Voltage Harmonic Reduction using Virtual Oscillator based Inverters in Islanded Microgrids

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Abstract—In islanded mode, the voltage and frequency of microgrids are determined by the interface voltage source inverters. Hence, the power quality can be deteriorated under unbalanced and nonlinear load conditions. This paper proposes a new method that combines Virtual Oscillator Control with Proportional-Resonant control to mitigate voltage harmonic distortion. This work proposes a modified nested loop proportional-resonant controller, in which the fundamental frequency unit is located in the outer loop, whereas the harmonic frequency units are used in the inner loop. The harmonic control units are introduced to reduce harmonics at the point-of-common-coupling and to guarantee non-fundamental power sharing among inverters. The proposed control structure eliminates the harmonics at selected frequencies, while retaining the main advantages of the virtual oscillator control method. Simulations in Matlab/Simulink verify the effectiveness of the proposed method.

Index Terms—Microgrid, Virtual Oscillator Control, Proportional – Resonant Control, Harmonic reduction, Virtual Impedance.

I. INTRODUCTION

A microgrid is a small-scale controllable power network, which is capable of operating in both grid-connected or islanded mode [1]. A general microgrid consists of distributed generations units (DGs), energy storage systems (ESS) and local loads [1], [2]. Since most of the DG and ESS outputs are in DC form or have a DC bus in the middle, power electronic based interface inverters (VSIs) are usually used to interconnect them with main utility grids and microgrids. The primary role of VSIs is to control active and reactive power delivery by adjusting voltage amplitude and phase angle.

So far, research has mainly focused on the development of control methods for VSIs in a microgrid, based on centralized or decentralized control. Centralized control methods, relying on the communication between VSI controllers, achieve good performance but limit system reliability, modularity, and expandability [3]-[4]. Distributed architectures can address these weaknesses, however, they often cannot guarantee performance and increase overall complexity of the control system. Among decentralized control methods, Virtual Oscillator Control (VOC) [5], [6] is a new and promising technique, which provides a way to synchronize and control interfaced inverters in islanded microgrids without the need of communication, by mimicking the behavior of nonlinear oscillators. This technique can guarantee
- synchronization of a connected electrical network from arbitrary initial conditions,
- droop-like voltage and frequency control and
- power-sharing accuracy.

In comparison with the other advanced method for VSC control in microgrids, namely droop control [7], [8], VOC differs in several aspects. It requires less computational workload, no specific frequency or amplitude reference while providing better performance [5], [9].

The continuous development and deployment of modern microgrids, especially in presence of a large number of unbalanced and nonlinear loads, poses significant technical challenges for controller design to fulfill system stability, synchronization, and stringent power quality requirements. These types of loads deteriorate power quality in islanded microgrids [10]. To overcome these challenges, passive or active power filters (APFs) have been used in utility grids [11], [12]. However, from the microgrid perspective, it is uneconomical to install additional devices. On the other hand, by appropriate control of VSIs, the power quality can also be guaranteed. In [13], a control approach in which a single-phase inverter was forced to act as a shunt active filter, was proposed. The controller was designed to inject the same amount of harmonics as in the load current, but with reverse phase angle. Most of the inverter control-based methods focused on harmonics at the inverter output bus. When the local controller of a DG tries to compensate for harmonics at its own output bus, the voltage at other (external) buses such as point-of-common-coupling (PCC) can be more distorted, which can cause problems to sensitive loads connected to it [14]. The method proposed in [15] aims at compensating voltage harmonics directly at the PCC. This method is also capable of providing accurate harmonic power-sharing between parallel

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inverters, by introducing virtual resistance at the harmonic frequency.

This paper proposes a new control strategy for harmonic compensation at the PCC, which considers the impact of line and transformer impedance on voltage harmonics distortion. The VOC output voltage is used as a reference to guarantee synchronization and power-sharing between parallel-connected inverters. The proportional – multi-resonant (PR) based controller which operates in αβ- and abc- frame is selected for inner voltage and current control loop.

II. VSI CONTROL IN ISLANDED MODE

This section presents the topology of the reference microgrid adopted in this work together with the structure of the proposed control strategy.

