Virtual Oscillator Control as Applied to DC Microgrids with Multiple Sources

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Virtual Oscillator Control as Applied to DC Microgrids with Multiple Sources

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***Abstract*—Simple reference-frame transformations allow to implement the method of Virtual Oscillator Control, originally conceived for AC microgrids, to parallel-connected converters in a DC microgrid network. As a result, based only on local measurements and without recourse to a communication link, the DC-DC converters in the microgrid share the load power in proportion to their power ratings without circulating currents, and may be readily interleaved. Simulations validate the proposals for a set of three half-bridge converters serving a common DC load.**

***Index Terms*—Distributed DC power systems, microgrids, nonlinear control, parallel synchronization.**

I. INTRODUCTION

In islanded operation of ac microgrids, the distributed generation units are responsible for the voltage control, the power balancing and the load sharing. As microgrids have different characteristics in comparison with traditional power systems, alternative operation and control methods have been developed [1]. Communication-based control strategies as usually encountered in uninterruptible power supplies can achieve good results in islanded microgrids. However, especially in large microgrids, a communication link can be impractical and costly. Since this link can form a single point of failure, it may also reduce the reliability of the system compared to the case where no communication is required for the network primary control. Therefore, droop controllers that are not based on a communication link are a preferable choice [1].

An innovative method to synchronize and control a system of parallel single-phase inverters without communication link has been introduced for ac microgrids, so-called Virtual Oscillator Control (VOC) [2-4]. Inspired by the phenomenon of synchronization in networks of coupled oscillators, this approach proposes that each inverter be controlled to emulate the dynamics of a nonlinear dead-zone oscillator. As a consequence of the electrical coupling between inverters, they synchronize and share the load in proportion to their ratings, for both linear and nonlinear loads. The authors in [2] outline a sufficient condition for global asymptotic synchronization and formulate a methodology for controller design such that the inverter terminal voltages oscillate at the desired frequency, while the load voltage is maintained within prescribed bounds.

Essentially, the general strategy of VOC is to control inverters to emulate the dynamics of a class of weakly nonlinear Liénard-type oscillators, leading to a time-domain alternative to droop control methods that linearly trade off voltage frequencies and magnitudes with active and reactive power injections. In comparison to droop control, which assumes a priori that the network operates in a quasi-stationary sinusoidal steady state, VOC is a globally stabilizing control strategy that can deal with higher-order harmonics and includes droop control in the harmonic steady state [5].

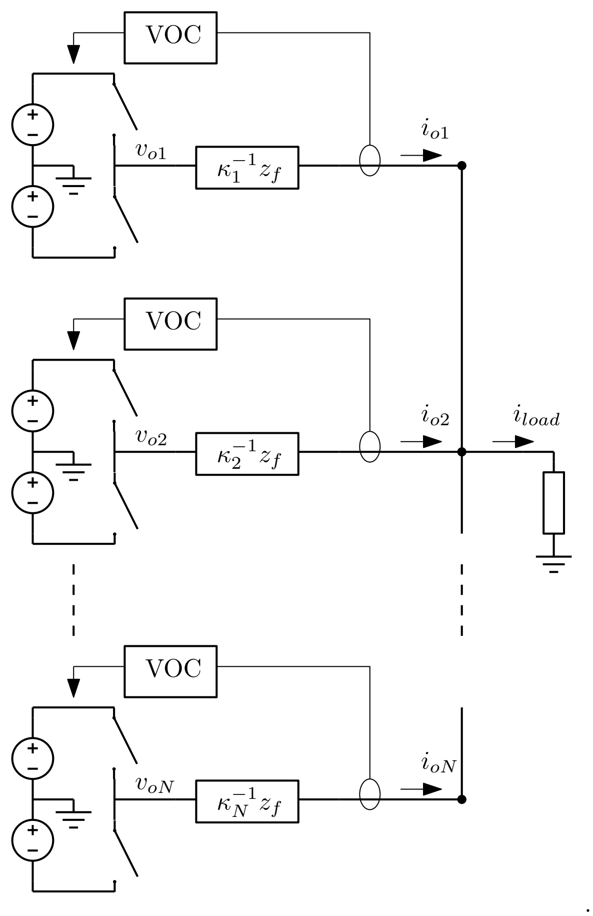

Fig. 1. AC microgrid with multiple parallel-connected sources under Virtual Oscillator Control sharing a common load [2].

