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Advanced-model of synchronous generator for hydropower plants numerical simulations

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ABSTRACT

This paper deals with the dynamic modeling of the synchronous generator (SG) and the simulation of different events in MATLAB/Simulink environment. A perfect symbiosis is achieved between the load, the rotor dynamics, the electrical part and the excitation system to obtain an efficient SG model suitable for most electrical power plants functioning with. The resulting flexible and versatile model can be used to perform various tests such as: the classical three-phase sudden short-circuit test, the field short-circuit test, the load rejection and line-switching tests. In order to prove the effectiveness of the proposed model, it is inserted in a full hydropower plant and extensive simulations using MATLAB/Simulink program are performed and discussed for different tests and plant scenarios (automatic voltage regulator (AVR) on and off).

1. Introduction

The IPCC (Intergovernmental Panel on Climate Change) Special Report on Renewable Energy Sources and Climate Change Mitigation (SRREN) provides a comprehensive review concerning these sources and technologies, the relevant costs and benefits, and their potential role in a portfolio of mitigation options. Among them, hydropower creates no atmospheric pollutants or waste associated with fuel combustion [1]. It is an environmental friendly mean of energy generation that easily achieves a symbiosis between quantity, and quality [2,3]. However, environmentalists and populations are increasingly opposed to the construction of new hydro plants [4]. Therefore, optimization of existing power plants which implies limiting power plants aging, increasing of energy generation [5] and the training of their stakeholders [3] are the key steps in solving the above-mentioned challenges. It is therefore essential to provide researchers with advanced accurate models of power plant components including the synchronous generator.

As the main component of a hydro plant, the development of a suitable, flexible and precise model of the SG for power system performances prediction, control, identification, stability analysis, training and diagnosis purposes remains a great challenge for power engineers and researchers. Several works on power plants modeling with SG have been reported in the literature. In many cases, rotor's dynamics is used for the implementation of the generator [2,6–8]. However, a full SG model should include both electrical equations and the rotor dynamics. Additionally, in many cases of plants including full models of the SG, equations are simply incorporated into Simulink's blocks [9,10]. Although these models are mostly dedicated to the power plant performances prediction, they are in general unusable in identification, optimization and diagnosis programs. A large number of state-based SG models that contributes to solve these problems are presented in the literature. In fact, the well-known and most used 'impedances models', only adapted for stator decrement tests simulations, and intensively applied for sudden short-circuit tests prediction, have been proposed [11–14]. Also, the hybrid model developed in [15] is adapted for the performances prediction of synchronous generator subjected to rotor decrement tests such as the load rejection and field short-circuit tests. An improved version of the hybrid model [15] able to predict armature currents following a rotor decrement tests has been proposed in [16]. Despite these last improvements, none SG model can both perform stator and rotor decrement tests as it should be in real life. Furthermore, the control variables of the model depend of the desired simulations. These shortcomings are overcome in the present paper. Much more, the rotor's dynamic is incorporated in such a manner that the versatile and flexible generator/(excitation-system) model is adapted for any electrical energy generation systems using it. To the best of our knowledge, it

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Nomenclature

Generator
I_f, v_f, ψ_f field current, voltage, and flux linkage
i_D, v_D, ψ_D d-axis damper current, voltage, and flux linkage
i_Q, v_Q, ψ_Q q-axis damper current, voltage and flux linkage
i_d, v_d, ψ_d d-axis current, voltage, and flux linkage
i_q, v_q, ψ_q q-axis current, voltage, and flux linkage
I_s, V_s, Ψ_s stator current, voltage, and flux linkage vectors
I_r, V_r, Ψ_r rotor current, voltage, and flux linkage vectors
ω_m, ω_n per unit rotational speed of the rotor and the natural network pulsation
m_{g0}, m_t, T_a, e_g load torque, mechanical torque, generator unit mechanical time-constant and the load self-regulation factor
GD^2, P_r, n_r generator unit inertia torque, generator-rated power output, and turbine-rated speed

Excitation system and it AVR
v_r, v_f, v_t, v_2, v_{ref} amplifier output, field, armature, controller output, and reference voltage
v_x transition variable
K_a, τ_a gain and time constant of the amplifier
K_e, τ_e gain and time constant of the exciter
K_g, τ_g gain and time constant of the generator
K_c, τ_c gain and time constant of the compensator
K_r, τ_r gain and time constant of the regulator/controller
f_{se} saturation factor

is the first time that such a model, derived in a compact state form is proposed in the literature. Thereby, using the tutorial tool given by the block-diagram representation, a synoptic of the hydropower plant including the SG to be modeled is depicted in Fig. 1 [17]. The generator/(excitation-system) models are derived in the space state form, while a strategy is used to include the mechanical power so that the full SG model is suitable for most electrical power generation systems using it [18]. The well-known MATLAB/Simulink program is used to numerically implement the full hydroelectric power plant in which the SG model is incorporated [19]. The proposed SG model in a nonlinear state form can be used to perform almost all simulations, for teaching, parameter determination, optimization, stability study and diagnosis processes.

