Electrical Power and Energy Systems 83 (2016) 541–546

Contents lists available at ScienceDirect

Electrical Power and Energy Systems

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

Short Communication

An HVDC line parameters estimation method without optimization [☆]

Jocelyn Sabatier [*], Toni Youssef, Mathieu Pellet

IMS Laboratory, UMR 5218 CNRS, Bordeaux University, 351 cours de la Libération, 33405 Talence Cedex, France

ARTICLE INFO

Article history:
Received 28 May 2015
Received in revised form 30 March 2016
Accepted 4 April 2016
Available online 2 May 2016

Keywords:
HVDC line
Line parameters estimation
Telegraphist's equation
Transmission line modelling
Impedance based method

ABSTRACT

This paper proposes a method to estimate HVDC line parameters. After a reminder on the transfer functions that characterize the dynamic behavior of a DC line, link between these transfer functions resonance frequencies and the line parameters is established. This link is then used to estimate the line parameters, the resonance frequencies being determined using the power spectral density of voltage signals at the input and output of the line. A numerical example highlights the efficiency of the proposed method which is finally reduced to a very simple algorithm. This algorithm does not involve optimization, thereby reducing the calculation time and the resources required for its implementation. This new estimation method can be used for fault detection and location.

Introduction

High-voltage direct current (HVDC) technology has become a credible alternative for transmitting power over long distances through submarine or underground cable crossings [1]. Indeed, the improvement of power electronics devices has opened new perspectives for transmission of electrical power through HVDC links, which offer extra means to control power flows [2] in interconnected power systems or between non synchronous areas.

HVDC links offers numerous environmental benefits [15], including "invisible" power lines, neutral electromagnetic fields and compact converter stations. The power HVDC transmission line is one of the major components of an HVDC electric power system. Its major function is to transport electric energy, with minimal losses, from the power sources to the load centers, usually separated by long distances. Losses are only 3% per 1000 km at a standard cost (losses can be further reduced to 0.3% for 1000 km, but at a higher cost). Possible applications include:

- connecting wind farms to power grids,
- underground power links,
- providing shore power supplies to islands and offshore oil & gas platforms,
- connecting asynchronous grids.

To ensure proper operation of an HVDC grid, a control system must be implement with main objectives [3]:

- control basic system quantities such as DC line current, DC voltage, and transmitted power accurately and with sufficient speed of response [28],
- control higher-level quantities such as frequency in isolated mode or provide power oscillation damping to help stabilize the AC network [4,5],
- ensure stable operation with reliable commutation in the presence of system disturbances,
- ensure proper operation with fast and stable recoveries during AC system faults and disturbances [6],
- diagnose of the line integrity [7,8] and faults location [25–27].

All these applications rely on correct underlying model information of the HVDC line that connects the grid node. To get this required information, system state estimation [21,22] are often used in power systems and parameter identification has often been studied in the context of state estimation literature as state estimators. Most of the other HVDC line parameters estimation methods found in literature are purely numerical or signal based methods that do not take into account the physical particularities of long transmission lines. For HVDC systems containing n-HVDC line a method that involves data processing algorithms that use line flow measurements and bus injection measurements is proposed in [23]. Another method that has undergone significant developments is the Numerical algorithm for Subspace State Space System IDentification (N4SID) [9]. It extracts dynamic parameters from phasor measurements. The collected data represent wide area

---

[☆] This research is supported by the French national project WINPOWER ANR-10-SEGI-016.

[*] Corresponding author.
E-mail address: jocelyn.sabatier@u-bordeaux.fr (J. Sabatier).

http://dx.doi.org/10.1016/j.ijepes.2016.04.001
0142-0615/

response to several kinds of probing signals, including low-level pseudo-random noise (LLPRN) and single-mode square wave (SMSW). The identified model is validated using a cross validation method. In [10], the open system model of a power system is estimated using the N4SID algorithm. In many cases, the current set-point change through the HVDC links is the set of input signals and the generators speeds are the set of outputs. Refinement of this method is presented in [24,11]. In [11] it is proposed to obtain the transfer function linking the rectifier firing angle (as input) to the dc current response. The identification is done for several operating points. The system being non-linear the operating point variations lead to model parametric variation. This method requires having an operational control for the HVDC system and may be interesting for the diagnosis of the modeled part. [19] deals with the modeling of Voltage Source Converter High Voltage Direct Current (VSC-HVDC) systems for power system analysis. In this paper and as a main contribution, the proposed models are valid for any topology of the DC grid. Therefore, they can be used to simulate multi-terminal VSC-HVDC systems. To obtain these models, generalized Multi-Terminal Direct Current (MTDC) equations have been introduced. The generalized equations of the DC circuit are obviously very ill-suited to software implementation. For diagnostic purpose, estimation of thermal breakdown voltage is addressed in [12]. In [16], the purpose is to obtain input/output dynamic model of the open loop system, where the d-axis current is the input and the dc-link voltage is the output. In the identification method, black box model is used, but the algorithm is not cited. The equivalent π-model is also often used to develop optimisation based estimation algorithm as in [13,17]. With this model, a double measurement method is introduced in [14]. The main inconvenient of these methods is loss of model physical meaning.