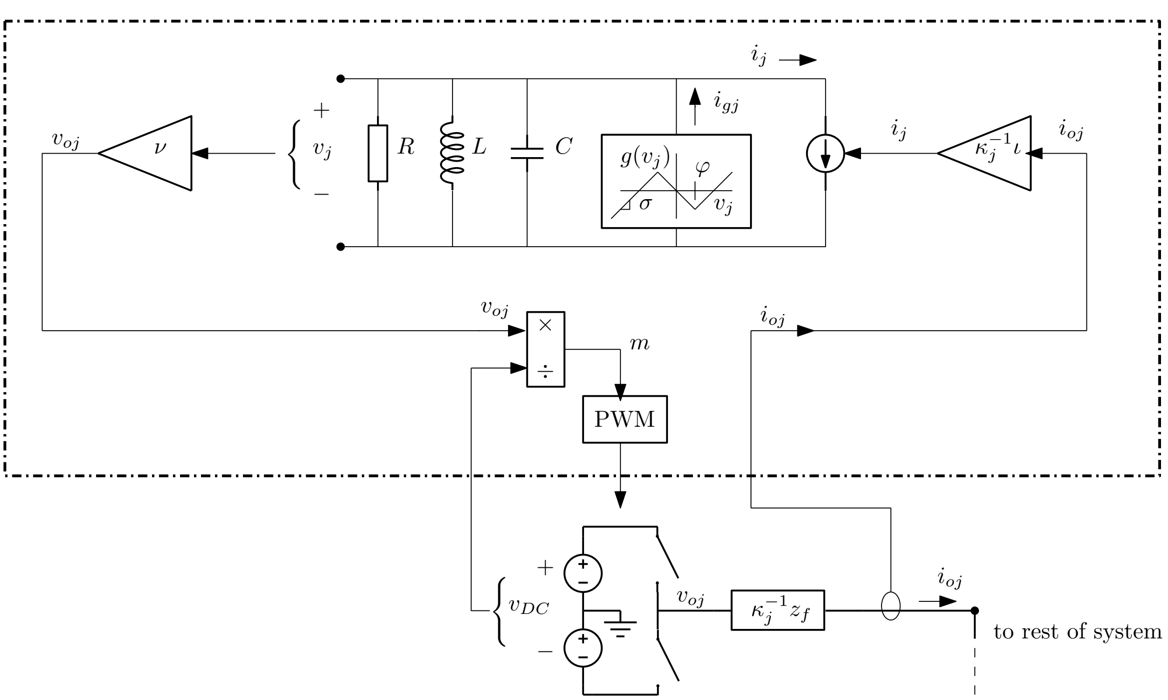

Fig. 2. Implementation of VOC for the j^{th} inverter in Fig. 1.

Similar to the situation in ac microgrids, load current sharing and circulating current are essential issues of parallel-connected dc/dc converters in low-voltage dc microgrids. Also here droop control is the popular technique for load current sharing. However, conventional droop methods may lead to poor current sharing and unsatisfactory voltage regulation. Circulating current issues could also arise due to mismatch in the converter output voltages [6].

In this paper it is shown that by performing simple domain transformations (from ac domain to dc domain and back) it is straightforward to apply the VOC method, which has been originally envisaged for ac systems, to parallel-connected dc-dc converters in a dc microgrid network. All the advantages of the control approach are preserved in the dc system: independent of load, requires no communication, independent of the number of converters, no circulating currents, load sharing in proportion to converter rating. Moreover, by introducing a virtual resistor in the digital implementation of the internal voltage control loop, impedance mismatch of the external interconnection cables to the common load point-of-coupling may be circumvented. Furthermore, the possibility of interleaving the output current waveforms is also readily made possible. Simulation results validate the proposed ideas.

II. VOC EXTENDED TO MULTIPLE DC/DC CONVERTERS

The VOC method, as conceived for the synchronized operation of parallel voltage source inverters, is comprehensively detailed by seminal papers [2-4]. Therefore, the focus herein is on the missing transformations aiming at application to dc systems. In the following sections, notation and background information are quite in line with the material presented in the VOC seminal papers.

