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Power system stability enhancement by WAMS-based supplementary control of multi-terminal HVDC networks

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A B S T R A C T

This paper deals with supplementary control of a MTDC network designed for the stability enhancement of a AC power system. The proposed control is a WAMS-based control modulating the real and reactive power at the terminals of the DC network. Relevant control formulas have been derived for a linear multi-machine system model with the application of the direct Lyapunov method. Validity and robustness of the proposed control has been verified by computer simulation for a multi-machine test system using a nonlinear model and detailed modeling of power system components. The proposed control is robust and insensitive to changes in the network configuration and loading conditions in the AC power system. In the case, when more of the MTDC networks and/or the HVDC links are used in one interconnected power system the proposed stabilizing control produces additive damping i.e. each controlled network element contributes to the positive damping. Some practical aspects have also been discussed. The proposed WAMS-based stabilizing control of the MTDC network is innovative by both its main concept and the derivation of control formulas using the direct Lyapunov method.

1. Introduction

The HVDC transmission links have various applications within AC power systems. For example, submarine (underwater) cable transmission, integration of large wind farms, formation of a framework for large highly controllable interconnected AC systems etc. (Arrillaga, Liu, & Watson, 2007; Bahrman, 2006; Lin et al., 2009; Scholtz, 2008). Series and shunt FACTS devices are used in AC power systems to control power flows and voltage profiles. It is well known (Kundur, 1994; Lu, Sun, & Mei, 2001; Machowski, Bialek, & Bumby, 2009; Rasolomampionona & Sohail, 2011; Robak, 2009; Robak, Rasolomampionona, & Januszewski, 2007; Vijay, 2004) that owing to their high speed regulation HVDC transmission links and/or FACTS devices can be used to enhance transient stability of AC power systems. For that purpose, the controllers of the HVDC links and/or FACTS devices can be equipped with supplementary control loops referred to as power system stabilizers (PSS). Most of the hitherto used PSS's apply locally measurable quantities as input signals. The disadvantage of PSS's that are based on locally measurable signals is that while damping power swings in one of the subsystems they can excite and/or amplify power swings in the remaining subsystems (Rasolomampionona, 2009). This disadvantage can be eliminated by the application of a state-variable control (Machowski et al., 2009; Mao, Zhang, Guan, Wu, & Zhang, 2008; Nogal & Machowski, 2009, 2010). In the case of such control, the input data must be supplied by a WAMS-based on a fast flexible communication platform. It is expected that control systems of that kind, referred to as WAMPAC, will be implemented to power systems in a near future. For the time being they are under investigations.

In most of the publications that deal with PSS's operating on locally measurable signals as input signals or WAMPAC's, parameters of the control devices are determined with the application of the objective function optimization based on a power system simulation (Lei & Lerch, 2001; Mao et al., 2008; Xiao-ming, Zhang, Guan, & Xiao-chen, 2006). In some other publications (Machowski et al., 2009; Machowski & Nelles, 1993, 1995; Machowski, Smolarczyk, & Bialek, 2001; Nogal & Machowski, 2009, 2010; Noroozian & Ghandhari, 2001) it is the direct Lyapunov method that is used to determine the control device parameters.

Until now, multi-terminal HVDC networks (MTDC) have not been used to enhance stability of AC power systems. A popular opinion claimed that the MTDC cannot efficiently damp power swings in two AC power systems connected by a MTDC network,

Abbreviations: DC, direct current; AC, alternating current; HVDC, high voltage direct current (transmission lines); MTDC, multi-terminal direct current (transmission lines); PSS, power system stabilizers; WAMS, wide-area measurement system; PMU, phasor measurement unit; FACTS, flexible AC transmission network; WAMPAC, wide-area measurement protection and control system

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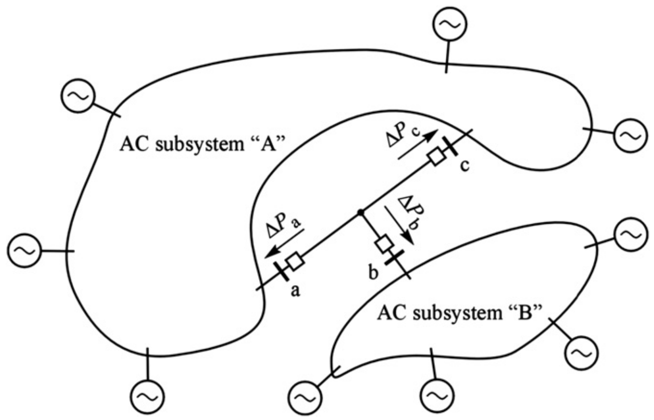

Fig. 1. Two subsystems connected by a MTDC network.

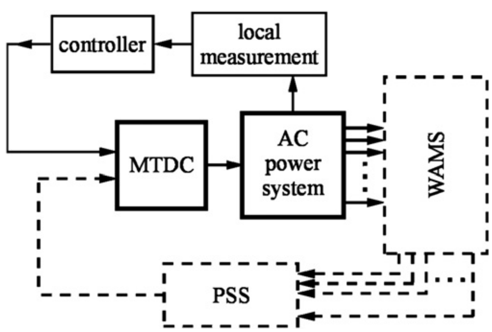

Fig. 2. Schematic illustration of a local control and a state-variable stabilizing control.

as shown in Fig. 1. When the MTDC network controllers are equipped with PSS's based on locally measurable signals the dynamic response of the whole system shows good damping over one area and poor damping over another area. For example, a PSS in the substation {a} can damp power swings occurring over the left-side area of the subsystem "A" and amplify power swings occurring over the right-side area of that subsystem as well as undesirably excite power swings in the subsystem "B". A desired efficient stabilizing control should guarantee uniform damping both over the whole subsystem "A" and over the whole subsystem "B".

