Computers and Mathematics with Applications 60 (2010) 944–953

Contents lists available at ScienceDirect

Computers and Mathematics with Applications

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

Coordinated control design of multiple HVDC links based on model identification

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ARTICLE INFO

Keywords:
Coordinated control
HVDC link
Modal analysis
Small signal stability
System identification

ABSTRACT

This paper presents a method for designing a centralized coordinated controller for several HVDC links. The controller increases the damping of the power oscillations by modulating the current through the HVDC links in a coordinated fashion. To design a centralized coordinated controller a reduced order open system model is estimated. The open system model of the power system is estimated using the Numerical Algorithms for Subspace State-Space System Identification (N4SID) algorithm which is a black-box system identification technique. The current set-point change through the HVDC links is the set of input signals and the speeds of the generators are the set of outputs. This controller design method increases the damping significantly, which is shown for a small power system.

1. Introduction

Power electronic equipment, in the form of High Voltage Direct Current links (HVDC) and Flexible Alternating Current Transmission Systems (FACTS), has been recognized as being of key importance for satisfactory operation of power systems in the future [1]. The increased power controllability, especially brought about by the HVDC links, provides new possibilities. Besides being efficient in the main function, bulk power transmission, the HVDC link possesses controllability which can be used for various stability enhancements.

Power systems are known to often be operated in the so called 'quasi-steady state' where the power systems are always subject to various, often small, disturbances [2]. Change of loading level and capacitor switching are typical examples of small disturbances that sometimes give rise to oscillations in the power system. In large interconnected power systems low frequency power oscillations are an important issue. Low frequency oscillations have become a serious bottleneck limiting power transfer [3]. All synchronously connected generators participate in inter-area oscillations to different degrees [4]. For large synchronously interconnected systems inter-area oscillations are a global problem. For each mode, these generators can be classified in two groups, swinging against each other. The use of Power System Stabilizers (PSS) is the most common way to improve system damping [4] and the use of HVDC power modulation is another effective approach [5–7]. In addition, various FACTS devices can be used [8]. As more devices come into operation the opportunity and need for coordinated control arises. Coordinated strategies must be employed in the controller designs to avoid interactions between the devices [9].

The weak damping problem relates to small signal stability; thus, a linear model representation of the power system dynamic behaviour is enough [4]. However, for large power systems, detailed linear models are often unavailable. Even if a linear model is available for one equilibrium point, changes in the system change the linear model. In addition, the changes in the system are often unknown and thereby the system model changes as well.

The fact that large systems are represented by large state-space models makes the analysis and control design difficult. Any controller using an observer and state estimate feedback has the same order as the system model. However, to be

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doi:10.1016/j.camwa.2010.02.037

practically implementable, the controller must be of sufficiently low order. A reduced order controller design can be obtained in two ways: either by using a reduced design model of the system or by obtaining a reduced order approximation to a high order controller. The former method is used more widely than the latter because high order controller design relies on the knowledge of high frequency mode parameters, which is usually inaccurate [10]. In these situations system identification techniques are necessary for achieving full or reduced linear models, which are adequate for describing the dominant dynamic behaviour. With an appropriate model a central controller, using state feedback, can be designed to enhance the damping. This paper presents a method of how to derive a centrally coordinated controller, including the model estimation, for several classical HVDC links in order to enhance the damping in the system.

2. Previous research

While there have been a significant number of contributions to the subject in recent years, there are still many aspects which are not clearly defined in the literature or research papers. An opportunity currently exists for the development of reduced order models together with centrally coordinated controllers of several HVDC links for power system oscillation damping. The proposed open system model estimation is based on system identification which is then used for the central controller design.

There have been some papers investigating system identification for modelling power oscillations [11–16]. In paper [11] the Numerical Algorithms for Subspace State-Space System Identification (N4SID) method is used to identify a single-input multi-output state-space system, using the power change in one HVDC link as the input and the power change in two lines as the output. Reference [12] compares different system identification techniques in order to identify a linear model, or more specifically the modes, based on random variations in the system and measuring the angular difference between two buses. The authors in [16] use the Prediction Error Method (PEM) to identify a model of a small part of the China Southern grid. This model is used to optimize the parameters in lead–lag blocks for the HVDC link power modulation controller. Earlier research papers have discussed system identification techniques for small power systems with only one HVDC link or one FACTS device. However, to the best of the knowledge of the authors no work has been presented using system identification in power systems with several HVDC links and the design of a central controller.

3. How to design a centrally coordinated controller

First, a reduced order open system model for the discrete state-space form of the power system is developed by using system identification tools. The controllable signals of the HVDC links are the set of input signals. The output signals are selected as appropriate signals which are measurable signals and signals affected by power oscillations. The signals are detrended before the N4SID method is used to estimate models of different orders. The estimated open system models are validated and a proper model order is selected. An observer is designed to estimate the states in the estimated open system model based on measured input and output signals of the power system. Finally, a centrally coordinated controller based on state feedback is designed, using the controllable inputs of the HVDC links. Fig. 1 shows an overview of the sequence of operations used to design a centrally coordinated controller.

4. State-space modelling

A Linear Time-Invariant (LTI) system can be presented in several ways. A particularly convenient description for multi-variable systems is the state-space form. An nth-order system with m inputs and p outputs has the state-space representation as follows:

$$\dot{x}(t) = Ax(t) + Bu(t) + Ke(t) \quad (1)$$

$$y(t) = Cx(t) + Du(t) + e(t) \quad (2)$$

where

$x(t)$ denotes the n-dimensional state vector,

A, B, C, D and, K denote the system matrices and are of dimension $n \times n$, $n \times m$, $p \times n$, $p \times m$, and $n \times p$, respectively.

The system is driven by an observable input signal $u(t)$ as well as the unobservable $e(t)$ zero-mean stochastic measurement noise, assumed to be white noise, and hence the output $y(t)$ is corrupted by $e(t)$.

The system is assumed to operate in an open loop (open system) and must be stable, i.e. all eigenvalues of A must strictly be in the left half-plane. 'Open loop' refers to the system not having any feedback loop in addition to Eqs. (1) and (2). Furthermore, the sought state-space model should be of minimum order; hence the pair (A, C) is without loss of generality assumed to be observable, whereas $(A, (B\, E[Ke(t)(Ke(t))^T]^{1/2}))$ is controllable [17]. Here $E[Ke(t)(Ke(t))^T]$ is the covariance matrix of the stationary stochastic process. Also note that unlike the impulse response, the state-space model is not unique. This means that the models' matrices cannot be directly compared, only their result.