Design of integrated synergetic controller for the excitation and governing system of hydraulic generator unit

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ABSTRACT

Synergetic control theory is introduced into hydraulic generator excitation system (HGES) and hydraulic generator governing system (HGRS) in this paper. Synergetic excitation controller (SEC), synergetic governing controller (SGC) of HGU have been designed. In order to enhance the terminal voltage control and mechanical power tracking performances simultaneously, the integrated synergetic controller (ISC) is also proposed. ISC implements synergetic control of terminal voltage, rotor speed, mechanical input power and guide vane opening. Namely, the ISC is considering both of the excitation system and governing system of hydraulic generator unit (HGU), which can provide control function instead of SEC and SGC. In addition, the control rules of the aforementioned three controllers are deduced from the nonlinear mathematical analytic model of hydroelectric generator unit. At the end of this paper, comparative case studies between the proposed SGC, SEC, ISC and classic PID controller are presented. The results show that the proposed ISC improves the nonlinear HGU system performance with a more accurate precision and shorter settling time in different operating conditions.

1. Introduction

Hydroelectric generator unit (HGU) is the key equipment of hydroelectric energy conversion system with complex transient characteristics influenced by hydraulic, mechanical and electrical factors. In this system, turbine governor and generator exciter are utilized to control the active power and terminal voltage of HGU. The design of controller for the excitation and governing system of HGU will directly influence the utilization efficiency of hydroelectric energy, the security and stabilization of power plant operation and the power quality sent to the grid (Chen et al., 2014a). However, hydraulic generator governing system (HGRS) and hydraulic generator excitation system (HGES) are complex nonlinear, time-variant and non-minimum phase control system, the control performances of which are affected by nonlinear plant characteristics, load changes and uncertain disturbance. It is still a challenging and important problem to model a suitable prototype and design proper control rules (Yuan et al., 2016). In this regard, a special kind of nonlinear control technique, synergetic control theory, is introduced into the control design of HGRS and HGES of HGU in the paper.

In the past decades, many advanced control techniques have been applied in controller design of HGRS and HGES, such as predictive

control (Jones and Mansoor, 2004; Nilsson et al., 2015), robust control (Singh et al., 2013; He et al., 2015), adaptive control (Liu et al., 2016), fuzzy control (Kishor, 2008; Nagode and Škrjanc, 2014), sliding mode controller (Yuan et al., 2015) or H_∞ robust control (Mei et al., 2007). However, there are still some practical problems for the strategies mentioned above to overcome the long-term operation of power systems in real-time applications (Yuan et al., 2016). For instance, it will result in low control accuracy since the chattering phenomenon of sliding mode controller. The classic PID controller has been designed specifically for a certain operating condition, which is not suited to the whole condition of HGU. In addition, existing control models of HGRS and HGES are often isolated from each other. HGRS controller ignores the transient changing of power angle and terminal voltage, and HGES regards load variation as a sudden step in the mechanical input power of the synchronous generator. Thus, a well-known nonlinear control strategy, synergetic control is introduced into the design of an integrated controller considering both of the excitation and governing system of HGU in this paper.

To remedy this chattering phenomenon of sliding mode controller, synergetic control is proposed (Kolesnikov, 2000; Kolesnikov et al., 2000), it has the advantages of order reduction and is similar to sliding mode control but without the disadvantage of chattering (Zhao et al.,

Nomenclature

T_y	Relay connecter response time of servomotor
u_f	Guide vane opening control signal
ω	Rotor speed
e_x	Partial derivatives of turbine torque with respect to the rotor speed
e_y	Partial derivatives of turbine torque with respect to the guide vane opening
e_h	Partial derivatives of turbine torque with respect to water head
e_{qx}	Partial derivatives of turbine flow with respect to the guide vane opening
e_{qy}	Partial derivatives of turbine flow with respect to guide vane opening
e_{qh}	Partial derivatives of turbine flow with respect to water head
E_f	Excitation voltage of the generator
V_{ref}	Reference value of terminal voltage
ω_{ref}	Reference value of rotor speed
P_{mref}	Reference value of rotor speed
y_{ref}	Reference value of guide vane opening
$x_{q\Sigma}$	Total synchronous reactance of q-axis
x_t	Short circuit reactance of transformer
x_L	Reactance of transmission lines

