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Employing phase trajectory length concept as performance index in linear power oscillation damping controllers

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ABSTRACT

In this paper, phase trajectory length concept is employed to introduce a performance index in order to investigate the oscillation of linear power systems. At first, Phase Trajectory Length (PTL) concept in the state space of a Multi Input Multi Output (MIMO) linear system is defined as the traversed distance from a certain point in the state-space to the equilibrium point of the system. Moreover, lower and upper bounds of the PTL are computed. In order to evaluate and compare the oscillatory nature of the power system, oscillation number is defined as the ratio of the PTL to the radial distance of a certain point to the equilibrium. Based on this criterion, it is demonstrated that shortening the PTL leads to effective oscillation damping for all variables which are linear combinations of the main states of the intended system. It is proven that considering the aforementioned index in controller design leads to satisfy a certain finite boundary for Integral Absolute Error (IAE) of system states. Predicated on expressed features of the PTL, corresponding Hamilton Jacobi Bellman (HJB) equations with Minimum Length Controller (MLC) is represented to design damping controller. In order to reduce the settling time in oscillation damping, the desired time weight is augmented in the calculation of the considered objective function. The proposed index can be employed to tune the controller parameters. In this regard, a numerical algorithm is suggested to design a full state feedback controller as MLC. At the end, the given linear power examples, both in simulation and experimental results, show the benefits of this approach for analyzing and designing the oscillation damping controller in linear power systems.

1. Introduction

Nowadays, due to economic and environmental restrictions and in order to increase the performance, modern systems have been designed to operate close to their control and operational limits. In this regard, damping the oscillation of systems has attracted the predominant attention among the different controller designing criteria [1]. Such a concept has been widely used in electronic vehicles [2], power systems [3] and civil engineering [4]. Power Oscillation Damping (POD) is one of the main origins of this subject [3].

Predicated on the aforementioned, several researches have been carried out in order to design a controller for the power systems in order to alleviate the oscillations. In such systems, low frequency oscillations which may lead to have serious consequences, involve many generators in an interconnected system. In order to evaluate the oscillation, several methods and criteria have been suggested in the literature where it can be pointed out to modal analysis [3], Prony method [5], Kalman filtering [6], Hilbert-Huang transform [7]. Moreover, in the high voltage direct current transmission systems, various methods such as input selection [8], Power System Stabilizer (PSS) damping [9,10], conventional PID controllers [11], Linear Quadratic Regulation (LQR) and Linear Quadratic Gaussian (LQG) controllers [12,13], model predictive based controllers [14] and robust controllers [15] have been utilized for damping the oscillation. The need for improving the damping in a wide range of oscillation modes (global, inter-area and local) led to the development of Multi-Band PSS (MB-PSS also known as PSS4B) [16–18]. Wide-Area Damping Controller (WADC) adds damping control to the generator's excitation system and the so-called supplementary damping controller provides additional damping functions on Flexible AC Transmission Systems (FACTS) devices [19]. FACTS systems highly gained the attention in the application of high power electronic devices for power flow and voltage control [20,21]. In addition, static var compensator [22] and unified power flow controller [23] have been introduced as the other existing methods in the literature. In [24], the impact of increased penetration of DFIG-based wind turbine generation in power oscillation damping was investigated.

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Nomenclature

γ	time weight
s	switching factor
$L(\boldsymbol{x}(t))$	PTL function
$r(\boldsymbol{x}(t))$	radius function
$r_{ON}(\boldsymbol{x}(t))$	oscillation number
$\boldsymbol{x}(t)$	state variable vector
ρ	state variables weight
K	full state feedback gain

List of acronyms

PTL	Phase Trajectory Length
ITSE	Integral Time weighted Square Error
MIMO	Multi Input Multi Output
HJB	Hamilton Jacobi Bellman
MLC	Minimum Length Controller
POD	Power Oscillation Damping
ONI	Oscillation Number Index
GA	Genetic Algorithm
PSS	Power System Stabilizer
SVD	Singular Value Decomposition
FACTS	Flexible AC Transmission Systems
ISE	Integral Square Error
IAE	Integral Absolute Error
LQR	Linear Quadratic Regulation
LQG	Linear Quadratic Gaussian
WADC	Wide-Area Damping Controller
SSSC	Static Synchronous Series Compensator
CHB	Cascaded H-bridge

