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Interconnection and damping assignment automatic voltage regulator for synchronous generators

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ABSTRACT

In this paper a new nonlinear regulation for synchronous generator excitation control is presented. This method comprises the nonlinear Interconnection and Damping Assignment (IDA) method together with the generator voltage feedback giving a nonlinear Automatic Voltage Regulator (AVR). First, the IDA excitation control is introduced in the third order salient pole synchronous generator mathematical model represented as a Port Controlled Hamiltonian (PCH) system. Thereafter, a generator voltage feedback signal is added. It is proven that adding the feedback to IDA control preserves a PCH structure of a system and the system is therefore passive. In the paper it is also proven that the gained system is stable and that the reference operating point corresponds to the minimal energy point of the system. Finally, the gained IDA AVR is tested with seventh order synchronous generator model and compared to classical generator excitation controllers. The simulations show the efficient tracking of generator voltage reference value, as well as the maintenance of stability in case of grid-side short-circuit occurrence. The main advantages of the proposed controller are efficiently generator voltage tracking and attenuation of electromechanical oscillations in case of a large disturbance, such as grid-side short-circuit.

1. Introduction

Nowadays, due to energy consumption increase, the electric power system is being continuously upgraded, not only with large power plants, but also with smaller renewable energy power sources making the system more complex and prone to sudden disturbances. A synchronous generator in such a distributed electric power system must be considered as a nonlinear system, as its operating point may considerably vary due to variations in load and topology of the electric power system. Possibility of sudden large disturbances, such as short-circuits that can occur in the electric power system near the plant, requires a better transient stability management.

The most frequently used generator excitation control is still consisted of linear regulators. The main control loop contains the Automatic Voltage Regulator (AVR), which controls the generator output voltage by changing the generator excitation voltage and, consequently, the generator excitation current. In the case of disturbances, AVR may amplify power swings, so an additional controller called a Power System Stabilizer (PSS) is introduced [1]. To enable synchronous generator optimal operation regardless of the operating point and to increase its transient stability, nonlinear regulation methods are being introduced to the synchronous generator excitation control circuit. Currently developed nonlinear controllers used for synchronous generator excitation are mainly implemented as PSS, without affecting the generator operating point. As reported in [2], the problem of possible impact of PSS on a steady-state operation of the system is managed by means of high-pass filters connected in series with the controller in order to eliminate the DC component of the control. The AVR is still linear, mainly PI controller.

The nonlinear methods used for PSS synthesis are adaptive regulation, feedback linearization, sliding mode regulation, synergetic control theory, model predictive control, Lyapunov regulation methods, energy based control and artificial intelligence methods. As shown in [3,4] the application of adaptive control gives a rather simple regulation structure, but there is a significant number of generator states that have to be measured or estimated. The feedback linearization also gives a simple regulation algorithm and is used in multimachine PSS control [5,6]. However, the system nonlinearities are neglected and this regulation method is not robust. The sliding mode control [7,8] is also used for multimachine PSS because they can affect only system state variables, whilst other variables are not subjected to control. The synergetic control theory is similar to the sliding mode control, with advantage of constant switching frequency operation, and better control of the off-manifold dynamics [9]. The PSS based upon this regulation method can

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be found in [10,11]. The improved synergetic excitation control with voltage regulation can be found in [12]. However, to achieve good transient stability, the authors propose online parameter adapting depending on the operating point. The artificial intelligence methods do not need the knowledge of generator complex mathematical model [13,14]. The main drawback of these methods is that they are based upon experience or the controller has to be learned according to certain scenarios expected in operation. The nonlinear model predictive control for synchronous generator power oscillation damping is introduced in [15]. In this case the future control sequence is also based on a certain performance index. Lyapunov regulation methods [16,17] ensure the system stability, but there is no simple algorithm for gaining desired regulation quality.

Energy based approaches have been proven to be specially well suited for the modelling and control of mechanical systems [18]. Lyapunov and passivity analysis provide, besides guaranties of stability, insight into the system's behaviour [2]. For a passivity based controller synthesis the system needs to be represented as a Port Controlled Hamiltonian (PCH) system. The PCH concept was first introduced in 1990s by Arjan van der Schaft and Bernhard Maschke [19–21]. Since that time it is being continuously developed and improved. As the PCH system preserves physical representation of potential and kinetic energy, as well as system interconnections and dissipations, its introduction led to development of Interconnection and Damping Assignment (IDA) control algorithm. In recent years, the IDA regulation is used in mechanical, thermodynamic and electric systems, e.g. [22,18]. The first PCH model of a single synchronous generator connected to an infinite bus through a transmission line is given in [23] and further used in [24,25]. This model has a mechanical power and field voltage for inputs, without the effect of pole saliency taken into account.

The goal of this paper is synthesis of a new nonlinear IDA excitation controller which will have an impact on the generator operating point in the role of AVR. This will be achieved by implementing the generator voltage feedback to IDA controller. In this way the robustness regardless of the system operating point will be achieved, and the generator voltage tracking will be ensured. First, the new model of a salient pole synchronous generator connected to an infinite bus through a transmission line with torque and field voltage as inputs will be introduced in PCH form. This model will be used to gain an IDA excitation controller. The main novelty of the paper is introduction of the voltage feedback to IDA control, which results in a forced closed loop PCH system. This being the case, the passivity and stability analysis will also be extended as in [26] and system passivity and stability will be proven both mathematically and through simulations, in the aspect of power system stability.

