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EPSR-5274; No. of Pages 11
ARTICLE IN PRESS
Electric Power Systems Research xxx (2017) xxx–xxx
Contents lists available at ScienceDirect
Electric Power Systems Research
journal homepage: www.elsevier.com/locate/epsr

Quasi-dynamic model of VSC-HVDC transmission systems for an operator training simulator application

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ARTICLE INFO

Article history:
Received 14 February 2017
Received in revised form 6 July 2017
Accepted 22 August 2017
Available online xxx

Keywords:
High voltage direct current
Operator training simulator
Power system operation
Quasi-dynamic modelling
Voltage source converter

ABSTRACT

This paper proposes a simplified quasi-dynamic model of two terminal voltage-source-converter (VSC)-HVDC transmission systems based on the existing full-order models for application in an operator training simulator (OTS). The simplified model is verified against the full-order model for some verification scenarios. The model stability and behaviour is assessed to check if the model meets the grid code requirements as stated in the ENTSO-E Network Code. These features include black-start capability, set point change, active power reversion, frequency contributions and reactive power-voltage regulations. The proposed linearized model is presented in state-space equations and is stabilized by state space feedback using the linear quadratic regulator (LQR) design. The model has sufficient accuracy, requires less input data compared to full-order model, is tuneable by any vendors and is easily implementable in an environment such as OTS.

1. Introduction

The German power system has seen an increased rate of growth in electricity generation from renewable energy sources (RES) in the last decade. Among them, the share of the northern offshore wind parks in electricity generation has been continuously rising from 0.9 TWh in the year 2013 to 8.7 TWh in the year 2015 [1]. According to the federal government targets, the installed power of the offshore wind parks – which are far from the load centres – would reach to 18.5 GW in the year 2035 compared to the 0.5 GW in the year 2013 [2]. Such a rise coincides with a 23% reduction in the installed power of the conventional power plants – which are mainly located at the load centres – in the same time interval. As the result, the bulk generated wind power by the offshore parks in future shall be transmitted from north down to the load centres in the south and southwest of Germany. Such prospective huge power transmission could not be predicted in former German grid planning studies which were mostly done based on load growth and load predictions [3].

A voltage-source-converter (VSC)-based high voltage direct current (HVDC) transmission system is a suitable component not only for transmitting such bulk generated power but also to enhance system stability [4] as they can provide several new operational services to the transmission system operators (TSO). Contributions to frequency stability, long-term voltage stability, etc. from normal to restoration system states are among such services [5]. The TSOs would like to know firstly, how the real-time system operation in the presence of such HVDC links might differ from the current situations without them. Secondly, they are eager to know how they can use the above mentioned services more effectively for a more reliable and secure grid operation [6].

One reasonable option is to train TSOs using operator training simulators (OTS). For the TSOs, the OTSs are in fact representations of their power system control centre (CC) tools, environments and energy management system (EMS) functions [7]. An OTS runs in real-time and is able to partly simulate the dynamics of power systems. TSOs may use OTS for performing operational actions such as line/breaker switching, re-dispatching and resynchronisation of generation units, etc. and for monitoring their grids during the training sessions [7]. On this basis, the OTS requires real-time models of VSC-HVDC links. Paper [6] proposes a full-order model of line-commutated-converter (LCC)-HVDC systems for an OTS. However, the ancillary services are not modelled and the OTS time restrictions are not taken into consideration. Papers [8] and [9] present simplified VSC-HVDC models which are mainly used for transient stability analysis. However, an integral

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http://dx.doi.org/10.1016/j.epsr.2017.08.029