Fig. 1 shows the power stage (and the control structure) of a microgrid, which consists of two DGs connected in parallel, and a nonlinear load connected to the PCC. Also, a distribution line represented as a resistance (Rline) is considered between each DG and the PCC. The inductor current of the LCL filters, the capacitor voltage and the voltage at the PCC are fed back to all local controllers of DGs. Inverter Inv 2 has a similar electric connection and controller scheme as inverter Inv 1.

The details of the proposed control scheme for controllers of DGk (k = 1, 2) is also shown in Fig. 1. The DC side voltage is considered constant because the primary aim of this control scheme is compensation of voltage harmonics distortion.

In this paper, the purposes of the control design are: 1) zero steady-state error (for harmonic content and fundamental frequency reference tracking), 2) harmonic rejection at the PCC, and 3) target accuracy of power-sharing among the inverters.

The reference voltage VOC of the controller of DGk, is generated by the VOC, the virtual impedance loop, and the harmonic control unit. Once it is compared with DG voltage output vC, the voltage controller generates a current reference signal to mitigate this error. Finally, the output of the current controller to the difference between inductor current and reference is transformed back to abc- coordinates to act as a modulation signal to control switches of the interfaced inverter. The phase compensation block is also used to improve the stability of the control system.

A. Virtual Oscillator Controller

Fig. 2 illustrates the Van der Pol VOC implementation for three-phase inverters utilized in this paper. It consists of an LC circuit to set the system frequency, a negative damping resistor R, and a cubic voltage dependent current source to sustain the oscillator. The inductor current if, which is multiplied by current scaling factor Kn, is fed back to the input of the VOC circuit. The resulting capacitor voltage Vc, which is multiplied with voltage scaling factor Kv, is used as a reference for PR controllers. The dynamic of the Van der Pol oscillator is governed by the equation below:

\[
\frac{d^2v_c}{dt^2} = \varepsilon \omega \sigma (1 - \beta v_c) \frac{dv_c}{dt} - \alpha^2 v_c - \varepsilon \omega K_v \frac{di_f}{dt} \quad (1)
\]

where

- \( K_v, K_n \): scaling factors to couple VOC input and output to physical electrical feedback signals.
- \( \omega (\sqrt{LC}) \): the resonant frequency of the VOC circuit

It is noticeable that if \( \varepsilon = \sqrt{LC} \to 0 \), the capacitor voltage output exhibits an approximately ideal sinusoidal waveform at the resonant frequency, which is referred to the quasi-harmonic regime [9].

![Figure 1. Microgrid configuration with local inverter controller](image-url)

![Figure 2. Schematic of VOC controller](image-url)
B. Proportional – Multiresonant Controller

Because the PI controller shows poor performance in steady-state error mitigation when regulating distorted sinusoidal voltage caused by the presence of nonlinear loads [16], the PR controller with selected harmonic reduction components has been chosen instead. For the purpose of tracking the fundamental reference component, the voltage controller consists of only the fundamental frequency resonance controller. On the other hand, since the bandwidth of the current loop is always higher than that of the voltage loop, the $5^{th}$, $7^{th}$, $11^{th}$ and $13^{th}$ resonant controllers are included to improve system stability and performance.

The transfer function matrices of these controllers are given in (2) as follows:

$$
 G_{v}(s) = \begin{bmatrix} 
 k_{v} + k_{r} & \frac{\theta_{v}s}{s^2 + 2\omega_{r}s + \omega_{r}^2} & 0 \\
 0 & k_{c} + k_{r} + \frac{\theta_{c}s}{s^2 + 2\omega_{r}s + \omega_{r}^2} & 0 \\
 0 & 0 & k_{r} + \sum_{n=5,7,11,13} k_{r} \frac{\theta_{n}s}{s^2 + 2\omega_{n}s + \omega_{n}^2} 
\end{bmatrix}
$$

where

- $k_{pV}, k_{pI}$: voltage and current proportional coefficient, respectively
- $k_{vI}, k_{vR} (n = 5, 7, 11, 13)$: voltage and current resonant coefficient, respectively.
- $\omega_{n} (n = 5, 7, 11, 13)$: cutoff frequency of the fundamental and selected resonant controllers.

It is worth mentioning that this structure does not increase computational workload, in comparison with conventional PR-based dual loop controller [16], while providing better performance. Furthermore, whereas the system frequency is controlled by VOC (see in (2) and Fig. 4), the rated frequency $\omega_{v}$ is used in both control loops, instead of actual operating frequency to avoid the risk of instability.

