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Novel Robust Control of Hydrogenerator: the synergetic approach

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Abstract: Usage of renewable energy and necessity to consider disturbances require application of fundamentally new modern control theory to a hydrogenerator nonlinear robust control. This paper presents a synergetic design technique of nonlinear robust control laws for hydrogenerator in accordance with integral adaptation principle of synergetic control theory. The obtained control laws provide implementation of desired technological invariants (control targets), i.e. stabilization of terminal voltage and ensure synchronous operation with the power supply network as well as suppression of external and parametric disturbances (so-called parametric robustness). This suppression is carried out without the construction of observers and it doesn't require operational identification of disturbances.

Keywords: nonlinear control systems, hydrogenerators, power system control, invariants, robustness.

1. INTRODUCTION

Hydropower is a vital renewable source of energy, which is most important due to the significant growth of electricity consumption in the XXI century. Hydroelectric power station is an extremely complex nonlinear system. It includes three types of subsystems: hydraulic one, mechanical one, and electrical one. Effect of hydraulic shock brings the problem of such systems control to the top. Traditionally used PID-controllers and linear optimal control methods based on the linearized models of the system are inefficient in many cases, especially when operating conditions differ significantly and under disturbances. For extra strong disturbances such linear controllers may even have a negative impact on the overall stability of the system. This fact provides the necessity to apply the fundamentally new synergetic principles and methods of control to power system plants instead of traditional ones. These new principles and methods are characterized by use of the most complete multidimensional and multi-connected nonlinear mathematical models, which ensure implementation of desired engineering invariants, or attractors, in the controlled system, and increase in the power system stability (or its engineering safety) (see: Kolesnikov, Kuz'menko and et al. (2000), Zhao, Yao and et al. (2015), Medjbeur, Harmas and Benaggoune (2012), Kolesnikov, Veselov, Monti and et al. (2002), Kuz'menko (2008), Kuz'menko (2012)).

In linear systems, adaptive control laws are usually designed by the classical methods of linear adaptive control theory. Nowadays the control systems adaptive and robust properties are ensured by combination of traditional linear regulators with methods of H_∞ -control theory, methods of the fuzzy control theory or methods of artificial neural networks theory (see: Ioannou and Sun (2012), Krstic, Kanellakopoulos and Kokotovic (1995), Narendra and Parthasarathy (1990), Shuzhi, Ge and Wang (2002)). In Lu, Sun and Mei (2001) noted that methods of nonlinear control theory are increasingly used to control all energy systems nowadays. The Introduction sections of Fusco and Russo (2011), Huerta, Loukianov and Canedo (2011) there is the methods list of the contemporary theory of nonlinear control mostly used in design of robust control systems for power plants including, but not limited to the synchronous generator (SG) excitation systems, namely Lyapunov direct method, method of feedback linearization, method of passification, method of energy functions, etc. Huerta, Loukianov and Canedo (2011) propose to use the sliding regimes to ensure power system robustness in respect of disturbances.

Nonlinear control of hydrogenerator is presented in Lu, Sun and Sun (1993) and allows significant improvement of the system dynamic stability. However, this and most of other papers do not consider disturbances that may have a very large impact on the stability of nonlinear systems. In fact, the real systems are constantly subjected to internal (parametric) and/or external disturbances from technological environment. Uncertain parameters and variable structure of the system should be treated as internal disturbances. Thus, the so-called robust control laws must take these disturbances into account. Eker and Aydin (2001) consider the design of a robust SIMO-controller for nonlinear model of hydrogenerator. The controller designed by a polynomial H_∞-optimization method is used to control the speed of the hydraulic turbine. This approach ensures better quality of control than the classical PI- and PID-controllers. Nevertheless, due to the resulting high-order robust controller, the controller is quite complicated and therefore questionable from a practical standpoint.

Synergetic approach is based on providing the stability of the object motion by means of appropriate design of nonlinear robust control laws that provide maximum area of asymptotic stability of the closed-loop system "ensuring controller–

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object". That design problem is solved by applying the basic method of synergetic control theory (SCT), namely the method of Analytical Design of Aggregated Regulators (ADAR). This method was developed in scientific school of Professor A.A. Kolesnikov with Southern Federal University (Russia) and has found wide application in various fields of modern technology: power electronics, power systems, electro-mechanics, etc. (see: Kolesnikov (2014), Kolesnikov, Kuz'menko and et al. (2000), Zhao, Yao and et al. (2015), Medjbeur, Harmas and Benaggoune (2012), Kolesnikov, Veselov, Monti and et al. (2002), Kuz'menko (2008), Kuz'menko (2012)).

