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Networked control of a power system: A non-uniform sampling approach

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ABSTRACT

This article deals with the damping of low-frequency power systems oscillations using a networked controller on a smart grid. We assume that the network channel is band-limited and has random communication delay whose probability distribution can be found. To mitigate the effect of delay on control system performance, the measurements from the system are sampled at a random and non-uniform period but the inputs are updated at a faster and constant rate. This makes the closed-loop control system a stochastic switching system. A framework to analyze the mean square stability of the closed-loop system is developed and a switching observer-based controller is designed to ensure the stability of the system at random sampling instants. A case study has been performed using the Western-System-Coordinating-Council (WSCC) 3-machines, 9-bus system for verification of the technique. The contribution of the paper is a bandwidth efficient delay compensation technique and its application to power systems stability enhancement in a smart grid.

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1. Introduction

One of the phenomena inherent in forming a power system network is the existence of low-frequency electromechanical oscillations that may arise when the system is disturbed from its equilibrium position. They may be classified as intra-plant mode, local-plant mode and inter-area mode, etc., based on their origin and part of the network being affected [1,2]. They may be triggered by the disturbances due to load changes in the system or a momentarily fault on a tie line and may cause instability if persists for a longer duration. These oscillations must be damped to prevent power outage due to large power variations. A mean to control these oscillations is to use a flexible AC transmission system (FACTS) controller, such as thyristor controlled series capacitor (TCSC). TCSC acts as a variable reactance which is controlled by firing angle of a thyristor. It is usually installed at a tie line in the power system network and can control multiple modes simultaneously.

Various methods have been employed to control the oscillations [3,4]. In [3], authors use controlled series compensation to improve the stability of multi-machine power system. They provide a technique to choose a suitable location for series compensation based on residue analysis and design a damping controller using the pole placement technique. In [4], linear quadratic regulator (LQR) and robust linear quadratic Gaussian (LQG) controls for TCSC are presented to control power system oscillations. The designed controllers are implemented on Western System Coordinating Council (WSCC) 3-machines, 9-bus system.

The conventional electrical grid has been modernized into the smart grid which has enabled the integration of communication and IT infrastructure [5]. It has made possible to employ networked controlled systems to enhance power systems stability [6]. Networked controlled systems have the advantages of easier installation, flexibility, lower cost, easier maintenance, and reliability. But the use of a networked controller poses challenges, such as, bandwidth limitations, delays in the channel, packets dropout, packets disordering and corruption, etc., which may degrade the performance of closed-loop control or cause instability. These issues have been addressed in literature [7–11]. In [7], stability analysis is performed for a networked control system on a smart grid where the channel has random packets dropout, modeled by the Bernoulli's random process. An LQG control is synthesized for TCSC to damp power system oscillations. In [8], a speed controller is designed for networked DC motor in the presence of channel

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delays and packet losses. Zero steady-state error and stability conditions are derived and estimation for distribution algorithm is used for optimization of controller parameters. In [9], a linear matrix inequality (LMI) based controller is developed based on wide area measurements. The communication effects like time delays, packets dropout, and disordering have been considered by incorporating time-varying delays in the system model. In [10], the effects of delay and packet dropouts are incorporated by representing the system as step delayed with switching nature. A static state space controller has been designed to guarantee asymptotic stability of the system. WSCC 3-machines, 9-bus system has been used as a case study where automatic voltage regulators (AVRs) are used as control elements to verify the performance. In [11], authors have given the concept of observer-driven system copy to design control on a constrained bandwidth network. It uses the nominal system model to generate measurement data when data from phasor measurement units (PMUs) is not available.

Different applications are being implemented in smart grid like state estimation, transient stability, small signal stability and voltage stability [12]. Each application has different communication requirements [13,14]. If a shared channel is used for communication, it may cause delays due to network congestion. The same problem may arise if a channel with limited bandwidth is used or some links in the channel are offline. In this case, a control strategy is required that ensures the stability of the control system and at the same time efficiently uses channel bandwidth.

