ANALYSIS AND MITIGATION OF RESONANCE PROPAGATION IN GRID-CONNECTED AND ISLANDING MICROGRIDS BY USING ANN

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Abstract—In this paper, a microgrid resonance propagation model is investigated. To actively mitigate the resonance using DG units, an enhanced DG unit control scheme that uses the concept of virtual impedance is proposed. It can be seen that a conventional voltage-controlled DG unit with an LC filter has a short-circuit feature at the chosen harmonic frequencies, whereas a current-controlled DG unit presents an open-circuit characteristic. Because of completely different behaviors at harmonic frequencies, specific harmonic mitigation methods shall be developed for current-controlled and voltage-controlled DG units, respectively. The application of underground cables and shunt capacitor banks may introduce power distribution system resonances. This paper additionally focuses on developing a voltage-controlled DG unit-based active harmonic damping technique for grid-connected and islanding microgrid systems. An improved virtual impedance control method with a virtual damping resistor and a nonlinear virtual capacitor is proposed. The nonlinear virtual capacitor is used to compensate the harmonic dip on the grid-side inductor of a DG unit LCL filter. Here we are using fuzzy controller compared to other controller due to its accurate performance. The virtual resistance is principally answerable for microgrid resonance damping. The effectiveness of the proposed damping method is examined using each a single DG unit and multiple parallel DG units.

Index Terms—Active power filter, distributed power generation, droop control, grid-connected converter, microgrid, power quality, ANN, renewable energy system, resonance propagation, virtual impedance.

I. INTRODUCTION

The increasing application of nonlinear loads can lead to significant harmonic pollution in a power distribution system. The harmonic distortion might excite complicated resonances, particularly in power systems with underground cables or subsea cables. In fact, these cables with nontrivial parasite shunt capacitance will form an LC ladder network to amplify resonances. In order to mitigate system resonances, damping resistors or passive filters can be placed in the distribution networks. However, the mitigation of resonance propagation exploitation passive components is subject to some well-understood problems, like power loss and additional investment. Moreover, a passive filter might even bring extra resonances if it’s designed or installed without knowing detailed system configurations. To avoid the adoption of passive damping equipment, numerous types of active damping methods are developed.

Among them, the resistive active power filter (R-APF) is often considered as a promising way to understand better performance. In addition, many changed R-APF ideas were additionally developed in the recent literature. Moreover, the operation of multiple R-APFs was also considered, where an interesting droop control was designed to offer autonomous harmonic power sharing ability among parallel R-APFs. On the other hand, renewable energy source (RES) based distributed generation (DG) units are adopted to form flexible microgrids and their interfacing converters even have the chance to address different distribution system power quality problems.

Fig. 1. Simplified one-line diagram of a single-phase microgrid. Simulated results are provided to confirm the validity of the proposed method.

For current-controlled DG units, the auxiliary R-APF function can be seamlessly incorporated into the primary DG real power injection function by modifying the current reference. However, conventional CCM will hardly provide direct voltage support throughout microgrid islanding operation. To beat this limitation, an enhanced voltage-controlled
method (VCM) was recently proposed for dg units with high-order LC or LCL filters. It can be seen that the control method in regulates the dg unit as virtual impedance, that is dependent on the present feeder electric resistance. once the feeder electric resistance is inductive, this method could not provide enough damping effects to system resonance.

II. MODELING OF DG UNITS IN MICROGRID SYSTEM

Fig. 1 illustrates the configuration of a single-phase microgrid system, where a few dg units are interconnected to the point of common coupling (PCC) through an extended underground feeder. This paper also assumes that shunt capacitor banks and parasitic feeder capacitances are equally distributed in the feeder.

Note that the static transfer switch (STS) controls the operation mode of the microgrid. when the most grid is disconnected from the microgrid, the PCC nonlinear loads shall be supplied by the standalone dg units.

A. Distributed Parameter Model in Grid-Tied Operation

For a protracted feeder, as illustrated in Fig. 1, a lumped parameter model isn’t able to describe its resonance propagation characteristics. alternatively, the distributed parameter model was mentioned in [3] and [6], where the voltage distortions at PCC induce a harmonic voltage standing wave on the feeders.

where the kth PCC harmonic voltage is assumed to be stiff and V peck • Vk(x) and Ik(x) square measure the feeder kth harmonic voltage and harmonic current at position x. The length of the feeder is l.

