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Coordinated control of multiple HVDC links using input–output exact linearization☆

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ABSTRACT

This paper is concerned with the investigation of a new control technique for the conventional High Voltage Direct Current (HVDC) link. The proposed technique relies upon nonlinear state feedback linearization of the AC/DC power system.

The idea in input–output exact feedback linearization is to algebraically transform nonlinear systems dynamics into a linear control problem using a nonlinear pre-feedback loop, and then for the linearized power system one can design another feedback loop using a well established technique such as a linear-quadratic regulator.

The primary goal of the controller presented in this paper is to contribute to the enhancement of both the transient and the small-signal stability of the power system. Since the proposed state feedback linearization does not rely on the assumption that there is only small deviation of the states from an equilibrium, the enhancement of both is feasible.

The simulation results obtained in the framework of the study show that the proposed controller is capable of stabilizing the system in various system operating conditions.

1. Introduction

Modern interconnected electric power systems are characterized by large dimensions and high structure complexity and dynamic phenomena associated with the power system operation and control. Power system deregulation, which took place in many countries worldwide, was one of the driving forces stimulated further utilization of power systems. This has in some cases led to a reduced stability margin, as the power systems became more stressed [1,2]. Under these circumstances it becomes quite important to seek new possibilities of enhancing both the transient and the small-signal stability of the power systems.

There are several obvious ways of improving the power system stability:

(i) building new transmission lines,
(ii) installing new generation capacity,
(iii) better utilization of the existing equipment in the power system.

This paper is primarily concerned with the third option, since it is the least costly option and can be relatively easy implemented in a power system. The central idea of the study presented in this paper is the utilization of several High Voltage Direct Current (HVDC) links for stability enhancement.

The main purpose of conventional HVDC transmission is to transfer a certain amount of electrical power from one node to another and enable fast controllability of real power transfer. If the HVDC link is operated in parallel with a critical ac line the load-flow of the ac line can be controlled directly. Even though the HVDC link is not operating in parallel with an ac line, there is still a possibility of controlling the load-flow. The presence of an HVDC link can therefore assist in improving the stability margin in the power system [3]. Many papers, with different approaches, discuss the improvement of stability in power systems by controlling the power through a single HVDC link [4,5]. In the case of several HVDC links in the system, the possibility arises of coordinating the control of the HVDC links to enhance the operation of the system, this can be achieved by altering the load-flow patterns for example. Coordination of the control could also improve the damping and the first swing stability even more.

Most research has focused on controlling only one HVDC link [6,7], but there has also been some research on coordinating several HVDC links [8–11].

Fig. 1 shows two synchronous power systems which are interconnected by two HVDC links. For each such interconnected power

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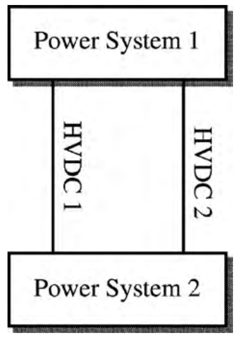

Fig. 1. General power system interconnected by two HVDC links.

system both transient and small-signal stability problems may limit the amount of available transfer capacity.

An input–output exact feedback linearizing coordinated controller has been developed in order to improve the transient stability and damp the oscillations after a fault has occurred. The method to be proposed is a nonlinear control strategy which is capable of stabilizing the system under various system operating conditions.

The outline of the paper is as follows. Section 2 describes the models and assumptions made in this paper. Section 3 describes the central idea of linearizing feedback and proposes a nonlinear feedback control law. In Section 4 an analysis is performed of the remaining linear system which has been achieved when the nonlinear feedback control law is applied. Section 6 shows simulation results achieved by the proposed control law. A discussion of how to use the input–output exact linearization in large power systems is given in Section 7. Finally, Section 8 highlights the key conclusions of the paper.

2. Model description

The used HVDC model and power system model are described below.

