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Small-signal modeling and parametric sensitivity of a virtual synchronous machine in islanded operation

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ABSTRACT

The concept of Virtual Synchronous Machines (VSMs) is emerging as a flexible approach for controlling power electronic converters in grid-connected as well as in stand-alone or microgrid applications. Several VSM implementations have been proposed, with the emulation of inertia and damping of a traditional Synchronous Machine (SM) as their common feature. This paper investigates a VSM implementation based on a Voltage Source Converter (VSC), where a virtual swing equation provides the phase orientation of cascaded voltage and current controllers in a synchronous reference frame. The control system also includes a virtual impedance and an outer loop frequency droop controller which is functionally equivalent to the governor of a traditional SM. The inherent capability of the investigated VSM implementation to operate in both grid-connected and islanded mode is demonstrated by numerical simulations. Then, a linearized small-signal model of the VSM operated in islanded mode while feeding a local load is developed and verified by comparing its dynamic response to the time-domain simulation of a nonlinear system model. Finally, this small-signal model is applied to identify the dominant modes of the system and to investigate their parametric sensitivity.

Introduction

Virtual Synchronous Machines (VSMs) have recently been proposed as a suitable concept for controlling power electronic converters in power system applications [1–4]. In the context of large-scale power systems, VSMs can provide a flexible approach for introducing additional damping and virtual inertia as an inherent part of the control system of grid integrated Voltage Source Converters (VSCs) [2,5,6]. A few proposed implementations of the VSM concept can also allow for stand-alone and parallel-connected operation in Microgrids or other isolated system configurations with similar performance and flexibility as traditional Synchronous Machines (SMs) [4,7–9].

The VSM concept is still in an early stage of development and many possible implementations, targeted for various types of applications, have been proposed, as reviewed in [4,10]. Thus, most publications until now have been mainly concerned with the development of particular VSM implementations and the presentation of case studies demonstrating the corresponding operational features. A systematic small-signal analysis of a specific VSM implementation was first presented in [11], intended for controller tuning and stability improvement by utilizing the sensitivities of the system eigenvalues with respect to the controller parameters.

The VSC control system investigated in [11] included only the VSM swing equation for damping and inertia emulation, a droop-based reactive power controller according to [12,13] and cascaded voltage and current control loops. However, there was no external power control included in the model, and the implementation of the damping of the VSM did not automatically take into account variations in the steady-state grid frequency. Thus, the applicability of the studied control system was limited to either stand-alone operation for feeding a local load or the operation in a strong grid with a known, fixed, frequency. An extension of the VSM control system design described in [11] was presented in [14]. To achieve full flexibility in allowable operating conditions, the resulting control system included an outer loop frequency droop controller with functionality equivalent to the steady-state control characteristics of traditional SMs [16]. A Phase Locked Loop (PLL) [17,18] was also introduced for tracking the actual grid frequency needed for implementing the VSM inertial damping under deviations from the nominal grid frequency. Furthermore, a virtual impedance, similar to the implementations proposed in [19,20], was included in the

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VSM to improve the decoupling between active and reactive power when operating in resistive grids. Active damping of LC-oscillations was also introduced to ensure stable operation of the VSM in case of LC or LCL filters as the grid side interface of the VSC [21,22]. Mathematical models for all the individual elements of the investigated VSM configuration were described in detail in [14], and a corresponding small-signal state-space model of the entire system was developed, verified and analyzed for grid connected operation. The same control system and the corresponding small signal model for grid connected operation was further elaborated and analyzed in [15].

Although the mathematical model and the analysis of the VSM implementation from [14] and [15] were only valid for grid connected operation, the presented VSM implementation was also intrinsically suitable for stand-alone operation. This paper will start from the same control system implementation and the corresponding model description as presented in [14], and will demonstrate the inherent capability of this VSM implementation for both grid-connected and stand-alone operation by time-domain simulations. A nonlinear analytical model for stand-alone operation will be formulated and linearized to obtain a small-signal state-space representation. This model will be validated by simulations of the nonlinear system model and applied to study the small-signal dynamic properties of the VSM in islanded operation. In particular, the model will be used to analyze the influence of operating conditions on the VSM performance in stand-alone mode, and to identify the parametric sensitivity of the dominant eigenvalues. Together with the results presented in [14], this will provide a complete framework for analyzing the tuning and the dynamic operation of the investigated VSM implementation in both grid-connected and stand-alone operation.

