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Application of the normal forms to analyze the interactions among the multi-control channels of UPFC

Z.Y. Zou[a], Q.Y. Jiang[a,*], Y.J. Cao[a], H.F. Wang[b]

[a]College of Electrical Engineering and National Laboratory of Industrial Control Technology, Zhejiang University, Hangzhou, Zhejiang 310027, China
[b]Department of Electrical and Electronics Engineering, University of Bath, BA2, 7AY, UK

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Abstract

One of the most important features of the unified power flow controller (UPFC) is its multiple control functions, which are implemented by multiple controllers. However, recent simulation studies have demonstrated the existence of the dynamic interactions among different controller channels of UPFC, i.e. power flow controller, AC voltage controller and DC voltage controller. This paper is concerned with the application of the normal forms to analyze the interactions among the multi-controller channels of UPFC in power systems. Moreover, a non-linear interaction index is developed to investigate the interactions among these UPFC controllers. The employed approach has been applied to two test systems: a single machine infinite bus power system (SMIB) and the New England test power system (NETPS). The simulation results validate the proposed approach.

Keywords: UPFC; Interaction; Normal forms; Non-linear interaction index

1. Introduction

The unified power flow controller (UPFC) was proposed to achieve the flexible AC transmission systems (FACTS) for several years. One of its important features is multiple control function, such as power flow control, AC voltage support and DC voltage control. If each UPFC control function is performed by a controller, there could be more than three controllers installed in the UPFC. Commonly, these controllers are designed separately in a sequence, i.e. the multiple functional UPFC is treated as a single-input single-output (SISO) system and the dynamic interactions among the various control channels or pairs are not considered. The phenomenon of interactions among different UPFC controllers was found [1] and development of the analytical tools for study and identification of interactions among different UPFC controllers has been under active investigations.

In recent years, normal forms theory has received considerable interest as a mean of dynamic analysis of power system non-linear behavior. With this technique, it is possible to obtain the simplest form of a set of non-linear differential equations and hence, to identify and study the nature of system oscillations using conventional linear analysis methodologies. Foremost, the normal forms theory has been used to determine the interacting modes of oscillation as well as to identify the nature and characteristics of the inter-area mode phenomenon. In Refs. [2–4], the significance of second-order contributions to the normal forms was investigated. The authors used normal forms theory to detect the onset of the inter-area mode phenomenon using several analytical indices. Recently, investigations suggest that non-linear modal interaction may significantly influence control system performance, namely the excitation system of generators [5–7]. Moreover, special effort is being devoted to employ normal form theory to investigate the non-linear interactions arising from the application of Static Var Compensators [8].

In this paper, an analytical approach based on normal forms theory is proposed for the study of non-linear interactions among the multi-control channel of UPFC installed in power systems. A non-linear interaction index is employed to identify and quantify the interactions of these UPFC controllers. According to this index, we can obtain a better understanding of the complex dynamic phenomenon among multi-controller channels of UPFC. The proposed method is general and easy to be extended to include other FACTS devices. A single machine infinite bus power system (SMIB) and the New England Test

* Corresponding author. Tel./fax: +86 571 87952814.
E-mail address: jqy@zju.edu.cn (Q.Y. Jiang).

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Power System (NETPS) are employed to illustrate the proposed methodology. Detailed non-linear time-domain simulations are finally conducted to validate the analysis.

2. Mathematical model of power system with UPFC

The power system consists of the dynamic models of synchronous machines and UPFC interacting through the quasi-stationary network representation. Fig. 1 shows a single-phase schematic diagram of the adopted system model with a UPFC.

2.1. Generator dynamic equations

Each synchronous generator is represented by the two-axis model and a static excitation system. The differential equations describing the dynamic behavior of the synchronous generator and the excitation system are given as follows.

Rotor swing equations:

$$\begin{aligned}\dot{\delta}_k &= \omega_0(\omega_k - 1) = f_{1_k}\\ \dot{\omega}_k &= \frac{1}{2H_k}(P_{m_k} - (E'_{d_k}I_{d_k} + E'_{q_k}I_{q_k}) - D_k(\omega_k - 1)) = f_{2_k},\end{aligned} \tag{1}$$

Internal voltage equations:

$$\begin{aligned}\dot{E}'_{q_k} &= \frac{1}{T'_{d0_k}}(E_{fd_k} - (x_{d_k} - x'_{d_k})I_{d_k} - E'_{q_k}) = f_{3_k}\\ \dot{E}'_{d_k} &= \frac{1}{T'_{q0_k}}(-E'_{d_k} + (x_{q_k} - x'_{q_k})I_{q_k}) = f_{4_k},\end{aligned} \tag{2}$$

Static excitation system:

$$\begin{aligned}\dot{E}_{fd_k} &= -\frac{1}{T_A}(E_{fd_k} + K_A(V_{tref_k} - V_t)) = f_{5_k}\\ V_t &= \sqrt{v_{dt}^2 + v_{qt}^2} = \sqrt{(E'_{d_k} + x'_q I_{q_k})^2 + (E'_{q_k} - x'_d I_{d_k})^2}.\end{aligned} \tag{3}$$

The state variables and parameter in the above equations have the usually physical meaning in Ref. [7].