2. PCH generator model and IDA excitation control

The PCH concept interprets a physical system as a group of interconnected subsystems between which energy conversion takes a place. According to that interpretation the subsystems can be classified as dissipative, storage, control and interconnecting elements. Their interconnection is given in a form of a Dirac structure. Authors introduce generalized variable pairs, product of which gives the power, i.e. energy change through the time. As explained in [27], for any skew-symmetric map $J\colon \mathscr{E} \to \mathscr{F}$ its graph given as $\{(f,e) \in \mathscr{F} \times \mathscr{E} \mid f = Je\}$ is a Dirac structure. System dissipation is modelled in a form of a Rayleigh dissipation matrix $\mathbf{R}$. Finally, PCH systems are defined as [27]:

$$\dot{\mathbf{x}} = [\mathbf{J}-\mathbf{R}]\frac{\partial \mathscr{H}(\mathbf{x})}{\partial \mathbf{x}} + \mathbf{g}(\mathbf{x})\mathbf{u}, \tag{1}$$

$$\mathbf{y} = \mathbf{g}^{\mathrm{T}}(\mathbf{x})\frac{\partial \mathscr{H}(\mathbf{x})}{\partial \mathbf{x}}. \tag{2}$$

where $\mathbf{x}$ represents the state variables vector and $\mathscr{H}(\mathbf{x})$ denotes the system Hamiltonian. Matrix $\mathbf{J}$ is called the Poisson structure matrix which has to be skew-symmetric ($\mathbf{J}(\mathbf{x}) = -\mathbf{J}^{\mathrm{T}}(\mathbf{x})$) to preserve the Dirac structure and the system passivity. For the same reason, the Rayleigh dissipation matrix must be symmetric and positive semi-definite ($\mathbf{R}(\mathbf{x}) = \mathbf{R}^{\mathrm{T}}(\mathbf{x}) \geqslant 0$). Matrix $\mathbf{g}$ represents the PCH input, whereas the PCH output vector $\mathbf{y}$ must be defined as in (2) to ensure the system passivity.

The IDA control method is based on the PCH system model, which makes the IDA control robust to unmodelled dynamics. The goal of the IDA control method is to gain the PCH form of a closed-loop regulation system. To gain an IDA control algorithm, following partial differential equations system should be solved [2]:

$$[\mathbf{J_d}-\mathbf{R_d}]\frac{\partial \mathscr{H}_c}{\partial \mathbf{x}} + [\mathbf{J_c}-\mathbf{R_c}]\frac{\partial \mathscr{H}}{\partial \mathbf{x}} - \mathbf{g}\mathbf{u} = 0, \tag{3}$$

where the subscript “d” denotes a desired closed-loop structure element and the subscript “c” denotes a controller element. A Hamiltonian gradient $\partial\mathscr{H}/\partial\mathbf{x}$ represents the sign of total energy change [28,29]. To ensure that the closed-loop energy function $\mathscr{H}_d$ has the stable minimum at the desired operating point $\mathbf{x}_*$, following conditions should be satisfied:

$$\left.\frac{\partial \mathscr{H}_d}{\partial \mathbf{x}}\right|_{\mathbf{x}=\mathbf{x}_*} = 0, \tag{4}$$

$$\left.\frac{\partial \mathscr{H}_d^2}{\partial \mathbf{x}^2}\right|_{\mathbf{x}=\mathbf{x}_*} > 0. \tag{5}$$

If these conditions are fulfilled, $\mathscr{H}_d$ represents the closed-loop system Lyapunov function. The control algorithm $\mathbf{u}$ can be obtained in the explicit form from (3):

$$\mathbf{u} = (\mathbf{g}^{\mathrm{T}}\mathbf{g})^{-1}\mathbf{g}^{\mathrm{T}}\left([\mathbf{J_d}-\mathbf{R_d}]\frac{\partial \mathscr{H}_c}{\partial \mathbf{x}} + [\mathbf{J_c}-\mathbf{R_c}]\frac{\partial \mathscr{H}}{\partial \mathbf{x}}\right), \tag{6}$$

where according to [25], the controller Poisson and dissipation matrices and the controller Hamiltonian can be expressed in the following way:

$$\mathbf{J_c} = \mathbf{J_d}-\mathbf{J}, \mathbf{R_c} = \mathbf{R_d}-\mathbf{R}, \mathscr{H}_c = \mathscr{H}_d-\mathscr{H}. \tag{7}$$

The partial differential equations (PDE) system (3) can be solved using one of the methods described in [30], such as algebraic IDA, non-parameterized IDA or interlaced algebraic-parameterized IDA methods. The new methods which simplify, or even avoid the PDE solution finding are proposed in [31,32].

2.1. Salient pole synchronous generator model as PCH

To get the IDA control algorithm for a synchronous generator excitation system, a synchronous generator model must be given in the PCH form. The model is gained by substituting armature flows with product of appropriate armature currents and inductances (in a p.u. system equal to reactances) in the generator stator voltage equations and in the generator mechanical equation. Further on, the armature current components in direct and quadrature axis, i_d and i_q, are extracted from voltage equations:

$$i_d = \frac{1}{X_d' + X_e}e_q' - \frac{U_{m0}}{X_d' + X_e}\cos\delta, \quad i_q = \frac{U_{m0}}{X_e + X_q}\sin\delta. \tag{8}$$

This generator model requires the knowledge of the synchronous direct axis reactance X_d, the transient direct axis reactance X_d', the synchronous quadrature axis reactance X_q, and the equivalent reactance X_e (the reactance of lines and transformers between the generator and the rest of power system modelled as an infinite bus). Armature current and flux linkage components are implemented in a torque equation [33]:

$$\frac{d\omega}{dt} = \frac{T_t - (\psi_d i_q - \psi_q i_d)}{2H}, \tag{9}$$