The present paper is divided into four main parts. The first part focuses on the overall hydro-power plant synoptic while highlighting the process of integration of each component into the generation system. The second part focuses on the models of the SG while emphasizing on its numerical implementation using the MATLAB/Simulink software. The third part presents other components of the hydro-plant. Finally, the last part outlines the simulation technique along with the analysis and discussions on the obtained results.

2. The overall system

The system under study is depicted by the dotted area in Fig. 1. It consists of the electrical and the mechanical parts, the excitation system with its AVR and the islanded load. The features of the MATLAB/Simulink program facilitate the use of exogenous variables to implement nonlinear state models of various sub-systems through S-functions (MATLAB/Simulink subroutines). In operation, the rotational speed is provided by the mechanical part, using the rotor's dynamics. It is maintained constant by the speed controller through a balance between the mechanical and the active electrical power via a comparator. The load also consumes the reactive power that is compensated by the excitation circuit and its AVR through the field current. This helps to keep constant the terminal voltage of the generator. Many means such as water, wind, coal and other can be used to generate the mechanical power. However, as stated in the introduction, hydropower is a mature and friendly and advantageous renewable energy source. The SG model is therefore integrated in a complete hydropower system production successful desired simulations are performed. All desired curved can be observed.

2.1. Modeling of the synchronous generator

The modeling process of the SG consists of modeling each component and bounding them together as depicted in dotted area of Fig. 1.

2.1.1. The electrical part

The classical well-known equivalent circuits of SG are given in Fig. 2.

The voltages equations of SG can be organized into matrix form as presented below [15]:

Flux equations

$$\begin{bmatrix} \Psi_s \\ \Psi_r \end{bmatrix} = \begin{bmatrix} -X_s & X_{sr} \\ -X_{sr}^t & X_r \end{bmatrix} \begin{bmatrix} I_s \\ I_r \end{bmatrix} \Leftrightarrow \Psi = XI \quad (1)$$

where

$$I = \begin{bmatrix} I_s & I_r \end{bmatrix}^t \quad I_r = \begin{bmatrix} i_f & i_D & i_Q \end{bmatrix}^t \quad I_s = \begin{bmatrix} i_d & i_d \end{bmatrix}^t \quad (2)$$

$$\Psi = \begin{bmatrix} \psi_s & \psi_r \end{bmatrix}^t; \quad \Psi_r = \begin{bmatrix} \psi_f & \psi_D & \psi_Q \end{bmatrix}^t \quad (3)$$

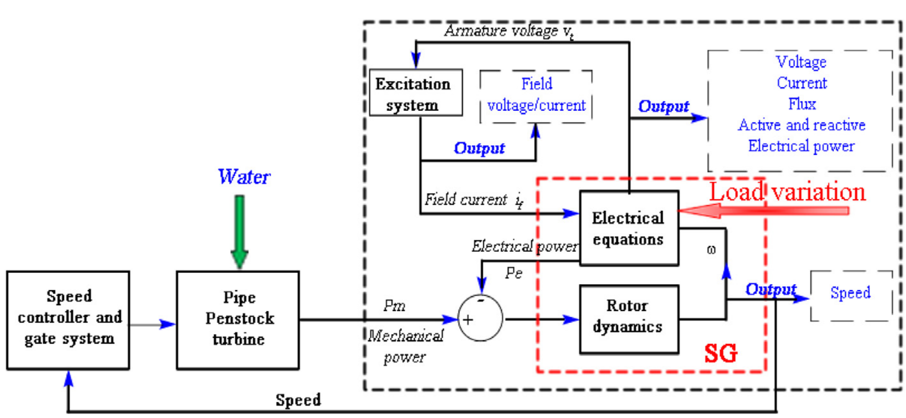

Fig. 1. Synoptic of the hydropower plant.