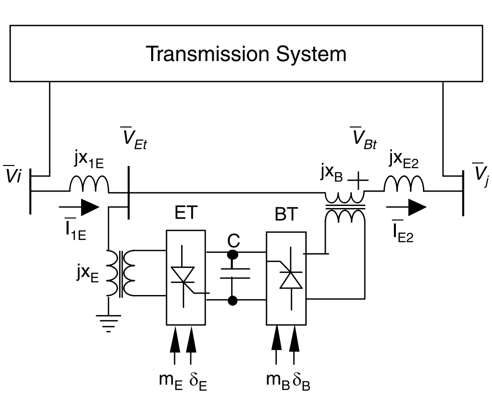

Fig. 1. An n-machine power system with UPFC installed.

2.2. Representation of UPFC

The UPFC is composed of an excitation transformer (ET), a boosting transformer (BT), two three-phase GTO-based voltage source converters (VSCs), and a DC link capacitor. In the Fig. 1, m_E, m_B and δ_E, δ_B are the amplitude modulation ratios and phase angles of the control signal of each VSC, respectively, which are the input control signals to the UPFC. If the resistance and transients of the transformers of the UPFC are neglected, the dynamic model of the UPFC can be described as follows [9]

$$\begin{aligned}\dot{V}_{DC} &= -\frac{3m_E}{4C_{DC}}[\cos\delta_E \ \sin\delta_E]\begin{bmatrix} i_{Ed}\\ i_{Eq}\end{bmatrix} - \frac{3m_B}{4C_{DC}}\\ &\quad\times[\cos\delta_B \ \sin\delta_B]\begin{bmatrix} i_{Bd}\\ i_{Bq}\end{bmatrix} = f_{6_k}.\end{aligned} \tag{4}$$

2.3. Network representation

To illustrate the nature of the proposed model, consider a general n-generator system with a UPFC. Without loss of generality, assume that a UPFC is to be installed in an n-machine power system between node i and j as shown by Fig. 1.

Before the UPFC is installed into the power system, the nodal balance equation is expressed in network D–Q coordinates as

$$\begin{bmatrix} 0\\ 0\\ \bar{\mathbf{I}}_{\mathbf{g}}\end{bmatrix} = \begin{bmatrix} \bar{Y}_{11} & \bar{Y}_{12} & \bar{\mathbf{Y}}_{13}\\ \bar{Y}_{21} & \bar{Y}_{22} & \bar{\mathbf{Y}}_{23}\\ \bar{\mathbf{Y}}_{31} & \bar{\mathbf{Y}}_{32} & \bar{\mathbf{Y}}_{33}\end{bmatrix}\begin{bmatrix} \bar{V}_i\\ \bar{V}_j\\ \bar{\mathbf{V}}_{\mathbf{g}}\end{bmatrix} = \bar{\mathbf{Y}}_t\begin{bmatrix} \bar{V}_1\\ \bar{V}_2\\ \bar{\mathbf{V}}_{\mathbf{g}}\end{bmatrix}, \tag{5}$$

where

$$\bar{\mathbf{I}}_g = \begin{bmatrix} \bar{I}_{g1} & \bar{I}_{g2} & \cdots & \bar{I}_{gn}\end{bmatrix}^T \qquad \bar{\mathbf{V}}_g = \begin{bmatrix} \bar{V}_{g1} & \bar{V}_{g2} & \cdots & \bar{V}_{gn}\end{bmatrix}^T.$$

From Ref. [1], we can obtain

$$\bar{\mathbf{I}}_{\mathbf{g}} = \bar{C}\bar{\mathbf{V}}_{\mathbf{g}} + \bar{\mathbf{F}}_{\mathbf{E}}\bar{V}_E + \bar{\mathbf{F}}_{\mathbf{B}}\bar{V}_B \tag{6}$$

where

$$\bar{\mathbf{C}} = \bar{\mathbf{Y}}_{33} - \begin{bmatrix}\bar{\mathbf{Y}}_{31} & \bar{\mathbf{Y}}_{32}\end{bmatrix}\bar{\mathbf{Y}}_{\mathbf{t}}^{\prime -1}\begin{bmatrix}\bar{\mathbf{Y}}_{13}\\ \bar{\mathbf{Y}}_{23}\end{bmatrix}$$

$$\bar{\mathbf{F}}_{\mathbf{E}} = -\begin{bmatrix}\bar{\mathbf{Y}}_{31} & \bar{\mathbf{Y}}_{32}\end{bmatrix}\bar{Y}_{\mathbf{t}}^{\prime -1}\begin{bmatrix} j(x_{E2} + x_B)/x_\Sigma\\ jx_E/x_\Sigma\end{bmatrix}$$

$$\bar{\mathbf{F}}_{\mathbf{B}} = -\begin{bmatrix}\bar{\mathbf{Y}}_{31} & \bar{\mathbf{Y}}_{32}\end{bmatrix}\mathbf{Y}_{\mathbf{t}}^{\prime -1}\begin{bmatrix} jx_E/x_\Sigma\\ -j(x_{1E} + x_E)/x_\Sigma\end{bmatrix}$$

$$\bar{\mathbf{Y}}'_{\mathbf{t}} = \begin{bmatrix} \bar{Y}'_{11} - j(x_{E2} + x_B)/x_\Sigma & jx_E/x_\Sigma\\ jx_E/x_\Sigma & \bar{Y}'_{22} - j(x_{1E} + x_E)/x_\Sigma\end{bmatrix}$$