Besides, in [25] the local mode oscillations are damped by tuning PSS installed on the generators for WADC. In the other studies, since system inertia plays a vital role in primary frequency control, the inverter-interconnected renewable generation has the tendency to decay frequency stability without appropriate active power balance management, either by means of storage [26], demand response [27] and inertial response emulation control loops for renewable generation [28]. By exploring the benefits of load voltage sensitivity for frequency stability improvement, the significance of voltage control through POD controllers has been considered in [29]. In Static Synchronous Series Compensator (SSSC) systems, the oscillating reaction attributable to the lightly damped internal dynamics could negatively influence the life cycle of the system and power quality. Also, it could bring about the failure of some components in such a way that they are working under a coincidental overloading condition [30]. In this regard, various studies on SSSC have been accomplished in the literature [31,32]. Considering this fact that the common complex pattern of oscillations in a large power system can be studied via linear, time invariant system at a specific operating point, [33] has considered the local oscillation of a single machine by means of a transfer function model. Moreover, in [34], employing pole placement techniques led to design the FACTS-POD stabilizers. In [35], physical interpreting of state feedback controller to damp power system oscillations designed in [36] was studied. Moreover, in [37], the application of polynomial control to design a robust POD was examined. In addition, employing the modern controller to settle the oscillation has become the focal point of the research interests [38]. Beside the classical methods, some intelligent control techniques such as fuzzy logic control, neural network control, adaptive based controller and their hybrid combinations have been successfully applied to power systems, recently [39–41]. In such an algorithm, controller parameters are tuned somehow that the closed loop response minimizes a predefined objective function [42–44].

Although various methods have been proposed to oscillation damping in the literature, there is no solid performance index to analyze damping oscillations completeness. This gap becomes more critical when the system dimension increases. Due to this drawback, the main contribution of this paper is two folded. The first contribution is employing phase trajectory concept as a performance index while in the second one, a systematic approach to design an oscillation damping controller in linear control systems is proposed. It is worth to mention, since the oscillatory behavior is not defined in the linear scalar systems the objective of this paper is founded on designing the linear controller based on the PTL concept for the linear systems in which their dimension is equal or greater than two. Also, since the oscillation damping is often demanded for physical variables among many possible state realizations of the system, the physical realization is considered for defining the PTL concept.

The outline of this paper is organized as follows. At first, the required definitions, conditions and theorems about the PTL concept is given in Section 2. In Section 3, by virtue of the expressed features of the PTL in the preceding section, oscillation number is defined as a performance index to evaluate and compare the oscillatory nature of the linear systems. Moreover, in this section, corresponding Hamilton-Jacobi-Bellman (HJB) equations with MLC are represented. In the subsequent section, a numerical method to solve the HJB based on the heuristic search is suggested to explore the state gain feedback in order to minimize the oscillation number of linear systems. To consider the effect of settling time, some modifications are implemented in the objective function. Subsequently, in Section 4, simulation examples demonstrating the efficacy of the method in oscillation damping are provided. Moreover, an experimental case study is provided to evaluate the performance of the proposed method, practically. Finally, in Section 5, concluding remarks are given.

2. Phase trajectory length concept in the linear system

In [45,46], phase trajectory length concept firstly was introduced as Arc-length Lyapunov function. The main focus of the aforementioned literatures was the stability and convergence of dynamical systems based on the intended concept. Moreover, in [47], the aforesaid concept was employed to estimate the domain of attraction of polynomial nonlinear systems. To the best of our knowledge, the related articles do not utilize the PTL function as a criterion for evaluating oscillatory nature of the control systems. In this paper, required theorems and definitions in order to present a performance index in oscillation damping controllers for linear control systems are provided. In this regard, consider the following unforced linear control system:

$$\dot{\boldsymbol{x}}(t) = \mathbf{A}\boldsymbol{x}(t), \quad \mathbf{A}^T = [\boldsymbol{a}_1,\ldots,\boldsymbol{a}_n] \tag{1}$$

$$\boldsymbol{x}(t) = [x_1(t),\ldots,x_n(t)] \in \mathbb{R}^n$$

where $\boldsymbol{x} \in \mathbb{R}^n$ denotes the state vector. Assuming the system is exponentially stable at the origin, a phase trajectory starts at $\boldsymbol{x}(t)$ and evolves to the origin from $\tau = t$ to $\tau = \infty$. Now, the PTL for the system presented in Eq. (1) is defined as a sum of the length differential elements on the phase trajectory curve from $\tau = t$ to $\tau = \infty$:

$$L(\boldsymbol{x}(t)) = \int_{\tau=t}^{\tau=\infty} dl(\tau) \tag{2}$$

where $dl(\tau)$ is defined through state differential elements as follows:

$$dl(\tau) = \sqrt{dx_1^2(\tau) + dx_2^2(\tau) + \cdots + dx_n^2(\tau)} \tag{3}$$

And since $d\boldsymbol{x}_i(\tau) = \boldsymbol{a}_i\boldsymbol{x}d\tau \quad (i = 1,2,\ldots,n)$, another representation of the PTL can be stated as follows:

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