = \omega - 1, \tag{3}$$

$$M_e = \Psi''_d I_q - \Psi''_q I_d, \tag{4}$$

$$T_m = 2H, \tag{5}$$

where: T_m - mechanical time constant, ω_N, ω - rated electrical angular speed and the instantaneous value of the electrical angular speed of the rotor, δ - load angle, P_M - mechanical power of the turbine, M_e - electromagnetic torque of the generator, H - mechanical inertia, Ψ''_d, Ψ''_q - d- and q-axis subtransient flux linkages in stator windings of the generator.

T_m and H are very important parameters. They allow determining the inertia of the complete shaft of the generating unit and, among others, are decisive in the reliable description of mechanical dynamics of the machine. However, verification of these parameters during standard tests (e.g. after repairs or modernizations) is not performed. In addition, repairs and modernizations of individual components of the generating unit (the turbine and the generator separately) are carried out by various entities. In such circumstances, disbelief in the catalogue data reliability is fully justified. However, it is possible to omit the mechanical motion equations during calculations without a decrease in the reliability of the model. This is possible using the generator angular speed deviation signal. Instead of calculating this signal on the basis of the motion equations, one can introduce it into the model as a measured quantity. In this case, the only difficulty lies in a direct measurement of the angular speed of the generator rotor. Fig. 3 shows a block diagram of the generator parameter estimation algorithm which includes the angular speed estimation based on the stator voltage V_S. The generator