The PR controller is implemented in MATLAB/Simulink by using two discrete integrators, as shown in Fig 3. This structure shows essential advantages: 1) it is easy to implement, 2) the term $\omega_{v}$ is separated from other parts, making it easy to apply frequency adaptation methods, and 3) each resonant component model can be obtained separately, instead of developing an equivalent scheme [17]. To improve dynamic behavior and maintain the stability of PR controllers, the phase compensation (in Fig.1) that is achieved through the transfer function below is usually used [18]:

$$
 G_{pv}(s) = \frac{\alpha_{p} + s}{\omega_{p} + s}
$$

where $\omega_{p}$ and $\omega_{p}$ is the zero and pole location which is calculated based on desired phase margin $\theta$ and switching frequency $F_{c}$.

C. Virtual Impedance Loop

In order to reduce power-sharing error among inverters caused by the mismatch of filter and line impedances, a general virtual impedance (VI) loop as shown in Fig. 4 is used [8]. The detailed design of VI control loop is out of the scope of this paper. However, it should be mentioned that increasing power-sharing accuracy can be obtained at the cost of increasing harmonics distortion because of the voltage drop in VI. Therefore, choosing $R_{v}$ and $L_{v}$ is the tradeoff between sharing accuracy and harmonics regulation.

D. Harmonic Control Unit

Fig. 5 shows the details of the harmonic control unit block. The fundamental and harmonic components of the PCC voltage are separated by using self-tuning filter (STF) [15]. The harmonic components are then multiplied by a positive gain $K_{G}$, which is proportional to the non-fundamental apparent power at the PCC. $S_{v}$, calculated based on IEEE 1459-2010 standards [19], to generate part of the reference signal for voltage control loop ($V_{harm}^{*}$). Finally, $V_{harm}^{*}$ is multiplied by the ratio $\frac{S_{k}}{\sum_{k=1,2} S_{k}}$ to guarantee inverters share load power in proportion to their rated power ($S_{k}$).

Considering the sign of $K_{G}$ and $V_{harm}^{*}$, the harmonic voltage reference is generated at the opposite phase to $V_{PCC}$, which will decrease harmonic distortion of the PCC. As the result, $S_{v}$ will decrease. According to Fig. 5, the final harmonic voltage reference $V_{harm}^{*}$ for inverter $k$ is calculated by:

$$
 V_{harm}^{*} = V_{PCC}^{*} + K_{G} \cdot S_{v} \cdot \frac{S_{k}}{\sum_{k=1,2} S_{k}}
$$
III. CONTROL SYSTEM PARAMETER DETERMINATION

In this paper, a microgrid with two inverters connected in parallel has been adopted as case study. The grid parameters are given in Table I. The rated power of DG1 is half of that of DG2. Once the parameters of DG1 are determined, those of DG2 will be given accordingly [5]. In this paper, since the DG controllers have identical control structure, it is assumed that there is no interaction between two inverters. The time-domain simulation results, partially shown in the following section, also demonstrate this assumption. Therefore, the stability is analyzed for DG2 (with DG1 decoupled), and similar results with DG1 can be achieved. Future research will cover stability analysis in cases when the two DG sets interact (e.g. at dissimilar PV irradiation condition as in [20]).

A. The Voltage and Current Control Loop

The single-phase equivalent diagram of the power circuit of the DG1 in Fig. 1 is presented in Fig. 6. The power stage of the inverter is considered as an equivalent controlled voltage source $v_{in}$.

![Figure 6. Equivalent representation of the power circuit](image)

The dynamic behavior of the system can be represented by a second-order differential equation:

$$LC \frac{d^2 v_o}{dt^2} + R_f C \frac{dv_o}{dt} + V_o + L \frac{di_o}{dt} + R_i i_o = v_{in} \quad (6)$$

Considering only the control part in Fig. 1, the transfer function of the controller is given as:

$$\left[\frac{v_o - V_o}{\alpha} \right] G_o(s) - I_f \right] G(s)G_{ph}(s) + G_{FP}(s)V_o = V_{in} \quad (7)$$