In Fig. 1, reproduced from [2], a set of parallel single-phase power-electronic inverters (half-bridges) sharing a passive load is shown. The implementation of VOC with a dead-zone oscillator for the individual inverters is illustrated in Fig. 2. Note that only local measurements are acquired.

With reference to Fig. 2, the oscillator is composed of a parallel RLC circuit, and a nonlinear voltage-dependent current source, $g(v_j)$. The inverter output current, i_{oj} , is the driving term, and the oscillator voltage, v_{oj}, is utilized as the PWM modulation signal. A design procedure for the oscillator parameters is outlined in [2-4] in order to obtain oscillations at the desired frequency, $\omega_{\text{rated}} = \sqrt{1/(LC)}$. Once the values of R, L, C, σ, ϕ, ι, and ν are computed, they are utilized by all oscillators in the system. The values of κ are selected in proportion to the inverter power ratings, and it is assumed that the per-unitized filter impedance of each inverter is identical, such that the filter impedance of the j^{th} inverter can be expressed as $\kappa_j^{-1}z_f$, as shown in Fig. 1. Altogether, global asymptotic synchronization of all inverters is guaranteed to occur with no communication.

As described in the following, the VOC method can be readily applied on the basis of simple transformations to parallel-connected dc-dc converter systems, such that load sharing in proportion to converter power rating, and waveform interleaving can also be ensured with no communication.

To illustrate the idea, let's consider that a set of half-bridges

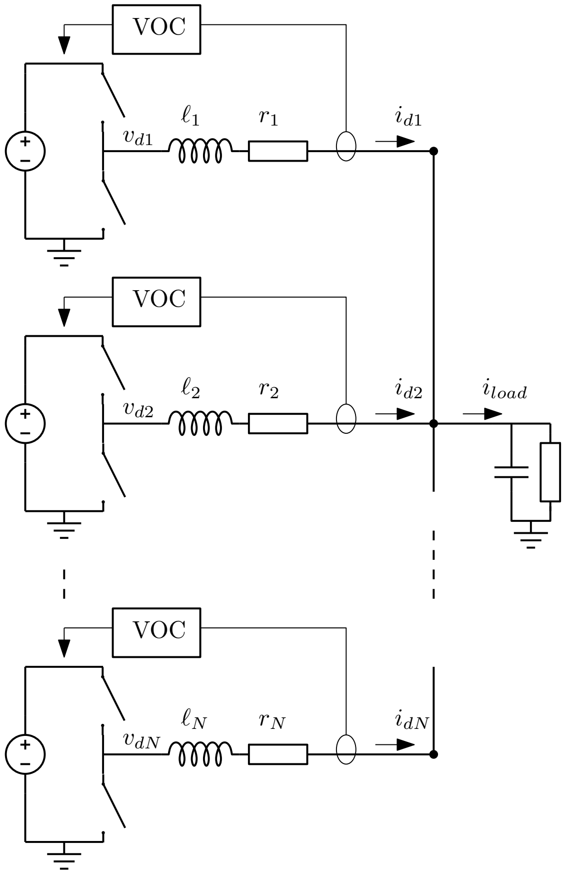

Fig. 3. DC microgrid with multiple parallel-connected sources and VOC.

operating as dc/dc converters in a dc microgrid network share the same load (a capacitive-resistive load in this case, without loss of generalization), as shown in Fig. 3. Now the bridge output filter impedances, (ℓ_j, r_j), which also incorporate the (parasitic) impedance of the connecting cables, are not necessarily supposed to have the same values.

The necessary adaptations to apply the VOC method to the converters in Fig. 3 are shown in Fig. 4. The main step is to consider the oscillator voltage v_{oj} to be describe as

$$v_{oj} = v_{dj}^{*} \cos\theta_j \tag{1}$$

and to extract in real-time its magnitude v_{dj}^{*} and harmonic part $\cos\theta_j$. For this purpose, orthogonal α/β signals are created by delaying v_{oj} (assumed to be the α-component) in order to obtain an associated quadrature signal (β-component). After squaring and addition follows the instantaneous value of v_{dj}^{*}, and, consequently, also $\cos\theta_j$. By this way, v_{dj}^{*} (in the dc domain) is directly associated to v_{oj} (in the ac domain).

