Electric Power Systems Research 101 (2013) 49–55

Contents lists available at SciVerse ScienceDirect

Electric Power Systems Research

journal homepage: www.elsevier.com/locate/epsr

Application of extremum seeking control to design power oscillation damping controller

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ARTICLE INFO

Article history:
Received 21 September 2012
Received in revised form 22 March 2013
Accepted 25 March 2013
Available online 19 April 2013

Keywords:
Power system stability
Extremum seeking control
Static Var Compensator

ABSTRACT

This paper presents an application of extremum seeking control to stabilize power system oscillations. This control methodology has been implemented as a supplementary control to Static Var Compensator for providing additional damping to power systems. The performance of the designed controller based on extremum seeking method has been compared with the controller based on H_∞ loop-shaping technique. With time domain simulations it has been shown that the controller based on extremum seeking methodology successfully reduces power system oscillations earlier than that with the H_∞ loop-shaping methodology. The effect of dither frequency and adaption gain on performance of extremum seeking controller has also been examined. The 14-Generator South East Australian equivalent power system has been used as a test system to demonstrate the ability of extremum seeking controller to reduce power system oscillations.

1. Introduction

With more long interconnections amongst power systems and penetration of renewable energy sources, maintaining the stability of a power system is of prime importance for today's power system operators. The increase in loading level of transmission lines sometimes can lead to voltage collapse due to a shortage of reactive power. At times generator power oscillations when subjected to disturbance, limit the inter-area power flow. This stability limit can be increased with proper placement and control of flexible AC transmission systems (FACTS) devices. Out of various FACTS devices, Static Var Compensators (SVC) have been widely recognized and used by many utilities around the globe. The primary objective of a fast operating SVC is to continuously provide the reactive power support to control node voltage, thereby improving the power transfer capability of the system. Recently, the use of this device for power oscillation damping has also attracted attention. To attain this objective, supplementary controllers referred to as power oscillation damping controllers (PODs) are often used. Many countries including Australia have started using PODs to enhance their oscillatory stability limit [1].

During the last decade there has been a growing interest among power system researchers to use advanced control techniques in designing these PODs. Lately, these control techniques and their various applications have been a major research topic in power system dynamics and stability. After the analytical proof of stability of extremum seeking (ES) feedback scheme for general non-linear dynamic systems in 2000 by Krastic and Hsin-Hsiung [2], this control scheme has also attracted many researchers. This has increased interest in the theory of extremum seeking with an increase in the number of research publications from about 100 in the 1990s to nearly 800 in the last decade [3].

The extremum seeking control (ESC) has been implemented successfully in various engineering applications. Some of the successful applications are in brake system control, electromechanical valve control, human exercise machine, optimizing neural network and fuzzy logic controllers and process controls. The exhaustive list of relevant applications of extremum seeking can be found in Ref. [3] and references therein. Different types of extremum seeking control methods have also been researched by power system researchers for adaptive maximum power point tracking (MPPT) control of fuel cells [4,5], ripple-based ESC for MPPT [6] and switched ESC for MPPT in PV system [7]. ESC has also been successfully used for fast tracking of input reference [8]. The work presented in this paper receives inspiration from the application of ESC to track input reference presented in [9]. During this work, the authors have used ESC to design a supplementary controller for SVC to control generator output power oscillations. The SVC used in this work has been placed to increase the loadability of the system using a Mixed Integer Quadratic Constraint Programming (MIQCP) technique [10]. An additional supplementary ESC loop has been designed in order to suppress generator terminal power oscillations.

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http://dx.doi.org/10.1016/j.epsr.2013.03.012

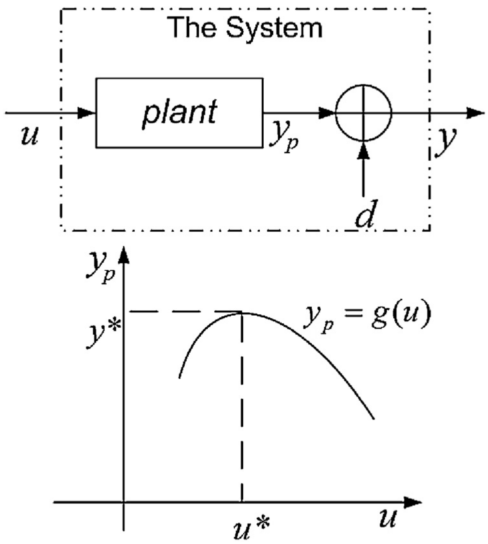

Fig. 1. Input-output steady state map of a plant.