![Fig. 2. Equivalent circuit of a single grid-connected DG unit at the kth harmonic frequency.](image)

It is easy to obtain the harmonic voltage–current standing wave equations at the harmonic order k as

\[ V_k(x) = Ae^{-\gamma x} + Be^{\gamma x} \]  
\[ I_k(x) = \frac{1}{z}(Ae^{-\gamma x} - Be^{\gamma x}) \]  

where A and B are constants, which are determined by feeder boundary conditions. z and γ are the characteristics impedance [3] of the feeder without considering the line resistance as

\[ Z = \sqrt{\frac{L}{C}} \]  
\[ \gamma = jk\omega_f\sqrt{LC} \]  

where \( \omega_f \) is the fundamental angular frequency and L and C are the feeder equivalent inductance and shunt capacitance per kilometer, respectively.

1) DG Units with CCM and R-APF Control: To determine the boundary conditions of the feeder, the equivalent harmonic impedance (ZADk) of the DG unit must be derived. First, the current reference (Iref) of a CCM-based DG unit can be obtained as

\[ I_{ref} = I_{reff} - I_{AD} = I_{reff} - \frac{H(s)\cdot V(l)}{R_V} \]  

where \( I_{reff} \) is the fundamental current reference for DG unit power control, IAD is the harmonic current reference for system resonance compensation, V(l) is the measured installation point voltage at the receiving end of the feeder, HD(s) is the transfer function of a harmonic detector, which extracts the harmonic components of the installation point voltage, and RV is the command virtual resistance.

\[ \omega_{DG} = \omega_f + D_p \cdot (P_{ref} - P_{LPP}) \]  
\[ E_{DG} = E + D_q \cdot (Q_{ref} - Q_{LPP}) + \frac{k}{s} (Q_{ref} - Q_{LPP}) \]  

where \( \omega_f \) and \( \omega_DG \) are the nominal and reference angular frequencies. E and EDG are the nominal and reference DG voltage magnitudes. PLPF and QLPF are the measured power with lowpass filtering. Dp and Dq are the droop slopes of the controller.

To mitigate the harmonic propagation along the feeder as

\[ V_{ref} = V_{reff} - V_{AD} = V_{reff} - R_V \cdot (H_D(s) \cdot I_{DG}) \]  

where \( V_{reff} \) is the fundamental voltage reference derived from droop control in (6) and (7), VAD is the harmonic voltage reference for DG unit harmonic impedance shaping, IDG is the measured DG unit line current (see Fig. 1), HD(s) is the transfer function of a harmonic detector, which extracts the harmonic components of DG unit line current, and RV is the virtual resistance command.
As will be discussed later, the imaginary part of $Z_{ADk}$ may affect the voltage harmonic suppression performance of the system. Since a grid-connected DG unit using either CCM or VCM can be modeled by an equivalent harmonic impedance at the receiving end of the feeder, the following boundary conditions can be obtained:

$$\frac{v_k(1)}{i_k(1)} = Z_{ADk}$$  
$$v_k(0) = V_{PCCk}$$ \tag{9}$$
$$\frac{v_k(1)}{i_k(1)} = Z_{ADk}$$ \tag{10}

By solving (1), (2), (9), and (10), the harmonic voltage propagation at the harmonic order $k$ can be expressed as

$$V(x)_k = \frac{Z_{ADk} \cos b/y(y_0-x) + z \sin b/y(y_0-x)}{Z_{ADk} \cos b/y(y_0-x) + z \sin b/y(y_0-x)} V_{PCCk}. \tag{11}$$

With the obtained equation in (11), the impact of DG active damping scheme to the harmonic voltage propagation along the feeder can be easily analyzed. Note that when the microgrid feeder is purely RL impedance, the DG unit can still work as a virtual harmonic resistor at the end of the feeder. In this case, the DG unit has the capability of absorbing some PCC nonlinear load current if it is designed and controlled properly.