Through standard PWM techniques v_{dj}^{*} is used as the reference value to generate the switching node output voltage v_{dj}, and , consequently, the converter dc output current i_{dj} (which is imposed by v_{dj} in the dc domain). Later on, $\cos\theta_j$ will be used to associate the average value of the dc output current, $\overline{i_{dj}}$, to the driving oscillator current i_{oj} (in the ac domain), with

$$i_{oj} = \overline{i_{dj}} \cos\theta_j, \tag{2}$$

such that $v_{oj}(t)$ in (1) and $i_{oj}(t)$ in (2) are in phase.

The half-bridge output filters in Fig. 3 incorporate inductances, l_j, which determine the dc current switching ripple, and also parasitic series resistances, r_j. In order to achieve load sharing in proportion to the converter power rating independently of the values of (l_j, r_j), the switching ripple in i_{dj} is reduced by low-pass filtering in the control implementation of Fig. 4 (for instance with bandwidth one decade below the switching frequency), leading to a moving average value, $\overline{i_{dj}}$, which excludes the impact of l_j on the oscillator signals. Then a virtual resistance r_v, with $r_j/r_v << 1$ for all dc/dc converters in the network , is added to obtain an internal voltage droop $(\kappa_j^{-1} r_v \overline{i_{dj}})$ from the dc reference v_{dj}^{*}. This way, the voltage droop generated by r_v dominates and virtually eliminates the influence of r_j on the load sharing.

Given the j^{th} and k^{th} dc/dc converters with ratings P_j and P_k, respectively, the values of κ_j and κ_k are selected such that

$$\frac{P_j}{\kappa_j} = \frac{P_k}{\kappa_k} \tag{3}$$

then the dc/dc converters share the load power in proportion to their ratings [2].

Since global asymptotic synchronization of all oscillators is guaranteed to occur, the internal voltages of the oscillator system with N dc/dc converters satisfy the condition

$$\lim_{t\to\infty} v_j(t) - v_k(t) = 0 \;\; \forall j,k = 1,..,N \tag{4}$$

That is to say, every virtual oscillator in the system will have internally available voltage waveforms which are identical in frequency and phase. Therefore, synchronized zero-crossing moments are readily available everywhere in the system. When the number of dc/dc converters is known, it is then straightforward to implement suitable time shifts for implementing interleaved PWM phase-leg switching carries. As a consequence, the resulting load current ripple can be minimized without a communication link between the dc/dc converters.

III. SIMULATION CASE STUDY

A simulation study is provided to demonstrate the application of VOC in a system of three parallel-connected half-bridge dc/dc converters serving a resistive load. For the sake of comparison with the results presented in [2], the half-bridges have ratings of 50W, 100W and 400W, such that the parallel converters are expected to share the load current according to a ratio 1:2:4. The phase-leg switching frequency is $f_{sw} =$ 10kHz, the output currents are filtered by 2nd-order low-pass filters with corner frequency at 1kHz, and the virtual oscillator frequency is chosen to be 50Hz. Other specifications are given in Table 1, close to the design choices in [2].

As illustrated in Fig. 5, the load is initially 150W ($R_{\text{load}} =$ 50Ω) and then undergoes a step change to 300W ($R_{\text{load}} =$