This article addresses the aforementioned two network constraints. In [15], the same authors discuss the rotor angle stability enhancement over a random delayed network but the method holds only if the total delay is less than the system sampling period. A Kalman filter based optimal stochastic control is designed for the system and it does not address the issue of bandwidth constraint. The article presented here explains an idea to deal with the random delay that may arise on a band-limited channel and the delay can be greater than the system sampling time. The idea is to sample the system measurements at a random and variable period to minimize the effects of delay on the system while using bandwidth efficiently. A switching observer-based controller is then designed to damp the oscillations. The use of non-uniform sampling period makes the system a stochastic switching system because it switches to different sampling periods. Stability analysis of the closed-loop system is performed to investigate the effects of change in delay probabilities and model parameters on system stability. Simulation results show that the proposed control provides sufficient damping to the oscillations even with variations in power system model and delay profile.

The paper is organized follows: In Section 2, a generalized model of a power system is described and its simplification to the form used for design purposes is presented. Assumptions about the network channel are made and the plant is discretized at a random sampling period. Structure of observer and controller is chosen in Section 3 and stability analysis of the stochastic switching system is performed. Section 4 deals with the design of an observer-based controller that takes non-uniformly sampled measurements to give control signal at a fast and constant rate. Also, the procedure for switching the observer-based controller is defined. Section 5 provides the method to choose sampling periods based on delay profile. Section 6 presents a case study using WSCC 3-machines, 9-bus power system to verify the performance of the proposed controller and observer. Section 7 concludes the paper.

2. Problem formulation

Consider a scenario of networked control on smart grid as shown in Fig. 1, where the power system block represents the oscillatory dynamics to be controlled along with actuator (TCSC) as shown in Fig. 2. The use of TCSC (FACTS controllers) to control power system oscillations by a remotely located controller has been enabled by smart grid technologies. There can be a single or multiple recording points depending upon the application but the data reaches the controller and then to actuator via a communication network. It can be seen that the measurements, $y(t)$, from the power system are sampled and sent to the controller through a shared communication network. The communication channel is assumed to be band-limited with random communication delay. In order to compensate for delay and to efficiently utilize the channel bandwidth, a non-uniform sampling strategy is adopted. The sampler which is adaptive in nature has an extra input for the time in seconds which is hard-wired to the decoder block. The sampler switches the sampling period according to the input signal. It is assumed that the delay can be measured online by time stamping the packets or by sending dummy packets between the measurement samples. The delay measurements are used to decide the period after which next sample will be taken. A mapping technique from the range of delay to sampling period is given in Section 5. The delay calculation and mapping are performed in the period calculation block. The controller is an observer-based one with dynamics switching with the sampling period. The block is event-driven meaning it will update its operation whenever a measurement packet is received. The controller output together with the sampling period is encoded into a single packet via the encoder block and sent to the plant. A decoder block on the plant side separates the sampling period and control input. The control input is applied to the plant via a zero-order-hold (ZOH) which holds the current sample value until next packet has arrived and the sampler adapts the sampling period.

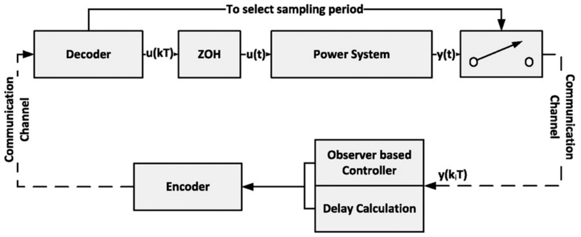

Fig. 1. A non-uniformly sampled networked control system on smart grid.

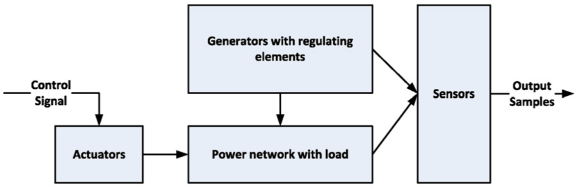

Fig. 2. Inside a power system block.

2.1. Power system modeling

The power system block consists of generators, actuators, sensors, and power network as shown in Fig. 2. The generator includes the dynamics of AC machine along with exciter, power system stabilizer, automatic voltage regulator and speed governor. The generators are connected to power transmission network which also models transformers and loads connected to the transmission lines. The actuators (FACTS controller, like, TCSC) take input from the control element and act as a variable reactance on a tie line in the power network.

Fig. 3 shows circuit of TCSC, the inputs and outputs are connected within the power network such that it is in series on a tie line, whereas, the firing angles of thyristors are provided by the

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