Voltage Quality Improvement in Islanded Microgrids
Supplying Nonlinear Loads

Mohammad T. Dehghani1, Abolfazl Vahedi2, Mehdi Savaghebi3 and Josep M. Guerrero4
1Department of Power Engineering, Saveh Branch, Islamic Azad University, Saveh, Iran
2Center of Excellence for Power System Automation and Operation, Iran University of Science and Technology, Iran
3Department of Electronics Engineering, Karaj Branch, Islamic Azad University, Karaj, Iran
4Institute of Energy Technology, Aalborg University, Denmark
taha.dehghani@yahoo.com, avahedi@iust.ac.ir, savaghebi@kiau.ac.ir, joz@et.aau.dk

Abstract—The aim of this paper is to provide high voltage quality at the terminals of the distributed generators (DGs) in an islanded microgrid. To achieve this goal, it is proposed to include separate voltage and current control loops for fundamental frequency and the main harmonic orders. This way, it will not be necessary to consider additional controllers to provide voltage harmonic compensation. The control system can be maintained very simple and stable. The control system of each DG mainly consists of active and reactive powers droop controllers and voltage and current control loops. The simulation results are provided to demonstrate the proposed control approach.

Index Terms—Distributed generator (DG), microgrid, voltage harmonics.

I. INTRODUCTION

The proliferation of different nonlinear loads in electrical systems has resulted in the voltage harmonic distortion. This distortion can cause variety of problems such as protective relays malfunction, overheating of motors and transformers and failure of power factor correction capacitors [1],[2]. Thus, in different standards some limits are recommended for voltage harmonics, e.g. IEEE Standard 519-1992 [3].

In addition to the conventional harmonic compensation tools such as active power filters, Distributed Generators (DGs) can be applied to provide compensation.

The control approaches presented in [4]-[6] are based on including control loops dedicated to output voltage harmonics compensation in the DG control system. In fact, these control loops are added to compensate shortcoming of inner voltage and current control loops to provide sinusoidal output voltage. These additional control loops will increase the complexity and computational effort of the control system and if not designed properly can make the control system unstable.

In this paper, it is proposed that instead of including additional control loops for harmonic compensation, inner loops are fortified by including separate voltage and current control loops at the fundamental and main harmonic frequencies to improve DG unit output voltage quality.

This idea is applied to voltage quality improvement in an islanded microgrid. Microgrid can be defined as a low voltage grid comprises DGs and loads which can operate in grid-connected (connected to the main grid) and islanded (isolated from the main grid) modes [7].

The control system of each DG mainly consists of droop controllers to share active and reactive powers among DGs and voltage and current control loops.

II. DG CONTROL STRATEGY

The overall configuration of each DG power stage and the proposed controller for each of the DGs is illustrated in Fig.1. The power stage consists of a DC prime mover, an inverter and an LCL filter. All the control loops of Fig.1 are in dq (synchronous) reference frame. Thus, the following park transformations are applied for transforming voltages and currents between abc and dq frames:

\[
X_{abc} = \frac{2}{3} \begin{bmatrix}
\cos \omega t & \cos(\omega t - \frac{2\pi}{3}) & \cos(\omega t + \frac{2\pi}{3}) \\
\sin \omega t & \sin(\omega t - \frac{2\pi}{3}) & \sin(\omega t + \frac{2\pi}{3})
\end{bmatrix} X_{dq}
\]

(1)

\[
X_{abc} = \begin{bmatrix}
\cos \omega t - \frac{2\pi}{3} & \sin \omega t & 0 \\
\cos \omega t - \frac{2\pi}{3} & \sin(\omega t - \frac{2\pi}{3}) & 0 \\
\cos \omega t - \frac{2\pi}{3} & \sin(\omega t + \frac{2\pi}{3}) & 0
\end{bmatrix} X_{qd}
\]

(2)

where \(x\) represents a control variable and \(\omega\) is the microgrid operating frequency which produced based on active power droop controller explained on subsection II.B. The details of the control system are provided in the following subsections.

A. Power calculation

In dq synchronous reference frame, the injected instantaneous active and reactive power components, \(p\) and \(q\), can be calculated as follows [8]:

\[
p = v_{od}i_{od} + v_{oq}i_{oq}
\]

(3)

\[
q = v_{od}i_{oq} + v_{oq}i_{od}
\]

(4)
The average active and reactive powers corresponding to the fundamental components are obtained by means of low pass filters as follows with the cut-off frequency of \( \omega_c \):

\[
P = \frac{\omega_c}{\omega_c + s} P \\
Q = \frac{\omega_c}{\omega_c + s} Q
\]  

(5)  
(6)

B. Active and reactive power control

Considering a DG which is connected to grid through the impedance \( Z \angle \theta \), the active and reactive powers injected to the grid by the DG can be expressed as follows [9]:

\[
P = \left( \frac{\frac{BV}{Z} \cos \varphi - \frac{V^2}{Z}}{\varphi} \right) \cos \theta + \frac{BV}{Z} \sin \varphi \sin \theta \\
Q = \left( \frac{\frac{BV}{Z} \cos \varphi - \frac{V^2}{Z}}{\varphi} \right) \sin \theta + \frac{BV}{Z} \sin \varphi \cos \theta
\]  

(7)  
(8)

where \( V \) is the grid bus voltage amplitude, \( \varphi \) is the power angle, and \( Z \) and \( \theta \) are the magnitude and the phase of the impedance, respectively. Knowing that phase angle of the grid is zero and \( \varphi \) will be equal to inverter voltage phase angle.