B. Distributed Parameter Model in Islanding Operation

The previous section focuses on the analysis of grid-tied DG units. For an islanding microgrid system, the VCM operation of DG units is needed for direct voltage support. To the best of the authors’ knowledge, the quantitative analysis of islanding microgrid harmonic propagation is not available. When only a single DG unit is placed in the islanding system, constant voltage magnitude and constant frequency (CVMCF) control can be used.

III. EVALUATION OF DAMPING PERFORMANCE

In this section, the performance of VCM-based DG units at different operation modes is investigated.

A. Evaluation of a Single DG Unit at the End of the Feeder

1) Grid-Tied Operation: first, the performance of a grid-tied DG unit with an LCL filter is investigated. The system parameters area unit listed in Table I. Fig. 4 shows harmonic voltage distortions on a 6 kilometer feeder. The harmonic voltage distortion issue here is normalized to the voltage distortions at PCC as $V(x)_k/V_{PCCk}$. when the conventional VCM while not damping.

TABLE I

<table>
<thead>
<tr>
<th>FEEDER PARAMETERS</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Feeder length</td>
<td>6 km</td>
</tr>
<tr>
<td>Number of nodes</td>
<td>7</td>
</tr>
<tr>
<td>Line inductance</td>
<td>1 mH/km</td>
</tr>
<tr>
<td>Capacitance C</td>
<td>20 μF/km</td>
</tr>
<tr>
<td>DG unit parameter</td>
<td>Value</td>
</tr>
<tr>
<td>With LCL filter</td>
<td>$L_1 = 2$ mH, $L_2 = 3.5$ mH, $C_f = 20$ μF</td>
</tr>
<tr>
<td>Command virtual resistance</td>
<td>$RV = 5.5 \omega$</td>
</tr>
</tbody>
</table>
It is seen that the feeder is sensitive to seventh harmonic voltage distortion at the PCC. Once the dg unit is controlled by the changed voltage control reference as shown in (8), it works as an equivalent RL impedance at the receiving end of the feeder. Consequently, the most obvious seventh harmonic voltage propagation is effectively reduced as shown in Fig. 4(c). Once a metric weight unit is coupled to the distribution system with an LC filter, the dg unit is like a harmonic damping resistor by the control scheme in (8). The corresponding performance of the system at different harmonic orders is additionally investigated in Fig. 4. Once a virtual harmonic damping resistor is placed at the end of the feeder, the voltage distortions at different positions of the feeder is nearer to the harmonic voltage content at PCC. Note that for a CCM-based dg unit using the harmonic compensation scheme in (5), the dg unit is additionally like a harmonic resistor at the harmonic frequencies.

Therefore, the obtained waveforms can be used to evaluate the performance of CCM-based DG units in a similar way. 2) Stand-alone Operation: In addition, a DG unit with an LCL filter in a standalone islanding system is also examined. In contrast to the performance during grid-tied operation, the voltage distortion at PCC is not stiff in this case and it is dependent on the harmonic current from the PCC nonlinear loads. As a result, the harmonic voltage amplification factor $V(x)$/$V_{PCC}$ that is used in grid-tied systems is not very appropriate for an islanded system. Alternatively, the feeder harmonic voltage over PCC load harmonic current ($V(x)/V_{Load}$) can be used to describe the harmonic propagation characteristic of the system. The associated harmonic propagation performance is obtained in Fig. 5.

B. Evaluation of Multiple DG Units at the End of the Feeder

The performance of a microgrid with multiple dg units is increasingly discussed in the recent literature. In addition to achieve correct power sharing among multiple dg units, realizing superior harmonic damping performance in a cooperative manner is also attractive. For parallel dg units as shown in Fig. 1, they shall share the active damping current according to their respective power rating [4].

As incontestible, the harmonic damping current of decigram unit one is in-phase with the harmonic voltage at the receiving finish of the feeder. At the same time, this of dg unit two is lagging of the harmonic voltage $V_k(l)$. With unequal current phase angles, harmonic circulating current among dg units is introduced.
The aim of this voltage compensation term is to cancel the harmonic voltage drop on the grid-side LCL filter inductor $L_2$. Once the modified voltage reference in (16) is determined, a high bandwidth voltage controller, such as deadbeat control, $H$-infinity control, and multiple loop control, can be selected to ensure satisfied LCL filter capacitor voltage ($V_C$) tracking. For instance, if a band-stop filter is selected to filter out the fundamental components as

$$H_D(S) = 1 - \frac{2\omega_{BP}S}{S^2 + 2\omega_{BP}S + \omega_f^2}$$

(17)

where $\omega_{BP}$ is the cutoff bandwidth of the band-stop filter, the voltage compensation term $V_{Comp}$ in (16) can be expressed as

$$V_{comp} = S(-L_2).H_D(S)I_{DG} = \left(-sL_2 + \frac{2\omega_{BP}L_2S^2}{S^2 + 2\omega_{BP}S + \omega_f^2}\right).I_{DG}$$