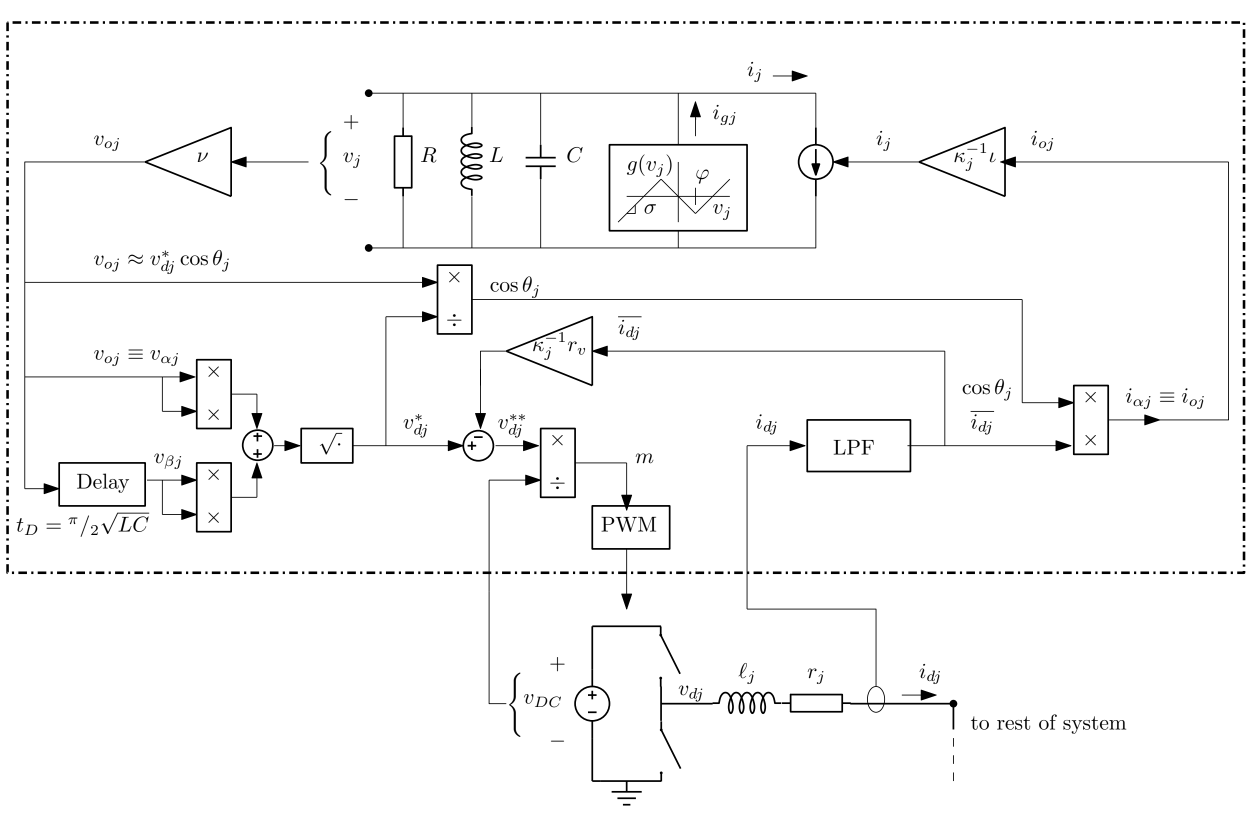

Fig. 4. Implementation of VOC for the j^{th} dc/dc converter in Fig. 3.

TABLE I
SIMULATION AND CONTROLLER PARAMETERS

$\omega_{\text{rated}} = 2\pi 50\text{rads}^{-1}$	$r_j = 0.1\Omega,\ j = 1, 2, 3$
$V_{\text{rated}} = 60V\text{rms}$	$\ell_j = 6\text{mH},\ j = 1, 2, 3$
$V_{\max} = 1.05V_{\text{rated}}$	$r_v = 2\Omega$
$V_{\min} = 0.95V_{\text{rated}}$	$\kappa_1 = 1, \kappa_2 = 2$
$R = 10\Omega$	$\kappa_3 = 4$
$L = 500\mu H$	$\varphi = 0.4695$
$C = 1/(L\omega_{\text{rated}}^2)$	$\iota = 0.1125$
$\sigma = 1\Omega^{-1}$	$\nu = \sqrt{2}V_{\text{rated}}$
$f_{\text{sw}} = 10\text{kHz}$	$R_{\text{load}} = 50\Omega \to 25\Omega$
$v_{\text{DC}} = \sqrt{2}V_{\text{rated}} \times 1.5$	$C_{\text{load}} = 10\mu F$

25Ω). Despite the relatively large transient, the steady-state load voltage remains close to the nominal value of 85V. In Fig. 6 details of the interleaved switching currents are shown, before and after the load step.

IV. CONCLUSION

On the basis of domain transformations, s system of parallel-connected dc/dc converters, a situation commonly encountered in dc microgrids, can be controlled as a class of weakly non-linear oscillators. The resulting system is modular and does not require communication between converters to obtain switching ripple interleaving and load sharing without circulating currents. The overall control performance shows an attractive time-domain alternative to classical droop control.

