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Power system damping from energy function analysis implemented by voltage-source-converter stations

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Abstract

Because weakly damped system oscillations can endanger the secure operation of power systems, this paper is a study on how damping can be increased. As the power system is nonlinear, an energy function approach, patterned after the direct method of Lyapunov function, is used in the analysis. The analysis develops an energy function *W* and shows that a real power term (proportional to local frequency) and/or a reactive power term (proportional to the line voltage differentiated with respect to time) increase the rate of diminution of the energy function *W*. This implies effective damping of power swings by such power signals and is verified by simulations of a multi-machine system model. The damping signals are introduced by voltage-source-converter (VSC) stations.

Keywords: VSC; Real and reactive power modulations; Energy function

1. Introduction

Large interconnected power systems often suffer from weakly damped power swings. Such lack of damping occurs particularly in areas connected by weak tie-lines, systems with longitudinal structures and generators connected by long lines to the rest of the system. To enhance the damping of power system oscillations, HVDC and FACTS controllers have been used [1–4]. This paper focuses on VSC stations (the inverters/rectifiers of VSC–HVDC and of distributed generation/renewable energy sources) [5–9], because on top of the steady-state real and reactive power deliveries, they allow real power modulation [7], reactive power modulation [8] and a combination of real and reactive power modulations [9] to be applied for dynamic performance enhancement.

So far, many studies have been based on small signal analysis of a simple model, which has certain limitations. Firstly, the linearized model is valid only in the vicinity of the chosen operating point. Then, power systems are large and complex. Therefore one needs a methodology that can deal with large nonlinear systems. To achieve this goal, this paper adopts the energy function method, patterned after the direct method of Lyapunov. Traditionally, Lyapunov theory deals with a dynamical system without inputs. Recently, it is also applied in feedback design by making the Lyapunov derivative negative when choosing the control [10]. Such ideas have been made precise with the introduction of the concept of a Control Lyapunov Functions for systems with control input, which has been successfully applied to FACTS controllers [11,12,16]. Developing on [11,12,16], this paper shows that real power term proportional to frequency and/or a reactive power term proportional to time rate of voltage differentiation, increase the rate of diminution of the energy function. Implicitly, the damping is increased. The theoretical conclusions are verified by simulations in a multi-area power system using VSC stations to implement the damping strategies.

The outline of the paper is as follows: In Section 2, a general power system is modeled for energy function stability analysis. The analysis identifies the type of real and reactive power modulations in the network buses which increase the rate of diminution of the energy function and therefore increase power system damping. Further, it describes how the aforesaid modulations are carried out by VSC stations. Simulations and the analysis of results are presented in Section 3. Conclusions are drawn in Section 4.

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2. System model and the control strategy

In the interest of arriving at the contributions of this paper quickly, the detailed derivations have been moved to Appendix A. Appendix A contains the standard techniques used by the energy function method but are nevertheless necessary for this paper to be self sufficient. This section is a sketch of how the present status of the research is reached and against this, the theoretical contribution of this paper can be appreciated. Following in the footsteps of [1], the equations are referenced with respect to the center of inertia (COI).

2.1. Generators

In the power system in Fig. 1, there are n generation sources, each represented by $V_i \angle \phi_i$ ($i = 1\ldots n$). The symbols V_i ($i = 1\ldots n$) represent constant emfs behind transient reactances x_i' and ϕ_i are the mechanical rotor angle.

The dynamic equation of motion of each generator ($i = 1\ldots n$) is [13]:

$$\dot{\phi}_i = \omega_i \tag{1}$$

$$M_i \dot{\omega}_i = P_{mi} - P_{ei} - D_i \omega_i - \frac{M_i}{M_T} P_{\mathrm{COI}} \tag{2}$$

where M_i represents moment of inertia, the turbine power is P_{mi}, the generated power is $P_{ei} = B_{ij} V_i V_j \sin(\phi_I - \phi_j)$ the subscript $j = i + n$ being the bus to which it is connected and the power associated with the center of inertia (COI) is $P_{\mathrm{COI}} = \sum_{i=1}^{n} (P_{mi} - P_{ei})$.

2.2. Network equations

There are $N = n + m$ buses, numbered $i = n + 1,\ n + 2, \ldots 2n,\ 2n + 1, \ldots 2n + m$, each bus having voltage $V_i \angle \phi_i$. At each bus i, the load $P_i(\omega_i) + jQ_i(V_i)$ is, in general, functions of frequency ω_i and voltage V_i. Usually, $P_i(\omega_i)$ are assumed to be constant. Emanating from the ith bus are connections to the other buses and the generators which take a total complex power $P_{Fi} + jQ_{Fi}$. It is assumed that the line resistances can be neglected.

$$P_{Fi} = \sum_{j=1}^{2n+m} B_{ij} V_i V_j \sin \phi_{ij} \tag{3a}$$

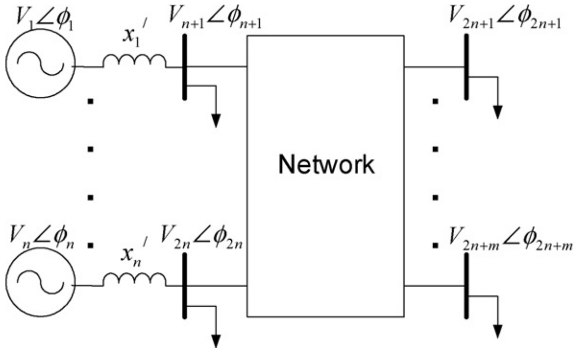

Fig. 1. Model of power system.

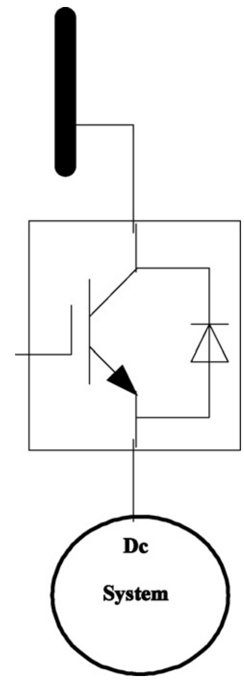

Fig. 2. Simplified model of VSC station.

$$Q_{Fi} = -\sum_{j=1}^{2n+m} B_{ij} V_i V_j \cos \phi_{ij} \tag{3b}$$

where $\phi_{ij} = \phi_I - \phi_j$.

Complex power balance at the ith bus requires;

$$\{P_i(\omega_i) + jQ_i(V_i)\} + (P_{Fi} + jQ_{Fi})\} = 0.0 \tag{4}$$

2.3. Energy function method

Following [13], the energy function W is defined as:

$$W = W_1 + W_2 \tag{5}$$

where W_1 is a positive definite function based on the kinetic energy of the generators:

$$W_1 = \frac{1}{2} \sum_{i=1}^{n} M_i \omega_i^2 \tag{6}$$

and W_2, which addresses the complex powers at the $n + m$ buses, consists of 6 components, and as Appendix A elaborates.

2.3.1. Status of energy function research

The end-point of existing research is the proof of negative definiteness in dW/dt. It is pertinent to draw attention to the fact that in the chain rule differentiation, when W_2 is differentiated with respect to ϕ_i, it has a dϕ_i/dt term and likewise when differentiated with respect to V_i, it has dV_i/dt. Although provision has been made that for the load $P_i(\omega_i) + jQ_i(V_i)$ at each bus i, to be functions of frequency ω_i and voltage V_i, in all previous work