Assuming mainly inductive electrical systems, \((Z \approx X \text{ and } \theta \approx 90)\) and considering this fact that \( \varphi \) is usually very small, the following equation can be extracted:

\[
P = \frac{BV}{Z} \varphi \\
Q = \frac{V}{X} (E - V)
\]  

(9)  
(10)

Therefore, active and reactive powers can be controlled by the voltage phase angle and amplitude, respectively. According to this, the following droop controllers are applied for power control [10]:

\[
\omega_0 = \omega_0 - m_P - m_d \frac{dP}{dt} \\
E^* = E_0 - nQ - n_d \frac{dQ}{dt}
\]  

(11)  
(12)

where :
- \( \omega^* \) : frequency reference
- \( E^* \) : voltage amplitude reference
- \( \omega_0 \) : rated frequency
- \( E_0 \) : rated voltage amplitude
- \( m \) : active power droop coefficient
- \( n \) : reactive power droop coefficient
- \( m_d \) : active power derivative coefficient
- \( n_d \) : reactive power derivative coefficient

Fig. 1. DG power stage and control system.
The derivative terms are considered to improve the dynamic performance of power control \[10\]. The power controllers are shown in Fig.1 as active reactive power droop controllers.

C. Voltage and Current controllers

The output of active and reactive power controller, \(\omega^*\) and \(E^*\) are fed to a three-phase voltage generator. The resulted voltage, \(V_{abc}\) in abc reference is fed to a abc/dq transformation which result in reference voltage in dq frame \(V_{dq1}\). In order to control this voltage, a PI controller is used:

\[
I_{dq1}^* = \frac{k_{Pd} V_{dq1} + k_{Iq} L_{dq1}}{s} \times (V_{dq1}^* - V_{dq1})
\]

which \(I_{dq1}^*, V_{dq1}^*, V_{dq1}, k_{Pd}, k_{Iq}\) are reference current in dq frame, reference voltage in dq frame, measured values of fundamental component in dq frame, voltage proportional coefficient and voltage integral coefficient, respectively. Another PI controller is used to control \(I_{dq}\) which is indicated in Fig. 1 as current PI controller. The following equation can be written for fundamental frequency current control:

\[
V_{dq1}^{PWM} = \frac{k_{Pd} I_{dq1} + k_{Iq} L_{dq1}}{s} \times (I_{dq1}^* - I_{dq1})
\]

The parameters of current and voltage PI controllers are listed in Table I.

In order to provide proper control of output voltage harmonics, it is proposed in this paper to consider separate current and voltage PI controllers for 5th and 7th harmonics (main harmonics). The measured output voltage should be transformed to dq reference frame, by using -5\(\omega^*\) and 7\(\omega^*\) as the rotation speeds for 5th and 7th harmonics extraction. Thus, we can have the harmonic voltages of 5th and 7th order, respectively. As shown in Fig. 1, in order to compensate these harmonics, similar PI voltage and current controllers are used, with this difference that the harmonic voltage references are set to zero.

The equations for 5th harmonic voltage and current set control are as follows:

\[
I_{dq5}^* = \frac{k_{Pd} V_{dq5} + k_{Iq} L_{dq5}}{s} \times (0 - V_{dq5})
\]

\[
V_{dq5}^{PWM} = \frac{k_{Pd} I_{dq5} + k_{Iq} L_{dq5}}{s} \times (I_{dq5}^* - I_{dq5})
\]

where, \(V_{dq5}^{PWM}\) reference voltage for PWM and \(k_{Pd}, k_{Iq}\) are voltage proportional, voltage integral, current proportional and current integral coefficients for 5th voltage harmonic compensation, respectively. These equations can be extracted for 7th harmonic voltage control.

As shown in Fig.1, \(V_{dq1}^{PWM}, V_{dq5}^{PWM}\) and \(V_{dq7}^{PWM}\) are transformed to abc frame to generate \(V_{abc1}^{PWM}, V_{abc5}^{PWM}\) and \(V_{abc7}^{PWM}\) which are added together to provide the reference voltage for the PWM block.

III. SIMULATION RESULTS

Fig. 2 shows the two-DG islanded microgrid used as the test system for simulation studies. The control system and power stage parameters are listed in Tables I and II, respectively. As seen in Fig. 2, a linear load (star-connected, \(Z_{L}=25+j0.628\)) and a nonlinear load (diode rectifier which supplies a constant-power resistive load, \(P_{NL}=1000W\)) are considered. As can be seen in Table II, the distribution lines of the DGs are selected with 2/1 ratio in order to simulate an asymmetrical microgrid.