Substituting (6) to (7), and noticing that $sCV_o + I_o = I_f$, we can derive the relationship between voltage and current output of the inverter to the voltage reference, as shown in (8)

$$V_o = V_o G(s) - Z_o(s)I_o \quad (8)$$

where

- $G(s)$ is the closed-loop transfer function of the voltage loop
- $Z_o(s) = Z_o(s) + Z_{ph}(s)$ is inverter output impedance after adding VI loop

$$G(s) = \frac{G_i(s)G(s)G_{ph}(s)}{L_f C_f s^2 + (R_f + G_i(s)G_{ph}(s))C_f + 1 - G_{FP}(s) + G_i(s)G(s)G_{ph}(s)}$$

$$Z_o(s) = \frac{L_f C_f s^2 + (R_f + G_i(s)G_{ph}(s))C_f + 1 - G_{FP}(s) + G_i(s)G(s)G_{ph}(s)}{L_f C_f s^2 + (R_f + G_i(s)G_{ph}(s))C_f + 1 - G_{FP}(s) + G_i(s)G(s)G_{ph}(s)}$$

Hence, the open-loop transfer function of the voltage loop is given as

$$G_{op}(s) = \frac{G_i(s)G(s)G_{ph}(s)}{L_f C_f s^2 + (R_f + G_i(s)G_{ph}(s))C_f s + 1 - G_{FP}(s) + G_i(s)G(s)G_{ph}(s)}$$

$$= \frac{G_i(s)G(s)G_{ph}(s)}{L_f C_f s^2 + (R_f + G_i(s)G_{ph}(s))C_f s + 1 - G_{FP}(s) + G_i(s)G(s)G_{ph}(s)} \quad (9)$$


![Figure 7. Bode diagram of voltage loop](image)

The Bode diagrams of $G_{op}(s)$ and $G(s)$ are presented in Fig. 7 using parameters shown in Table II. It can be seen from Fig. 7 that the voltage loop has high gain at selected frequencies (> 40 dB) which guarantees the steady-state error less than 4%. The phase margin of 41 degrees ensures the system stability as well.

<table>
<thead>
<tr>
<th>TABLE I. POWER SYSTEM PARAMETERS</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Description</strong></td>
</tr>
<tr>
<td>Rated Power</td>
</tr>
<tr>
<td>Inverter-side filter inductance</td>
</tr>
<tr>
<td>Load-side filter inductance</td>
</tr>
<tr>
<td>Filter capacitance</td>
</tr>
<tr>
<td>Damping resistance</td>
</tr>
<tr>
<td>Line impedance (R_{in}, X_{in})</td>
</tr>
</tbody>
</table>

B. Virtual Oscillator Control

Each inverter receives a reference voltage signal from its VOC. Therefore, parameters of VOC have to be chosen in order to satisfy a sufficient condition of synchronization below [6]:

$$L_{in} C_{in} s^2 + (R_{in} + G_{in}(s)G_{ph}(s))C_{in} + 1 - G_{FP}(s) + G_{in}(s)G(s)G_{ph}(s)$$
\[
\max \left| \frac{K_v K_c G(j\omega)^{-1} Z_v(j\omega) Z_{VOC}(j\omega)}{K_v K_c G(j\omega)^{-1} Z_v(j\omega) + Z_{VOC}(j\omega)} \right| < 1
\]  
(11)

where: \( Z_{VOC}(s) = R \| sC \|^{-1} \) in Fig. 2 is the equivalent impedance of the passive circuit. The procedure of VOC parameter selection followed the steps that were extensively described in [9] and are briefly summarized here:

- The scaling factors are set as \( K_v = V_{oc} \), \( K_i = V_{min} \cdot P_{rated}^{-1} \), where \( V_{oc} \) and \( V_{min} \) are maximum, minimum allowable voltage, respectively.
- Based on requirements of ensuring voltage output of inverters is bounded between the safe limits, as the power is varied between 0 and nominal power, \( \sigma \) and \( \alpha \) in (1) is chosen as

\[
\sigma = \frac{V_{oc}}{V_{min}} \frac{V_{oc}^2}{V_{oc}^2 - V_{min}^2}, \quad \alpha = \frac{2\sigma}{3}
\]  
(12)

- The R, L, and C values are selected based on the frequency regulation, rising time, and third harmonic design specifications. Values of L and C also have to satisfy \( \omega_0 = (LC)^{-1} \).
- Repeat the above steps in case voltage and frequency is out of predefined limits when load change from zero to rated value.