The goal of this paper is to propose a different approach that requires synchronized voltage and current measurements from each side of the transmission line as in [18] but that does not require optimisation algorithm. After a reminder on the transfer functions that characterize the dynamic behavior of a DC line, a relationship between these transfer functions resonance frequencies and the line parameters is established. This relationship is then used to estimate the line parameters, the resonance frequencies being determined using the power spectral density of voltage signals at the input and output of the line. A numerical example highlights the efficiency of the proposed method that thus can be a new useful tool for line fault diagnosis and location [7,8,25–27].

HVDC line dynamical model and resonance frequencies

Analytical model of HVDC lines

A HVDC transmission line can be characterized by the following parameters [12]:

- line length: L_{line},
- line series resistance r and inductance l,
- line shunt capacitance c and conductance g.

The series resistance relies basically on the physical composition of the conductor at a given temperature. The series inductance and shunt capacitance are produced by magnetic and electric fields around the conductors, and depend on their geometrical arrangement. The shunt conductance is due to leakage currents flowing across insulators and air. These parameters values determine the power-carrying capacity of the transmission line and the voltage drop across it at full load.

As shown by Fig. 1, the HVDC line dynamical behavior can be modeled by a quadrupole $F(s)$, that links:

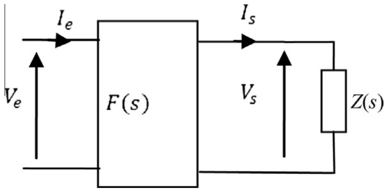

Fig. 1. HVDC line model and connected load.

- V_e: line input voltage,
- I_e: line input current,
- V_s: line output voltage,
- I_s: line output current.

The HVDC line is connected to a load of impedance $Z(s)$ constituted of a resistance R_{ch} in parallel with a capacitor C_{ch}, and thus:

$$Z(s) = \frac{R_{ch}}{1 + R_{ch}C_{ch}s} \tag{1}$$

Solution of the Telegraphist's equation permits to show that the currents and voltages at the HVDC line terminals are linked by the relation

$$\begin{bmatrix} V_s(s) \\ I_s(s) \end{bmatrix} = F(s) \begin{bmatrix} V_e(s) \\ I_e(s) \end{bmatrix} \tag{2}$$

with

$$F(s) = \begin{bmatrix} F_{11}(s) & F_{12}(s) \\ F_{21}(s) & F_{22}(s) \end{bmatrix} = \begin{bmatrix} \cosh(\gamma(s)L_{line}) & -Z_c(s)\sinh(\gamma(s)L_{line}) \\ -\frac{\sinh(\gamma(s)L_{line})}{Z_c(s)} & \cosh(\gamma(s)L_{line}) \end{bmatrix} \tag{3}$$

and

$$\begin{aligned} \gamma(s) &= \sqrt{(g+cs)(r+ls)} \\ Z_c(s) &= \sqrt{(r+ls)/(g+cs)} \end{aligned} \tag{4}$$

If a load of impedance $Z(s)$ is connected to the line, then the following transfer functions can be computed (among others):

$$\begin{aligned} \frac{V_s(s)}{V_e(s)} &= \frac{\lambda(s)}{\lambda(s)\cosh(\gamma(s)L_{line}) + \sinh(\gamma(s)L_{line})} \\ \frac{I_s(s)}{V_e(s)} &= \frac{1}{Z_c(s)}\,\frac{1}{\lambda(s)\cosh(\gamma(s)L_{line}) + \sinh(\gamma(s)L_{line})} \end{aligned} \tag{5}$$

with

$$\lambda(s) = \frac{Z(s)}{Z_c(s)} = \frac{R_{ch}}{1 + R_{ch}C_{ch}s}\sqrt{\frac{g+cs}{r+ls}} \tag{6}$$

The gain of transfer functions $F_{21}(s)$ and $I_s(s)/V_e(s)$ are plotted in Fig. 2, using the following realistic numerical values for a HVDC line proposed in [20]:

$$L_{line} = 300\ (\mathrm{km}), \quad r = 3\mathrm{e}^{-2}\ (\Omega\,\mathrm{km}^{-1}),$$

$$l = 1.05\mathrm{e}^{-3}\ (\mathrm{H\,km}^{-1}), \quad c = 11\mathrm{e}^{-9}\ (\mathrm{F\,km}^{-1})$$

$$g = 6.5\mathrm{e}^{-9}\ (\Omega^{-1}\,\mathrm{km}^{-1}), \quad R_{ch} = 200\ (\Omega), \quad C_{ch} = 50\mathrm{e}^{-6}\ (\mathrm{F})$$

Fig. 2, but also Fig. 3, permit to highlight a property*: the zeros of $F_{21}(s)$ correspond to the resonance frequencies ω_k, $k \in N^*$, of transfer functions $I_s(s)/V_e(s)$ and $V_s(s)/V_e(s)$.* The first resonance ω_0 results in the load connected to the line. The separation between ω_0 and ω_k, $k \in N^*$ tie in a well-built HVDC line since the bandwidth of the line must be higher than the one of the load. This property is now used to deduce a link between the ω_k, $k \in N$.