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Assessment and performance evaluation of DC-side interactions of voltage-source inverters interfacing renewable energy systems

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ABSTRACT

This paper presents a performance characterization and efficient modeling of the dc-side interactions between renewable dc resources and interfacing voltage-source inverters (VSIs). The VSI is considered in both grid-connected and islanded modes of operation. On the other side, the dc source is modeled by an equivalent and a detailed circuit. In the former, an ideal current-source in parallel to a dc capacitor is used to represent a non-dispatchable source whereas an ideal dc voltage source is used to represent a dispatchable dc source. In the latter, an additional dc/dc boost converter interfaces the dc source to regulate the input dc-link voltage of the VSI. In all topologies, computationally-efficient small-signal admittance-based models, i.e. transfer-functions, are thoroughly developed for the dc source as well as the VSI. Using the Nyquist stability criterion, it is shown that the dc-link voltage dynamics is negatively affected under some operating conditions. The worst performance is yielded when the dc source is modeled by an ideal voltage source where the dc-link voltage is not controlled by the VSI. On the contrary, the dc/dc boost converter enhances the system damping. The dc-link voltage-controlling VSIs show the most damped performance. In order to enhance the system damping, active stabilizing compensators are proposed and embedded in the conventional control structure of VSIs. Large-signal time-domain simulation model is implemented under Matlab/Simulink environment to validate the small-signal models and show the effectiveness of the proposed compensators.

1. Introduction

Distributed generation (DG) has become a widely adopted concept to overcome the environmental and economical challenges associated with fossil-fired power generation. Micro-grids that cluster multiple DG units and local loads are formed to improve the power quality, enhance the system reliability, and provide ancillary services [1,2]. Micro-grids can be classified into ac and dc types [3–7]. Moreover, the hybrid ac–dc micro-grids concept is emerging to combine the advantages of both systems [7–9]. Power electronic converters are the main building-block device in micro-grid applications in order to interconnect different types of DG units and/or loads, and achieve better controllability and power quality [10–12].

Fig. 1(a) shows structure of the interfacing VSI in the grid-connected or islanded mode of operation, based on the status of the switch (SW). As shown in Fig. 1(b), the non-dispatchable dc source is equivalently modeled as an ideal current source in parallel to a dc capacitor (C_s) whereas the dispatchable dc source is modeled as an ideal voltage source. Fig. 1(c) shows the detailed structure of the dc side when an intermediate dc/dc boost conversion stage is utilized to regulated the input dc-link voltage of the VSI (V_{in}).

In the basic self-contained one-dc-source-one-converter system, the system stability is maintained with well-designed controllers. However, with larger systems, where multiple dc renewable energy resources are interconnected by multi-cascade power electronic stages, the dc-side stability requires further attention. In large systems, the overall system stability might be affected even if each power electronic stage is inherently stable [13]. The Nyquist stability criterion has been utilized in literature as an efficient tool to investigate the stability of multi-power electronic stages [9,13–16].

On the ac side of the voltage-source converter (VSC), the ac-impedance has been developed and addressed in [17] to evaluate the converter-grid interactions and investigate stability conditions. Similarly, the ac-side impedance (or harmonic impedance) of VSIs is addressed in [18,19] under different control topologies but

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Nomenclature

C_{dc}	The dc-link capacitance of the VSI.
C_s	The equivalent dc capacitance of the power source.
D	The duty ratio of the dc/dc boost converter.
F_{sw}	Switching frequency of the VSI.
I_{dc}	The injected dc current to the VSI.
I_{in}	The dc cable current.
i, i_o, i_l, i_g	The inductor, the output, the local load, and the utility-grid three phase current of the VSI, respectively.
I	The ideal dc current of the equivalent power source (non-dispatchable source).
K_p^x, K_i^x	The proportional and integral gains of the PI controller $G_x(s)$, respectively.
P_o, Q_o	The delivered active and reactive power from the LC filter of the VSI.
P, Q	The delivered active and reactive powers from the ac terminals of the VSI.
R_f, L_f, C_f	Per-phase resistance, inductance, and capacitance of the ac LC filter of the VSI, respectively.
R_g, L_g	Per-phase resistance and inductance of the utility-grid impedance, respectively.
R_s, L_s	The equivalent resistance and inductance of the dc cable connecting the dc source to the VSI.
R, L, C	The dc resistance, inductance, and capacitance of the dc/dc boost converter.
s	Laplace operator.
Superscript "*"	The reference value of the variable.
U_{nd}, U_{nq}	The equivalent *d*-*q* components of the three-phase quantity u_n in the rotating reference frame.
V_{dc}	The dc-link voltage of the VSI.
V_{in}	The ideal dc voltage of the equivalent voltage source (dispatchable source).
v, v_o, v_g	Three-phase terminal, output, and utility-grid voltage, respectively.
V	The input dc voltage of the dc/dc boost converter.
ω	The angular frequency.
Z_l	The local ac load with per-phase resistance R_l and inductance L_l.

assuming ideal dc-side dynamics. A similar work is presented in [20] to provide analytical modeling of the harmonic interactions between the utility-grid and the DG inverters. The importance of the output ac-impedance of VSC also appears in [21] where a sub-synchronous torsional stability analysis is performed to study the interaction dynamics induced by a current controlled VSC that is electrically located nearby a synchronous machine. From [17–21], it can be concluded that the ac-side stability for VSCs is well tackled based on the ac admittance modeling.