In Kuz'menko (2008), Kuz'menko (2012), Kuz'menko, Synitsin and Zyiryanova (2014) is noted to implement the synergetic approach to the design of adaptive control systems, SCT offers the following basic approaches: 1) for identification of parametric and/or external disturbances the relevant synergetic nonlinear perturbations observers are used. In this case the control laws designed by ADAR method are supplemented by observation subsystem performing dynamical estimation of the unmeasured parameters and disturbances, as well as their suppression; 2) for implementation of the integral adaptation principle, when the influence of parametric and/or external disturbances on the system performance is suppressed by means of nonlinear control laws designed with specially introduced integrators. This suppression is carried out without the construction of observers and it doesn't require operational identification of disturbances.

This report illustrates the use of the integral adaptation principle of the ADAR method for the design of nonlinear robust control laws in hydrogenerator. It ensures implementation of desired control objectives (in terms of the SCT: invariants) and the suppression of external and parametric disturbances.

2. STEPS OF THE ADAR METHOD

According to Kolesnikov (2014), the main steps of the ADAR method will be briefly outlined below.

1. The original differential equations of a control object are written, and then we add the differential equations describing the disturbances that affect the object. Thereby they are being "immersed" into the overall structure of the system:

$$\dot{\mathbf{x}}(t) = \mathbf{A}(\mathbf{x}) + \mathbf{B}\mathbf{U}(\mathbf{x}) + \mathbf{H}\mathbf{z};$$
$$\dot{\mathbf{z}}(t) = \mathbf{D}\mathbf{z},$$

where $\mathbf{x}$ is state variables vector, $\dim \mathbf{x} = n$; $\mathbf{U}$ is vector of control actions, $\dim \mathbf{U} = m$; $\mathbf{z}$ is vector of distributive actions, $\dim \mathbf{z} = \mu$; $\mathbf{A}(\mathbf{x})$ is the functional matrix with dimension $n \times 1$; $\mathbf{B}, \mathbf{H}, \mathbf{D}$ are numerical matrixes with dimension $n \times m$, $n \times \mu$, $\mu \times \mu$.

Thus, we explore the extended system and set a problem to synthesize the control laws to suppress disturbances and ensure specified dynamic properties of a closed-loop system: we need to find the control vector $\mathbf{U}(\mathbf{x})$ that will provide a relocation of the representation point (RP) of the extended object from an arbitrary initial state (at some valid area) firstly into some manifolds $\boldsymbol{\psi}_\mathbf{k}(\mathbf{x}) = 0$ an then into a given state.

2. In order to design the control laws for extended system we introduce the parallel set of invariant manifolds, which number is equal to number of control channels

$$\psi_k = x_k + \varphi_k(\mathbf{x}, \mathbf{z}) = 0, \; k = \overline{1, m}, \tag{1}$$

where x_k is k[th] stated variable for which the right-hand side of the differential equation with respect to this variable includes the appropriate control law $U_k(\mathbf{x})$.

Parallel set of manifolds (1) must satisfy the basic solution of a system of ADAR method functional equations:

$$T_k \dot{\psi}_k(t) + \psi_k = 0, \; k = \overline{1, m}. \tag{2}$$

We note that in general the ADAR method functional equations may have a form different from (2): they may be nonlinear differential equations of 1[st] as well as 2[nd] order. This issue is described in Kolesnikov (2014), Kuz'menko (2008) in more details. The condition of stability (2) has the simplest form $T_k > 0$.

As per ADAR method, under the influence of the vector of "external" control laws $\mathbf{U}(\mathbf{x})$ the extended system RP falls into the neighbourhood of manifold intersection $\psi_1 = 0, \ldots, \psi_m = 0$, because the system RP couldn't be at the same time on different manifolds and moves along it to the specified location of the phase space. Movement of RP along the manifold intersection $\psi_k = 0, k = \overline{1, m}$ is described by the equations of the "internal" dynamics, i.e. by the following decomposed system:

$$\dot{x}_{i\psi}(t) = f_i(x_{1\psi}, \ldots, x_{(n-m)\psi}, \varphi_1, \ldots, \varphi_k), \; i = \overline{1, n-m},$$

where $f_i(x_{1\psi}, \ldots, x_{(n-m)\psi}, \varphi_1, \ldots, \varphi_k)$ are continuous and differentiable functions.

Functions $\varphi_1, \ldots, \varphi_k$ represent "internal" controls for the decomposed system. These controls provide the desired dynamic properties of RP while driving along intersection of manifolds $\psi_1 = 0, \ldots, \psi_m = 0$. Functions $\psi_k = 0, k = \overline{1, m}$ are invariants of the system in terms of ψ_k and remain constant all along the path of movement at the phase space. Dimensionality of decomposed system is equal to (*n-m*), i.e. less than the dimension of the original space of initial conditions from which RP starts to move. Thus, the control laws implement the compression process of the phase flow, completed to the final desired invariant manifold, which actually is system given invariant. So there are may be several stages of such movement and, consequently, levels of decomposition; but their number is determined by the dimension of the object original model and by the number of control channels.