This paper deals with a question whether it is generally possible to develop supplementary stabilizing control of a MTDC network that can enhance the transient stability of the whole interconnected AC power system and can damp power swings in the subsystem where the short-circuit occurred with only slight influence on the other subsystem. The answer to that question is positive, which can be mathematically proved with the second Lyapunov method. A WAMS-based stabilizing control system is proposed. Its operation during the transient state is illustrated by simulation results. Some practical aspects are discussed. The proposed WAMS-based stabilizing control of a MTDC network is innovative by both its main concept and the derivation of control formulas using the direct Lyapunov method.

2. WAMS-based supplementary control

A structure of the proposed control system is shown in Fig. 2. The main control loop (the upper part of Fig. 2) is based on locally measurable signals and is meant to control power flow at normal (undisturbed) operation conditions of the AC power system. The supplementary stabilizing loop (the lower part of Fig. 2) is a WAMS-based control meant to damp power swings at transient (disturbed) state caused by short-circuits appearing in the AC network.

For the structure shown in Fig. 2 it is assumed that the implementation of the proposed WAMS-based supplementary control loops to the existing MTDC networks and/or HVDC links will not cause any changes in the main control loops based on locally measurable signals.

This paper deals with the following questions: (a) derivation of relevant control formulas for the supplementary control, (b) simulation tests for a multi-machine test system with detailed models of power system components, (c) checking whether the proposed supplementary control is sensitive to changes in the network configuration and loading conditions in the AC network, and (d) discussion of some practical aspects.

3. Mathematical model

In order to answer the question formulated in the Section 1, a linear model $\dot{\boldsymbol{x}} = \boldsymbol{Ax} + \boldsymbol{Bu}$ of the power system that comprises a MTDC network has been elaborated. Specifically, the considerations focus on the case of an interconnected power system as shown in Fig. 1, where there is no AC tie lines between the subsystems "A" and "B". The assumption is important for the structure of matrices that describe the subsystems.

It is assumed that to the nodes {a,b,c} a MTDC network of a star-shaped structure is connected. According to Kirchhoff's law, for a MTDC network $P_a + P_b + P_c = 0$ has to occur. Further considerations concern two cases:

Case 1. Real power is modulated at the terminals {a,b} i.e. the increments ΔP_a, ΔP_b are controlled variables and ΔP_c results from the Kirchhoff's law:

$$\Delta P_c = -(\Delta P_a + \Delta P_b) \tag{1a}$$

Case 2. Real power is modulated at the terminals {a,c} i.e. the increments ΔP_a, ΔP_c are the controlled variables and ΔP_b results from the Kirchhoff's law:

$$\Delta P_b = -(\Delta P_a + \Delta P_c) \tag{1b}$$

For the subsystems shown in Fig. 1 increment models are elaborated and they can be described by the following equations:

$$\begin{bmatrix} \Delta \boldsymbol{P} \\ \Delta \boldsymbol{Q} \end{bmatrix} = \begin{bmatrix} \boldsymbol{H} & \boldsymbol{K} \\ \boldsymbol{N} & \boldsymbol{W} \end{bmatrix} \begin{bmatrix} \Delta \boldsymbol{\delta} \\ \Delta \boldsymbol{V} \end{bmatrix} \tag{2}$$

where $\Delta \boldsymbol{P}$ and $\Delta \boldsymbol{Q}$ are the column matrices of the real and reactive power increments at all the system nodes, $\Delta \boldsymbol{V}$ and $\Delta \boldsymbol{\delta}$ are column matrices of voltage magnitude and angle increments, $\boldsymbol{H}$, $\boldsymbol{K}$, $\boldsymbol{N}$, $\boldsymbol{W}$ are the Jacobian submatrices (Machowski et al., 2009).

In the discussed models generators are modeled by means of voltage sources with transient emf behind transient reactance of a generator. For fictitious generator nodes it is assumed that magnitudes of transient emf's are constant, which means that for those nodes $\Delta \boldsymbol{V} = \Delta \boldsymbol{E} = \boldsymbol{0}$. It also means that the lower part of Eq. (2) makes sense only for the nodes {a,b,c}, whereto the MTDC network is connected. After having considered changes in voltages and reactive power, on the basis of Eq. (2) the following can be written:

$$\begin{bmatrix} \Delta \boldsymbol{P}_A \\ \Delta P_a \\ \Delta P_c \\ \Delta Q_a \\ \Delta Q_c \end{bmatrix} \cong \begin{bmatrix} \boldsymbol{H}_{AA} & \boldsymbol{H}_{Aa} & \boldsymbol{H}_{Ac} & \boldsymbol{K}_{Aa} & \boldsymbol{K}_{Ab} \\ \boldsymbol{H}_{aA} & H_{aa} & H_{ac} & K_{aa} & K_{ac} \\ \boldsymbol{H}_{cA} & H_{ca} & H_{cc} & K_{ca} & K_{cc} \\ \boldsymbol{N}_{aA} & N_{aa} & N_{ac} & W_{aa} & W_{ac} \\ \boldsymbol{N}_{cA} & N_{ca} & N_{cc} & W_{ca} & W_{cc} \end{bmatrix} \begin{bmatrix} \Delta \boldsymbol{\delta}'_A \\ \Delta \delta_a \\ \Delta \delta_c \\ \Delta V_a \\ \Delta V_c \end{bmatrix} \tag{3a}$$