Unlike the ac-side studies, the interaction dynamics between the dc sources and input of the VSI is still demanding further investigation. To fill-up this gap, this paper develops the small-signal dc-side admittance models of the VSI and the dc source under different operating modes and control topologies. From the dc-side, the input dc source to the VSI is considered dispatchable or non-dispatchable. In the former, no dc-link voltage control is needed from the VSI stage whereas the dc voltage has to be regulated by the VSI in the latter [22,23]. From the ac-side, the VSI can operate in grid-connected or islanded mode. Grid-connected VSIs only requires active/reactive current control whereas the islanded systems requires additional ac voltage controller.

The remainder of this paper is organized as follows. In Section 2, the modeling and conventional control of the VSI under different modes of operation is introduced whereas the modeling and control of the dc source are introduced in Section 3. A general design approach for the conventional controllers in the VSI is introduced in Section 4. The small-signal dc-side admittance models of the VSI and dc source are then analytically developed in Sections 5 and 6, respectively. Section 7 validates the developed small-signal admittance models of the VSI and dc source using large-signal non-linear Simulink models. The characteristics of the admittance of the VSI and its sensitivity analysis are investigated in Sections 8 and 9, respectively. The dc-side stability of the renewable-resource-VSI system is investigated in Section 10 using the Nyquist stability criterion. The proposed active compensators are embedded in the conventional control structure of the VSIs to facilitate the integration of renewables and increase the system stability margin. Evaluation results using time-domain simulations are presented in Section 11 and the conclusions are drawn in Section 12.

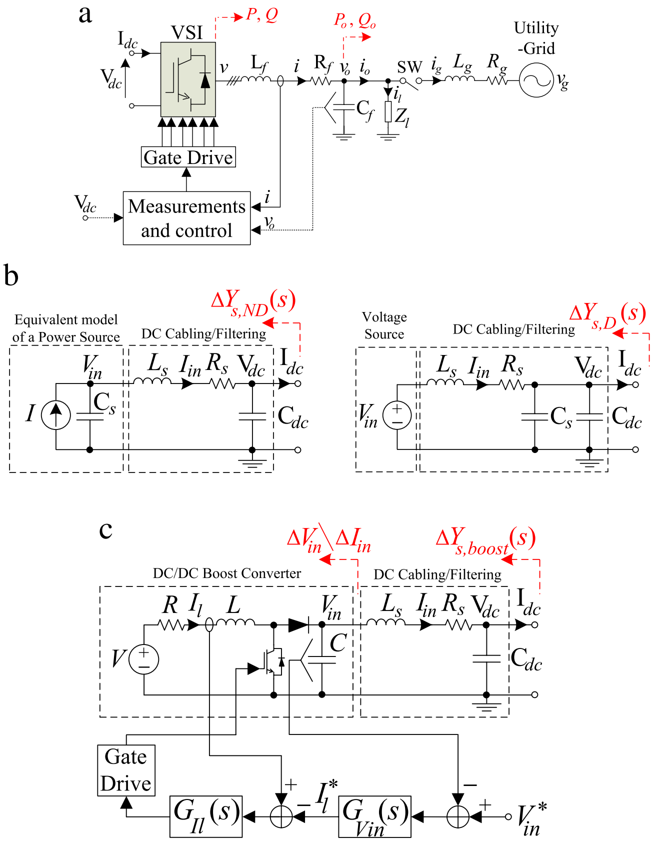

Fig. 1. System under study. (a) The interfacing VSI in either grid-connected or islanded mode. (b) Equivalent model of the dc source — Left: Non-dispatchable source — Right: Dispatchable source. (c) Detailed model of a dc source with a dc/dc boost converter.

2. Modeling and control of the VSI in grid-connected and isolated modes

In this section, the modeling and control schemes of the VSI in the grid-connected and islanded modes of operation are provided. The power circuit of the VSI is shown in Fig. 1(a) where the LC ac filter interfaces a local load (Z_l) and the utility-grid through a switch SW. The model of the LC filter is shown in (1)–(4) in the direct-and-quadrature (*d*-*q*) rotating reference-frame that synchronously rotates with the angular frequency of the inverter output voltage [24].

$$V_d - V_{od} = R_f I_d + L_f \frac{d}{dt} I_d - \omega L_f I_q \tag{1}$$