IV. SIMULATION RESULTS

The power system under analysis is implemented in Matlab/Simulink. The rated values of phase voltage and frequency are 400 V and 50 Hz, respectively. DG controllers are discretized using the discrete integrator-based method, with a sampling frequency of 10 kHz.

In order to analyze the performance of the proposed control system, two scenarios are examined, each featuring the three modes of operation described below. In the first mode of operation (in the period from 0 to 0.5 second), only conventional VOC controller is activated for synchronization and load sharing, no harmonic compensation is carried out. Then, the PR controller is activated at 0.5 second but the harmonic control unit is not yet active. Finally, the HCU is activated at 1.0 second.

A. Single DG powering a nonlinear load

Fig. 8 shows the THD in percent for the PCC voltage for the three simulation modes. Before activating PR and HCU controller, conventional VOC cannot mitigate voltage distortion at the PCC (THD = 11.01%). With the appearance of PR and HCU in the third period, THD decreases and satisfies the limitation implied in [19] with THD = 4.37%. Fig. 9 compares the harmonic spectrum of the PCC phase voltage for the three modes of operation. It can be observed that harmonics at the selected frequencies are significantly reduced.

B. Two DGs serving a common nonlinear load

In this scenario, the same power system is analyzed with the similar three-mode operation, but in this case two DGs are connected in parallel to supply the load. This scenario is used to investigate and verify the power-sharing performance of the proposed controllers. Fig. 10 shows the THD variation of the PCC and inverter output voltages.

One can see from Fig. 10, that the proposed control method still shows good performance in harmonic reduction, since the THD in modes 2 and 3 are reduced as compared to mode 1. Also, in the third period, it is observed that THD of the DG1 output voltage \( v_C \) is almost half of that of DG2, which implies that the non-fundamental power is shared in proportion to their nominal powers.

It is generally expected that inverters supplying a microgrid share the load proportionally to their power ratings. Fig. 11 has shown that the proposed control method makes this approximately possible also for the case of harmonics, and thus improves conventional VOC controller design.
TABLE II. PARAMETERS OF THE PROPOSED CONTROL SYSTEM

<table>
<thead>
<tr>
<th>VOC Controller</th>
<th>DG 1</th>
<th>DG 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K_v$</td>
<td>242.48</td>
<td>242.48</td>
</tr>
<tr>
<td>$K_r$</td>
<td>0.4388</td>
<td>0.2194</td>
</tr>
<tr>
<td>R-L-C</td>
<td>-0.1641 $\Omega$, 576 mH, 0.1759 F</td>
<td>-0.1641 $\Omega$, 576 mH, 0.1759 F</td>
</tr>
</tbody>
</table>

Proportional – Resonant controller

<table>
<thead>
<tr>
<th>Voltage and Current Loop</th>
<th>STF</th>
<th>HRU</th>
</tr>
</thead>
<tbody>
<tr>
<td>$k_p^v$</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>$k_v^v$</td>
<td>205</td>
<td></td>
</tr>
<tr>
<td>$k_{pin}$</td>
<td>1.9</td>
<td></td>
</tr>
<tr>
<td>$k_n(n = 5, 7, 11, 13)$</td>
<td>150</td>
<td></td>
</tr>
<tr>
<td>$\omega_n(n = 5, 7, 11, 13)$</td>
<td>n*0.6283</td>
<td>K</td>
</tr>
<tr>
<td>$R_v$</td>
<td>0.1 $\Omega$</td>
<td>0.2 $\Omega$</td>
</tr>
<tr>
<td>$L_v$</td>
<td>2 mH</td>
<td>4 mH</td>
</tr>
</tbody>
</table>

V. CONCLUSION

This paper presents a new method for harmonic compensation at the PCC. Together with the basic structure of VOC controller, the proposed method is able to share both fundamental and non-fundamental power between parallel inverters. The simulation results show that the THD at the PCC is significantly reduced, whereas the power-sharing in proportion with nominal power of DGs is guaranteed.

According to our experience, the proposed control method still retains the advantages of the basic VOC controller such as synchronization, voltage and frequency regulation – however, future work has to include a more systematic investigation of these phenomena.

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REFERENCE


