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IFAC-PapersOnLine 49-27 (2016) 060–065

Extending control stability results from voltage-source to current-controlled AC or DC power converters

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Abstract: Many control stability results consider the interaction of voltage-source converters, but most real converters use a nested current loop. This paper develops a general method to extend voltage-source stability results to current-controlled converters. Nonlinear dead-zone oscillator (DZO) control, a control method originally formulated for voltage-source inverters, is experimentally validated with a three-phase system of current-controlled inverters. This validates the equivalence of current-based control, and also demonstrates DZO control in three-phase hardware for the first time. The extension to current-controlled converters enhances safety and increases the breadth of application for existing control methods that assume voltage-source converters. In addition, current-based control can manipulate the load sharing between converters using a virtual output impedance.

Keywords: power converters, power electronics, nonlinear control, limit cycles

1. INTRODUCTION

The increasing penetration of power converters has raised new problems and opportunities in the control of small power systems and microgrids, a trend noted by Trudnowski et al. (2006); Dong et al. (2011); Salehi et al. (2012). Power conversion decouples the physical dynamics of generators and loads from the rest of the system, but allows almost any set of dynamics to be substituted. Converter dynamics can be designed to facilitate load sharing and voltage regulation among multiple generators in both AC and DC power systems, as well as frequency regulation and synchronization in AC power systems (see Bidram et al. (2014)). Of specific recent interest are efforts to replicate the stability and convergence results for coupled oscillators of various types in AC systems of coupled inverters Dörfler et al. (2013); Simpson-Porco et al. (2013).

Numerous theoretical results are available on these topics, but relatively few are tested in hardware. Most approaches approximate a switching power converter as an ideal voltage source. Controller dynamics are assigned to command this output voltage, and the feedback is output current. This is a logical approach for control of voltage-source converters.

In practice, however, it is far more common to have a low-level nested control loop in the converter to render it a controlled current source. One major reason is that semiconductors are very sensitive to overloads of even very short duration, and the current-controlled formulation makes it easy to enforce protective limits. This is especially important during fault conditions and rapid transients. The current control also provides some benefits during low-voltage ride-through conditions when the converter must output full rated current into a faulted (zero voltage) grid. Converter control based on the voltage-source formulation presents no immediately obvious way to satisfy these protective limiting requirements, which presently limits its commercial deployment.

This paper attempts to bring these converter control methods closer to deployment through two main contributions. The first is a general approach that can extend a voltage-source analysis into a current-controlled version while maintaining its stability proofs, enabling more direct implementation into the current-controlled converters common today. The approach is then used to implement a voltage-source algorithm in current-controlled inverters, and demonstrate dead-zone oscillator (DZO) control with three-phase inverters for the first time. The resulting AC grid demonstrates self-synchronization, voltage and frequency regulation, and power sharing without dedicated communications.

DZO control entails controlling inverters to emulate the dynamics of nonlinear DZOs. The inverter terminal voltages oscillate in a stable, sinusoidal limit cycle, and the DZO parameters can be tuned such that parallel-connected inverters self-synchronize with no communication other than that inherent to their common electrical coupling. In Johnson et al. (2014c) DZO control was presented for implementation in single-phase systems of parallel-connected voltage-source inverters, and a method was developed to control the relative power contribution or "load-share" of inverters. In Johnson et al. (2014b), DZO control was experimentally validated and sufficient conditions for the synchronization of parallel inverters were derived. The extension of DZO control to a three-phase system of parallel-connected voltage-source inverters was introduced and simulated in Johnson et al. (2014a), and a method of controlling the relative power contribution of inverters by altering their current feedback gains was introduced.

The DZO control in all of these works assumes ideal voltage-source inverters. Here, this analysis is extended to hardware testing of current-controlled three-phase inverters. We also demonstrate new method of controlling the

Peer review under responsibility of International Federation of Automatic Control.
10.1016/j.ifacol.2016.10.720

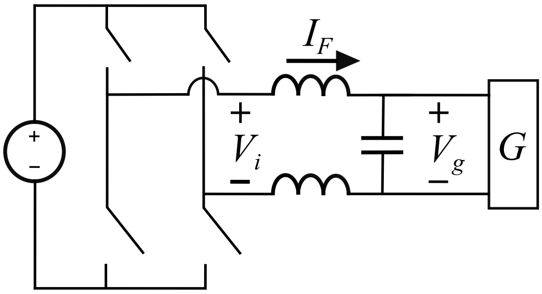

Fig. 1. General model of a voltage-source converter.

relative power contributions of current-controlled inverters that uses virtual output impedances.