Nomenclature

Variables

$\boldsymbol{A}$	State matrix in the state space model
$\boldsymbol{B}$	Input matrix in the state space model
$\boldsymbol{C}$	Output matrix in the state space model
C	Aggregate capacitances (F)
$\boldsymbol{D}$	Feedthrough or feedforward matrix in the state space model
D	Load frequency contribution factor (%)
DR	DC droop slope (MW/kV)
f	Frequency (Hz)
FDR	Frequency droop factor (%)
I	Current (kA)
$\boldsymbol{K}$	State feedback matrix in the state space model
K	Frequency droop slope (MW/Hz)
k	Controller gain (s/–)
L	Inductance (H)
M	Switching Mode
P	Active power (MW)
Q	Reactive power (MVAr)
$\mathbf{r}$	Reference vector in the state space model
R	Line resistance (Ω)
s	Laplace operator
$\underline{S}$	Complex apparent power (MVA)
T	System mechanical starting time (s)
$\mathbf{u}$	Input variable vector in the state space model
$\underline{u}$	AC voltage phasor (kV)
U	Voltage (kV)
$\mathbf{x}$	State variables vector in the state space model
X	Reactance (Ω)
$\mathbf{y}$	Output variable vector in the state space model
φ	Power factor angle (degree)

Indexes

0	Initialized value
(1)	Positive sequence
1	Rectifier
2	Inverter
c	Converter
C	Capacitor
cap.	Capacitive
d	Direct axis
dc	Direct current
eq.	Equivalent
f	Filter
fix.	Fixed value
freq.	Frequency
g	Generated
G	Generator
int.	Integrator
L	Load
M	Mechanical starting time
max	Maximum
meas.	Measured
min	Minimum
n	Nominal
P	DC power
PCC	Point of common coupling
prp.	Proportional
q	Quadratic axis
QU	Reactive power/voltage
r	Rated
ref.	Reference
set	Set point
trf.	Transformer
U	DC voltage

simplified VSC-HVDC model which works for real-time applications and is responsive to various long-term system phenomena has not been proposed yet.

In this paper, a simplified quasi-dynamic model of a two-terminal voltage-source-converter (VSC)-HVDC transmission system for application in a real-time OTS is proposed. As the VSC-HVDC system can provide more ancillary services than LCC-HVDC technology, the former is considered to be more influential in training of power system operators and is on the focus of this paper. The model is able to operate from normal to restoration system states and deliver various long-term ancillary services. The model shall be generic to cover different VSC-HVDC vendors despite limited access to the products data for the system operators.

2. Modelling requirements

2.1. OTS modelling requirements

Real-time dynamic simulation of large power systems requires high computation time. The required computation resource increases drastically when full order models of each and every single constituent system component are used in the simulator. Therefore, if it lacks sufficiently powerful hardware or an appropriate parallelisation of computation, the OTS may not guarantee a dynamic response within a specified timeframe (i.e. 100 ms) [10]. This is against the characteristics of a real-time system.

In power system CCs, TSOs receive the input data for their EMS functions via the supervisory control and data acquisition (SCADA) system. The SCADA system has a time resolution of 2–4 s [11]. Any power system incidents with time constants lower than the SCADA time resolution find sufficient time to be damped. Therefore, they are not observable in CC applications. The TSOs also require a minimum time to comprehend a phenomenon and react accordingly. This time duration is apparently bigger than the transient time constant of the system event. Hence, it is acceptable to have a trade-off between the model complexity and reasonable time resolution in CC for the TSOs [10]. Therefore, simplified quasi-dynamic models of the components are sufficient for OTS. The full-order model description that contains high order differential equations can be presented by lower order differential equations or even simple algebraic equations. The models should however have sufficiently accurate response to long-term system events and shall produce results on the safe side of operation [10,12].

A second challenge is to collect the required input data for the full-order models including all controller parameters. This challenge can be partly solved by the model simplifications since the input data for the model transients and sub-transients responses are not required anymore. The simplified model however still requires input data, which are mostly not available to the TSOs [13]. These data are either time consuming to collect or they are not allowed to be shared due to their confidentiality or property rights. If the full-order model data are available, building and tuning of the simplified model tend to be more accurate and straightforward. Should this not be the case, referring to the publicly available grid connection codes such as ENTSO-E Network Code on HVDC connections can be considered as a suboptimal solution. It is based on the minimum requirements stated in the grid code for the model certifications for grid integration.