Virtual synchronous machine modeling

This section presents the investigated VSM-based control scheme and the modeling of its functional elements. It is assumed that the dc-link of the VSC is connected to an energy storage unit or to a source with sufficient available buffer capacity. The dc voltage is assumed to be determined by this source, so the modeling and control of the dc side of the converter will not be further discussed. Although most parts of the model description are available in [14], all main equations and descriptions are repeated here for completeness of the presentation when introducing the adaptations required to represent the VSM in stand-alone operation.

System configuration and control system overview

An overview of the studied VSM configuration is shown in Fig. 1, where a VSC is connected to a grid or a local load through an LC filter. For simplicity in the modeling, the local load is connected in parallel to a stiff voltage source. Thus, the investigated system will represent grid connected operation when the breaker indicated in the figure is closed as discussed in [14], while it will represent stand-alone operation for feeding a local load when the breaker is open.

As indicated in Fig. 1, the VSM-based power control with virtual inertia provides frequency and phase angle references to the VSC control system while a reactive power controller provides the voltage amplitude reference. Thus, the VSM inertia and the reactive power controller appear as outer loops providing the references for the cascaded voltage and current controllers in a synchronously rotating reference frame. A PLL detects the actual grid frequency, but it should be noted that this frequency is only used for implementing the damping term of the VSM swing equation. Thus, the reference frame orientation of the inner loop controllers of the VSC is determined only by the power-balance-based synchronization mechanism of the VSM inertia and does not rely on the PLL as in conventional control systems. This applies both when grid connected and in stand-alone operation where the operating frequency of the VSM will be determined by the power balance of the VSM and the power-frequency droop settings. This functionality will not be influenced by the PLL, which will continue to track the actual frequency of the voltage at the filter capacitors independently of changes in the operating mode.

Non-linear system model

In the following subsections, the mathematical models of the different elements of the system from Fig. 1 are presented as basis for developing a nonlinear mathematical model of the investigated VSM configuration in stand-alone operation. This model captures the main dynamics of the proposed implementation, including the nonlinearity introduced by the active and reactive power

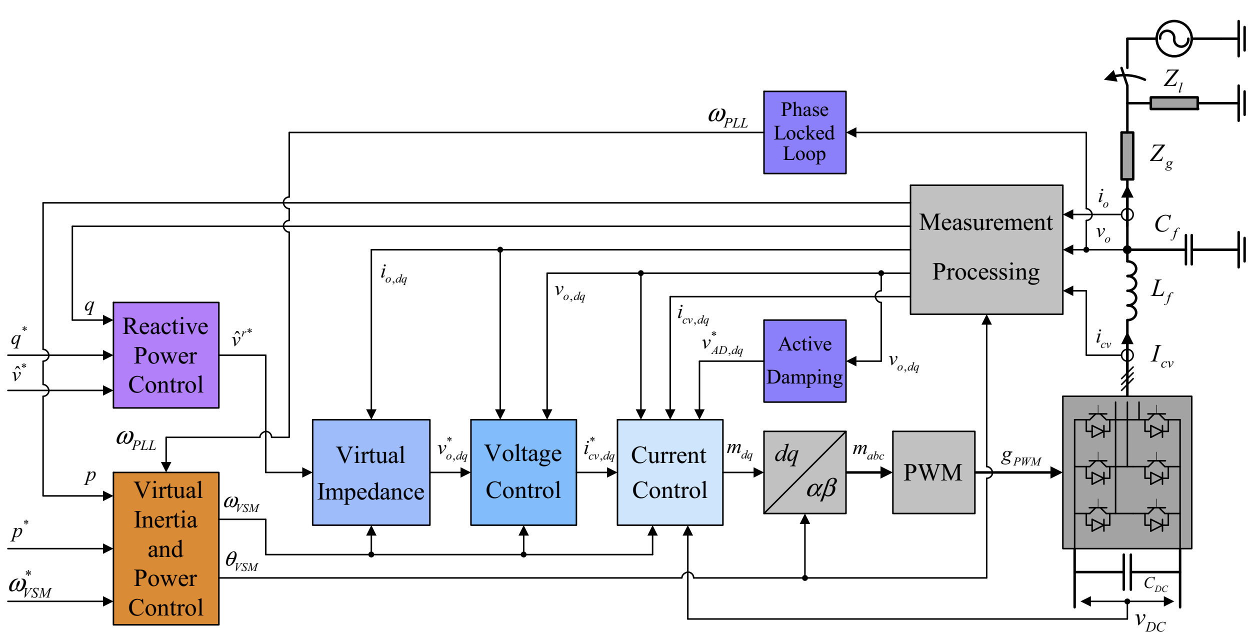

Fig. 1. Overview of investigated system configuration and control structure for the virtual synchronous machine in grid connected and islanded operation.