Section 2 describes the extension of voltage-source stability results to the current-controlled case. Section 3 summarizes DZO dynamics, Section 4 describes our implementation of DZO control, and Section 5 contains the results.

2. CURRENT CONTROLLED EQUIVALENT OF A VOLTAGE-SOURCE ALGORITHM

2.1 Converter Model

A typical voltage-source converter is shown in Figure 1 with ideal semiconductor switches. The voltage at the output of the inverter bridge is V_i, and current is measured at that location. The converter has an output filter with an inductor and a parallel capacitor, which may be omitted depending on filtering requirements. The voltage at the output terminals is V_g. The "Grid" component G reflects everything else in the system: impedances, loads, and other inverters. It establishes a voltage V_g based on the injected current and activity in the rest of the system. While a single-phase AC converter is shown here, other switch configurations can create three-phase or DC converters.

This system can be simplified into Figure 2 by assuming the switching dynamics are fast enough to be neglected and treating the inverter bridge as an ideal voltage source. The inductor or any series output filter element is reflected in the system F_s which takes voltage drop $V_i - V_g$ as input and calculates a current. The output capacitor or parallel filter elements are lumped into the grid system, now denoted G'.

2.2 Voltage source analysis

Stability analysis of a DC or AC interconnected converter system includes assumptions about three elements: the controller dynamics; the grid impedance and interconnections seen from the voltage source; and the switching dynamics, which are fast and often neglected.

The controller dynamics operate in software as $C(I_F)$ and assign a voltage based on the measured output current I_F. The output filter system F_s uses the voltage drop to produce a current. Note that all the components C, F, and G may be nonlinear. The basic equations are thus

$$V_i = C(I_F). \tag{1}$$
$$I_F = F_s(V_i - V_g) \tag{2}$$
$$I_F = F_s(C(I_F) - G'(I_F, u_{1-N})) \tag{3}$$

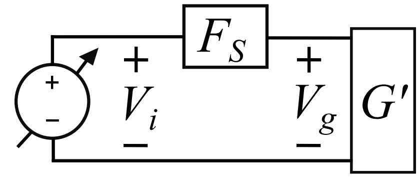

Fig. 2. The converter switches can be represented as an ideal voltage source. Series filter components are represented as F_S, while parallel filter elements are lumped into the grid to become G'.

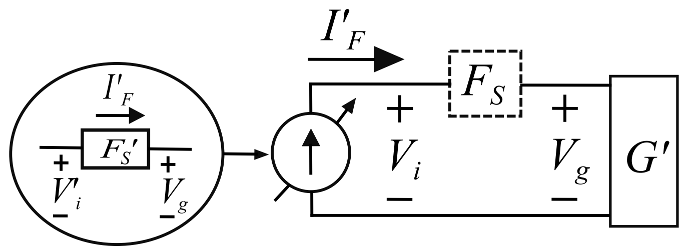

Fig. 3. A current-controlled inverter with a sufficiently fast PI loop can enforce any I'_F. Thus, given a simulated output voltage V'_i, it can enforce any $F'_s(V'_i - V_g)$. Note that when $F'_S \neq F_s$, in general $V'_i \neq V_i$.

where the nonlinear F_s in (2) becomes an admittance in the linear case. The effect of other inverters is u_{1-N}.

2.3 Current controlled equivalent

To change the analysis for a current-controlled version, we assume an arbitrarily fast PI (or similar) current-control loop that enforces a desired output current by varying the converter output voltage. The output impedance G' must be bounded. Current-control requires some ability to modulate output current and will not function with an open circuit. This condition can be satisfied with a parallel-connected filter capacitor as in Figure 1 even if the grid interface to the converter terminals G is unconnected.

Such an ideal current-controlled converter removes the effects of F_s on current as it is within the closed-loop portion. However, we can simulate the effects of any F'_s in software, as shown in Figure 3.

We take the controller output V'_i, and subtract the measured terminal voltage V_g to create the voltage difference needed to calculate output current with F'_s. This current is then fed back as the current command. Assuming the current controller is very fast and well-tuned, a singular perturbations argument allows us to treat it as a current source so that I_F matches exactly the desired I'_F. We can then replace the closed-loop current controller with a current source for analysis.

For a voltage-source model, the output impedance includes the series output filter of the inverter F_s in Figure 2, which is a physical hardware component. For the current-controlled version, the physical output filter impedance is neglected due to the ideal current control loop, but a simulated filter impedance is included in the controller dynamics. This makes the full system analysis and system dynamics identical to the previous case, except for that filter dynamics F_s are now virtual rather than real.