In the simulation studies, two paralleled DG units are supplying the linear load from the beginning. Then, a nonlinear load is connected to the system at \(t = 3s\). In these simulation steps, only voltage and current controllers of fundamental frequency are acting. The, controllers for 5th and 7th harmonic frequencies starts acting from \(t = 5s\).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated frequency</td>
<td>(\omega_0)</td>
<td>100 rad/s</td>
</tr>
<tr>
<td>Rated voltage amplitude</td>
<td>(E_0)</td>
<td>230V</td>
</tr>
<tr>
<td>Active power droop coefficient</td>
<td>(m)</td>
<td>13.3x10^{-6}</td>
</tr>
<tr>
<td>Reactive power droop coefficient</td>
<td>(n)</td>
<td>9.6x10^{-2}</td>
</tr>
<tr>
<td>Active power derivative coefficient</td>
<td>(m_d)</td>
<td>2x10^{-4}</td>
</tr>
<tr>
<td>Reactive power derivative coefficient</td>
<td>(n_d)</td>
<td>2x10^{-3}</td>
</tr>
<tr>
<td>Voltage cont. proportional</td>
<td>(k_p)</td>
<td>13.3x10^{-2}</td>
</tr>
<tr>
<td>Volt cont integral</td>
<td>(k_l)</td>
<td>1.2</td>
</tr>
<tr>
<td>Current cont. proportional</td>
<td>(k_p)</td>
<td>7.5x10^{-2}</td>
</tr>
<tr>
<td>Current cont integral</td>
<td>(k_l)</td>
<td>38.46</td>
</tr>
<tr>
<td>5th harmonic Voltage cont. proportional</td>
<td>(k_p)</td>
<td>48</td>
</tr>
<tr>
<td>5th harmonic Volt cont integral</td>
<td>(k_l)</td>
<td>25x10^{-2}</td>
</tr>
<tr>
<td>7th harmonic Voltage cont. proportional</td>
<td>(k_p)</td>
<td>8x10^{-2}</td>
</tr>
<tr>
<td>7th harmonic Volt cont integral</td>
<td>(k_l)</td>
<td>15.6x10^{-1}</td>
</tr>
<tr>
<td>5th harmonic current cont. proportional</td>
<td>(k_p)</td>
<td>12x10^{-2}</td>
</tr>
<tr>
<td>5th harmonic current cont integral</td>
<td>(k_l)</td>
<td>37.5x10^{-2}</td>
</tr>
<tr>
<td>7th harmonic current cont. proportional</td>
<td>(k_p)</td>
<td>5x10^{-2}</td>
</tr>
<tr>
<td>7th harmonic current cont integral</td>
<td>(k_l)</td>
<td>62.5x10^{-3}</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>DG prime mover</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Inverter filter inductance</td>
<td>(L_i)</td>
<td>3 mH</td>
</tr>
<tr>
<td>Inverter filter capacitance</td>
<td>(C)</td>
<td>25 (\mu F)</td>
</tr>
<tr>
<td>DG1 distribution line</td>
<td>(Z_{L1})</td>
<td>0.1+0.628j</td>
</tr>
<tr>
<td>DG2 distribution line</td>
<td>(Z_{L2})</td>
<td>0.2+1.256j</td>
</tr>
</tbody>
</table>

---

Fig. 2. Test system for simulation studies.
Figs. 3 and 4 show three-phase voltages of DG1 and DG2, respectively. As can be seen in Figs. 3(a) and 4(a), before connection of nonlinear load at $t=3$sec, fundamental frequency voltage and current controllers are able to maintain a good output voltage quality. As can be seen in Fig. 5, total harmonic distortion (THD) of the DGs output voltage before $t=3$sec is about 1%.

Also, according to Figs. 6(a) and 6(b), active and reactive powers are shared properly among microgrid DGs in spite of asymmetrical line impedances. It demonstrates the effectiveness of power droop controllers.

As can be seen in Figs. 3(b), 4(b) and 5, addition of nonlinear load at $t=3$sec makes DGs output voltage noticeably distorted. However, active and reactive power well-sharing is maintained as shown in Fig. 6.

As mentioned before, current and voltage controller for 5th and 7th harmonic frequencies starts acting from $t=5$sec. As demonstrated in Figs. 3(c), 4(c) and 5, the voltage harmonic distortions of both DGs are improved noticeably as a result of harmonic loops activation. Furthermore, active and reactive powers are still shared, properly as can be observed in Fig. 6.

It should be noted that in this paper, harmonic loops are activated at the last simulation step to demonstrate the proposed controller effectiveness. However, in practice harmonic loops are activated form beginning; thus, the transient behavior seen in Figs. 5 and 6 can be avoided.
Fig. 5. THD values of DG1 and DG2.

IV. CONCLUSIONS

A novel structure is proposed for voltage and current controllers of DG units in order to improve voltage quality in an islanded microgrid. The main paper contribution is including separate voltage and current control loops for the main harmonic orders (here, 5th and 7th harmonics) to mitigate DG output voltage harmonic distortion. The presented simulation results show that applying the proposed control approach, the voltage quality can be improved noticeably; while, active and reactive powers are shared properly among the microgrid DGs.

REFERENCES