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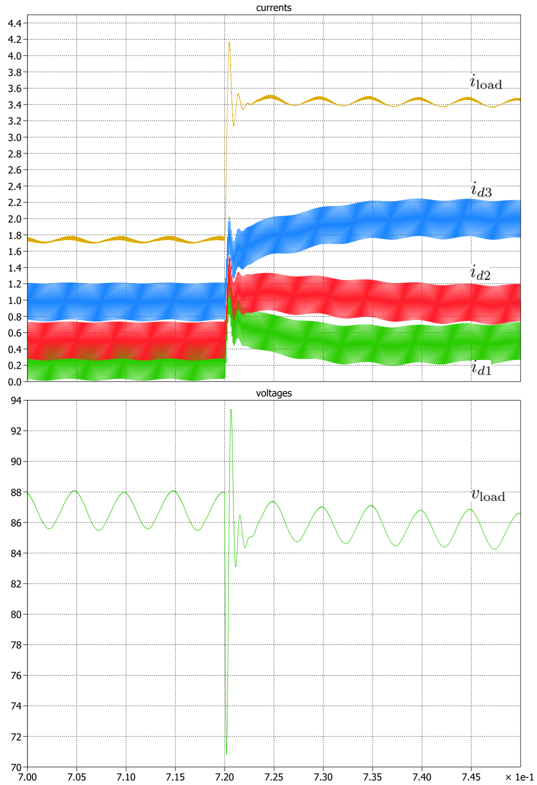

Fig. 5. System with three paralell-connected half-bridge dc/dc converters, sharing the load current according to the ratio 1:2:4; upper traces: output currents (i_{d1}, i_{d2}, i_{d3}) and load current (i_{load}), bottom trace: load voltage (v_{load}). Load step (from 150W to 300W) at 0.72s. Time scale: 5ms/div.

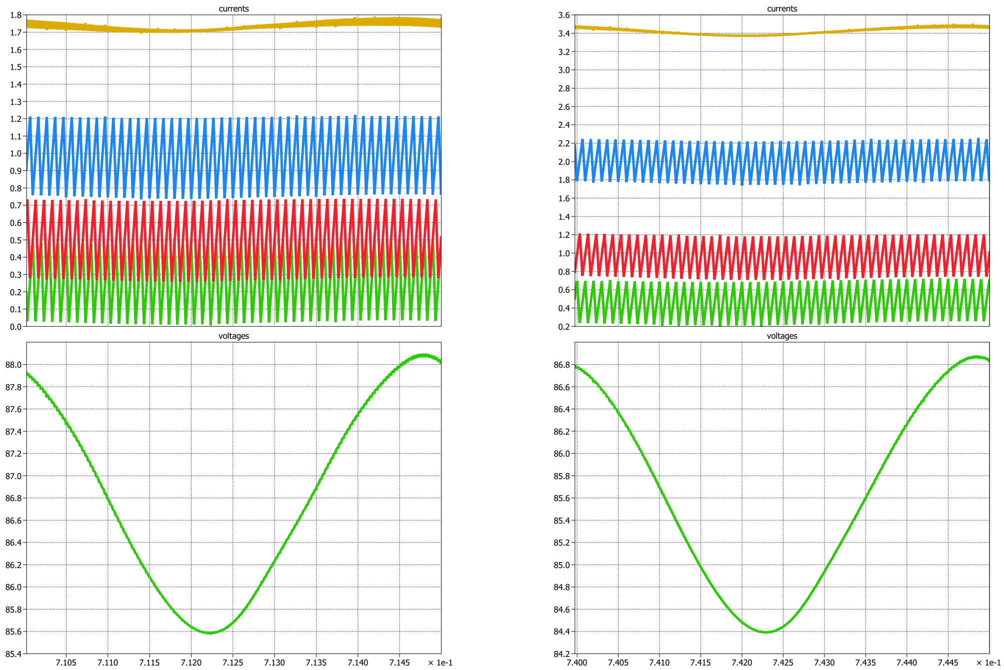

Fig. 6. Zoomed details of the waveforms in Fig. 5, before and after the load step. Time scale: 500μs/div.