(18)

The diagram of a DG unit with negative virtual inductor control is shown in Fig. 8. As illustrated, the DG unit is interfaced to long feeder with an LCL filter.

**B. Implementation of Nonlinear Virtual Capacitor**

In this subsection, a well-understood double-loop voltage controller is selected for DG unit voltage tracking. In the outer filter capacitor voltage control loop, the proportional and multiple resonant (PR) controllers are used as

$$V_{ref} = G_{outer}(s).V_{ref} - V_C = \left(K_p + \sum_k K_{ik}\frac{2k\omega_{ck}S}{S^2 + 2\omega_{ck}S + (k\omega_f)^2}\right).V_{ref} - V_C$$

(19)

where $K_P$ is the outer loop proportional gain, $K_{ik}$ is the gain of resonant controller at fundamental and selected harmonic frequencies, $\omega_{ck}$ is the cutoff bandwidth, and $I_{inner}$ is the control reference for the inner control loop. In the inner loop controller ($G_{inner}(s)$), a simple proportional controller ($K_{inner}$) is employed and the inverter output current ($I_{inv}$) is measured as the feedback.
Fig. 9. Mitigation of harmonic propagation using virtual resistor and nonlinear virtual capacitor.

By further utilizing the resonant controllers in (19) to avoid the derivative operation, the paper proposes a nonlinear virtual capacitor control method instead of the use of negative virtual inductor. However, for a capacitor with fixed capacitance, its impedance magnitude is inversely proportional to harmonic orders. This feature is in contrast to the characteristics of a virtual inductor. To cancel the impacts of LCL filter grid-side inductor without using derivative operation, a nonlinear virtual capacitor with the following frequency-dependent capacitance is needed:

\[
L_2(\omega f t) - \frac{1}{C_{\text{eq}}(\omega f t)} = 0
\]  

(20)

where \( \omega f \) is the fundamental angular frequency and \( CV_t \) is the command capacitance at the harmonic order. To realize this task, the traditional harmonic detector in (17) can be replaced by a family of selective harmonic separators to extract DG line current harmonic content (IDGt) at each selected harmonic frequency. Afterwards, the voltage drops on the nonlinear virtual capacitor can be obtained as

\[
V_{\text{comp}} = \sum t \frac{1}{sC_{\text{eq}}} \cdot I_{\text{DG}} = \sum t \frac{1}{sC_{\text{eq}}} \cdot (H_D(s) \cdot I_{\text{DG}})
\]

(21)

where \( HD(s) \) is the harmonic detector to detect the \( th \) DG harmonic current IDG.

**TABLE II**

**DG UNIT PARAMETERS**

<table>
<thead>
<tr>
<th>Control Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated voltage</td>
<td>RMS 60 V</td>
</tr>
<tr>
<td>Rated frequency</td>
<td>( f = 44 ) Hz</td>
</tr>
<tr>
<td>Deep coefficients</td>
<td>( D_1 = 1/100, D_2 = 1/300, D_3 = 1/30 )</td>
</tr>
<tr>
<td>Proportional gain</td>
<td>( K_P = 0.31 )</td>
</tr>
<tr>
<td>Resonant gain</td>
<td>( K_I = 10, K_F = 16, K_C = 15, K_G = 15, K_D = 10 )</td>
</tr>
<tr>
<td>Cutoff frequency</td>
<td>( \omega_c = 1 rad/(s) = 3.5, 5, 6.9 )</td>
</tr>
<tr>
<td>Inner loop controller</td>
<td>( K_{\text{inc}} = 20 )</td>
</tr>
<tr>
<td>DC-link voltage</td>
<td>( V_{\text{DC}} = 1000 ) V</td>
</tr>
<tr>
<td>Sampling and switching frequency</td>
<td>12 kHz</td>
</tr>
<tr>
<td>Circuit parameter</td>
<td>Value</td>
</tr>
<tr>
<td>AC filter</td>
<td>( L_1 = 3 mH, L_2 = 3 mH, C_1 = 20 \mu F )</td>
</tr>
<tr>
<td>LC filter</td>
<td>( L_1 = 3 mH, L_2 = 3 mH, C_1 = 20 \mu F, C_2 = 10 \mu F )</td>
</tr>
<tr>
<td>Command virtual resistance</td>
<td>( R_f = 3.5 ) ( \Omega ) (DC unit in Figs. 10-15), ( R_n = 11 ) ( \Omega ) (DG unit and DG unit in Figs. 14 and 15)</td>
</tr>
</tbody>
</table>