It is also worth mentioning that there exist a number of modern control techniques which have been used to design either power system stabilizer or PODs to reduce generator oscillations. These include Linear-Quadratic-Gaussian (LQG) method, the Linear-Quadratic-Regulator (LQR) technique, μ-synthesis and H_∞ control methods etc. [11]. Out of these various control schemes, SVC supplementary controller based on H_∞ loop-shaping (HLS) control theory (without any bias), has been compared with that based on extremum seeking control. The main contribution of this work is to design a controller based on extremum seeking approach rather than the comparison. This paper presents an application of extremum seeking method. An in-depth analytical solution and proof of various theorems, including averaging analysis, stability and convergence of ESC can be found in Ref. [12].

The remainder of the paper is organized as follows. Section 2 explains the general idea about ESC and its operation. Section 3 describes H_∞ loop-shaping technique. Section 4 shows general information about the test system. The problem formulation and controller design is illustrated in Section 5. Section 6 presents simulation results and conclusions are drawn in Section 7.

2. Extremum seeking control

This section presents a conceptual understanding of extremum seeking control (ESC). The idea of extremum seeking is rather old, but interest in using extremum seeking control gained more attention after its first stability proof using averaging analysis and singular perturbation in the year 2000 by Krstic and Hsin-Hsiung [2]. A controller based on extremum seeking approach can be used to find the area around distinct minima or maxima in the steady state map of the plant. This scheme is independent of plant model for controller synthesis. For a general reference tracking problem the output is defined as the norm of the difference between a reference value and plant output [13].

Fig. 1 shows a broad sketched view of extremum of the plant [3]. The description of the process starts with input u and output y_p that has a well defined steady state characteristic, which resembles a general power system. The steady state map can be expressed as $y_p = g(u,p)$. Assuming that the relationship g exhibits a desired external situation, $y^*(p)$, an extremum seeking control finds $u = u^*(p)$ and maintains this condition despite variation in p. It is worth noting that extremum seeking algorithms achieve this without prior knowledge of the system.

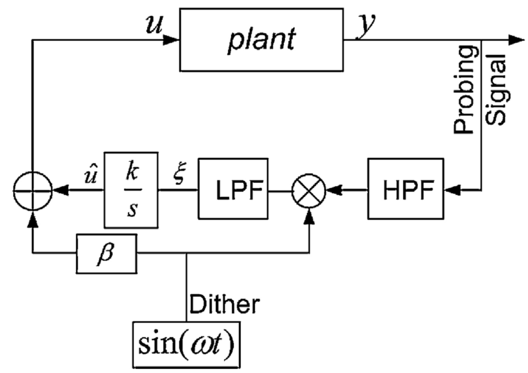

Fig. 2. Basic block diagram of extremum seeking control (ESC) scheme.

2.1. Theory of ESC loop

A more generalized extremum seeking scheme is shown in Fig. 2 [13,14]. A concise working of ESC is explained here. An in-depth working of an ESC loop and the analytical proof of stability convergence can be found in Ref. [13]. Fig. 2 shows the structure of the basic extremum seeking control loop.

Extremum seeking control (ESC) often uses a periodic signal, also known as "dither" to track the operating point over a period of time. This signal is often known as 'excitation signal'. The method of sinusoidal perturbation has been the most popular in the extremum seeking scheme. This method allows fast adaptation to the new operating point of plant. The 'dither' signal '$\sin(\omega t)$' with amplitude (β) creates a periodic response of output y. The high pass filter eliminates any DC component of the probing signal.

The initial control input u_0, is superimposed with a sinusoidal signal $\beta\sin(\omega t)$, which has a small value of amplitude β and ω is the frequency of signal.

$$u(t) = u_0 + \beta\sin(\omega t)[\Delta u(t)] \quad (1)$$

If the time scale of this perturbation is much higher than the highest time constant of the plant, the output of the process will also be approximately close to sinusoidal.

$$y(t) \approx y_s + af'\sin(\omega t) \quad (2)$$

with, $y_{s,0} = f(u_0)$

This perturbation output is examined to identify the gradient of the plant map. To obtain this, the mean value of output y_s is removed by a high-pass filter (HPF). The product of this filtered output and sine signal indicates the slope of the unknown plant map. This product leads to a non-zero mean signal obtained with a low-pass filter (LPF) as long as the performance objective has not been met. In this case, the norm of the plant output $y(t)$ and reference signal $r(t)$, is the performance objective. This signal works in conjunction with the HPF. Next, with the integration of this gradient signal, asymptotic stability of the closed loop system will make the gradient die out and achieves the optimum value of cost function. The compensator ε may enhance the transient performance by compensating the input/output dynamics [15].

With this information an additional term $\hat{u}$ is calculated by time integration and multiplication of adaptation gain ε. The adaptation of u finally converges to u^*. The sign of ξ provides the direction to the integrator moving toward the optimal operating point. Extremum seeking is a model-free method, which iteratively modifies the input of a plant function to achieve local minimum or maximum.

The choice of parameters of ESC loop affects the system performance. As suggested in Ref. [3], a meaningful algorithm requires that the dither signal belongs to the pass band of both the low pass and high pass filters. Moreover, the period of excitation signal must be small compared to the integration time. Based on the averaging