x_q	Synchronous reactance of q-axis
v_f	Excitation voltage control signal
T'_{d0}	Time constant of field windings
y	Guide vane opening
h	Water head
P_m	Mechanical input power
δ	Rotor angle of generator
H	Inertia time constant of generator
D	Damping coefficient of generator
P_e	Electrical power of generator
E'_q	Transient potential of q-axis
x_d	Synchronous reactance of d-axis
x'_d	Transient reactance of d-axis
$x_{d\Sigma}$	Total synchronous reactance of d-axis
$x'_{d\Sigma}$	Total transient reactance of d-axis
E_q	Potential of q-axis
V_s	Voltage of the infinite bus
ω_0	Synchronous angular speed
T_ω	Water inertia time constant
K_a	Magnification
T_a	Time constant of excitation
V_t	Terminal voltage of generator
I_d	Stator current of d-axis
I_q	Stator current of q-axis

2015). The comparison results indicate that synergetic control theory is purely analytical and nonlinear, which provides asymptotic stability and reduces the chattering phenomenon compared to sliding mode control (Bounasla et al., 2015). Synergetic control is ideal for digital control implementation with a fairly low bandwidth (Santi et al., 2004). In recent years, with the mature of synergetic control theory in engineering practice, which has been successfully applied designing controllers for power electronics (Jiang and Dougal, 2004), synchronous generator (Ademoye and Feliachi, 2012), permanent magnet synchronous motor (Bastos et al., 2004), power system stabilizers (Zhao et al., 2014; Jiang, 2009). For instance, Bouchama et al. (2016) proposed an adaptive fuzzy power system stabilizer using robust synergetic control theory and terminal attractor techniques. Variable speed synergetic control is introduced into eliminating the chaotic oscillation of power system in paper (Ni et al., 2014). Also, synergetic control theory was satisfactorily applied in asynchronous electric traction drives of locomotives (Veselov et al., 2014).

In this paper, synergetic control theory is introduced into the HGRS and HGES, synergetic excitation controller (SEC), synergetic governing controller (SGC) and integrated synergetic controller (ISC) of HGU have been designed, and the control rules of them are deduced from nonlinear mathematical analytic model, which can guarantee the macro-variables run into the constructed manifold in a finite time. In order to closely reflect the transient process of voltage control and load frequency control, the terminal voltage, rotor speed, mechanical power, and guide vane opening are included in the manifold for the purpose of achieving global asymptotic stability and voltage regulation, mechanical power regulation simultaneously in ISC controller. To the best of authors' knowledge, this is the first paper to investigate the integrated nonlinear control system contained both of the excitation system and governing system of HGU using synergetic control theory, and additionally, standard third-order synchronous generator model is taken into consideration in HGRS model. At the end of this paper, comparative cases between proposed SGC, SEC, ISC and classic PID controller are presented, the results of numerical simulation experiments indicate that the proposed SGC, SEC and ISC generally respond more quickly than PID, and ISC has little overshoot as a whole. It means that ISC has a superior performance compared with SEC, SGC and PID controller.

For a clear presentation, the remainder of this paper is structured as follows. In Section 2, theory of synergetic control is introduced. Section 3 briefly presents the modeling of the excitation and governing system of HGU. In Section 4, SEC, SGC and ISC controller are designed. Meanwhile, the control rules of the SEC, SGC and ISC are deduced from mathematical analytic model of HGRS and HGES. Then, comparative experiments are designed and the results are discussed in Section 5. Finally, conclusions are presented in Section 6.
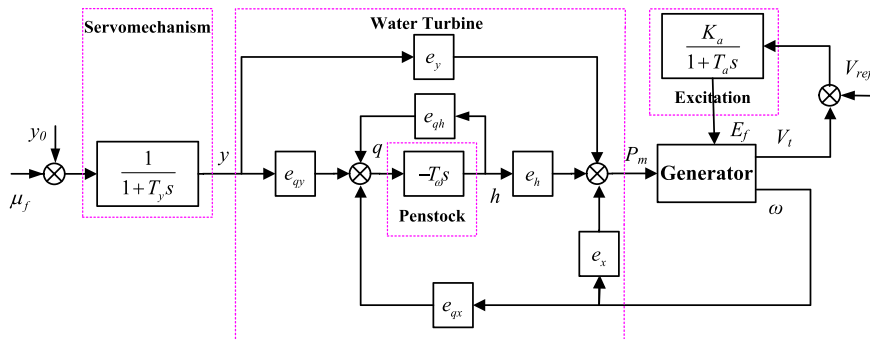

Fig. 1. Block diagram of hydraulic turbine governing system and excitation system.