2.1. HVDC model

The HVDC links considered in this paper are of conventional type which means that the active power through the link can be controlled and that reactive power is consumed. A simplified model is used for the HVDC link with ideal control capabilities and the power factors are assumed to be equal at both inverter and rectifier side. The system is also considered to be lossless, but losses in the transmission lines could easily be included in the equations. If the losses are included a governor is needed to keep the power balance. The currents injected by the HVDC links are considered with positive sign in node 2 and 3, and negative signs in node 1 and 4 according to Fig. 2. The injected current of the HVDC link is given by:

$$\bar{I}_{rec} = \frac{-P_{rec} + jQ_{rec}}{\bar{U}^*_{rec}} \tag{1}$$

$$\bar{I}_{inv} = \frac{-P_{inv} + jQ_{inv}}{\bar{U}^*_{inv}} \tag{2}$$

where

$\bar{I}_{rec}$ and $\bar{I}_{inv}$ are the HVDC current at the rectifier and inverter side, respectively,
$P_{rec} = -P_{inv} = P_{DC}$ is the active power component of the HVDC link,
$Q_{rec} = Q_{inv} = Q_{DC}$ is the reactive power component of the HVDC link,

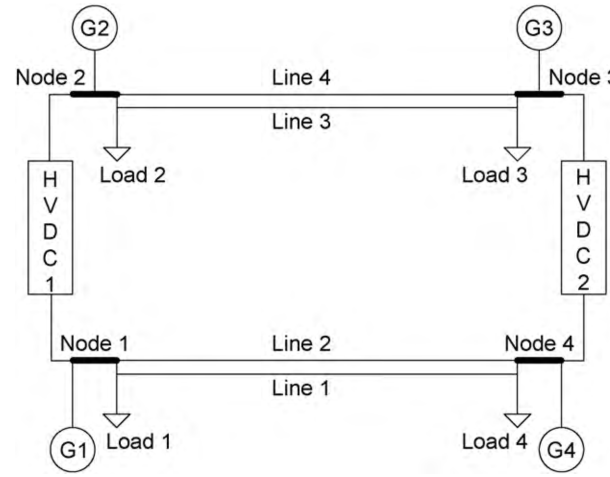

Fig. 2. Power system consisting of four synchronous machines and two HVDC links.

$\bar{U}^*_{rec}$ and $\bar{U}^*_{inv}$ are the complex conjugate of the AC rectifier and inverter bus voltage, respectively.

2.2. System model

The loads are assumed to be constant impedances and the generators are modeled by the classical model. The reduced network model (internal node representation) is used to eliminate the algebraic equations [12,13]. It is assumed that the HVDC can control the injected current since the power through the HVDC is controllable. The current produced by generator k is given by:

$$\bar{I}_{gk} = \frac{\bar{E}'_{qk} - \bar{U}_k}{jx'_{dk}}, \quad \forall k = 1, \ldots, n \tag{3}$$

where

$\bar{E}'_{qk}$ and $\bar{U}_k$ are the voltage at the internal and external buses k,
x'_{dk} is the transient reactance of generator k,
$\bar{I}_{gk}$ is the current injected by generator k,
n is the number of generators.

Based on Kirchhoff's current law, the following equation is then obtained:

$$0 = \sum_{l=1}^{n} \bar{Y}_{kl}\bar{U}_l - \bar{I}_{gk} - \sum_{j=1}^{m} \bar{I}_{hvdck_j}, \quad \forall k = 1, \ldots, n. \tag{4}$$

where

$\bar{Y}_{kl}$ is the system admittance matrix at position k, l,
$\bar{I}_{hvdck_j}$ is the injected current at bus k of HVDC link j,
m is the number of HVDC links.

In compact form:

$$\begin{pmatrix} I_G \\ I_{HVDC} \end{pmatrix} = \begin{pmatrix} Y_A & Y_B \\ Y_C & Y_D \end{pmatrix} \begin{pmatrix} E \\ U \end{pmatrix}. \tag{5}$$

By solving for U, the following is obtained:

$$\begin{aligned} I_G &= (Y_A - Y_B Y_D^{-1} Y_C)E + Y_B Y_D^{-1} I_{HVDC} \\ &= Y_{RNM}E + Y_{HVDC}I_{HVDC} \\ &= (G + jB)E + Y_{HVDC}I_{HVDC}. \end{aligned} \tag{6}$$