**Fig. 10.** Harmonic voltage amplification during a single DG unit grid-connected operation (without damping) [from upper to lower: (a) PCC voltage (THD = 4.0%); (b) node 1 voltage (THD = 4.56%); (c) node 3 voltage (THD = 10.91%); (d) node 5 voltage (THD = 12.59%); (e) DG unit filter capacitor voltage (THD = 0.38%)].

In addition, the regulation of virtual resistor and virtual capacitor mainly focuses on the performance at selected harmonic frequencies. Therefore, parallel harmonic resonant controllers can be utilized to control these virtual impedances. Once the conventional PR controller is separated into two parts, the modified outer loop control scheme is illustrated as follows:

**TABLE III**

**HARMONIC SPECTRUM OF A GRID-CONNECTED MICROGRID WITHOUT ACTIVE DAMPING**

<table>
<thead>
<tr>
<th>Harmonic</th>
<th>1st Harmonic</th>
<th>5th Harmonic</th>
<th>9th Harmonic</th>
<th>11th Harmonic</th>
<th>13th Harmonic</th>
<th>THD</th>
</tr>
</thead>
<tbody>
<tr>
<td>PCC voltage</td>
<td>2.00%</td>
<td>2.00%</td>
<td>2.00%</td>
<td>2.00%</td>
<td>2.00%</td>
<td>0%</td>
</tr>
<tr>
<td>Node 1 voltage</td>
<td>1.81%</td>
<td>2.14%</td>
<td>2.00%</td>
<td>1.93%</td>
<td>0.93%</td>
<td>0.65%</td>
</tr>
<tr>
<td>Node 3 voltage</td>
<td>1.84%</td>
<td>2.25%</td>
<td>2.56%</td>
<td>2.58%</td>
<td>1.80%</td>
<td>0.80%</td>
</tr>
<tr>
<td>Node 5 voltage</td>
<td>1.84%</td>
<td>2.76%</td>
<td>2.76%</td>
<td>2.56%</td>
<td>2.56%</td>
<td>1.39%</td>
</tr>
<tr>
<td>DG voltage</td>
<td>0.84%</td>
<td>0.84%</td>
<td>0.84%</td>
<td>0.84%</td>
<td>0.84%</td>
<td>0.2%</td>
</tr>
</tbody>
</table>

**Fig. 11.** Harmonic voltage amplification during a single DG unit grid-connected operation (with virtual nonlinear capacitor and resistor based active damping) [from upper to lower: (a) PCC voltage (THD = 4.0%); (b) node 1 voltage (THD = 4.1%); (c) node 3 voltage (THD = 3.7%); (d) node 5 voltage (THD = 3.2%); and (e) DG unit filter capacitor voltage (THD = 5.4%)].
ANN

Introduction

In the last few decades, as the chemists have got accustomed to the use of computers and consequently to the implementation of different complex statistical methods, they are trying to explore multi-variate correlations between the output and input variables more and more in detail. With the increasing accuracy and precision of analytical measuring methods it becomes clear that all effects that are of interest cannot be described by simple uni-variate and even not by the linear multivariate correlations precise, a set of methods, that have recently found very intensive use among chemists are the artificial neural networks (or ANNs for short).

Therefore, the analytical chemists are always eager to try all new methods that are available to solve such problems. One of the methods, or to say more Due to the fact that this is not one, but several different methods featuring a wide variety of different architectures learning strategies and applications.

![Image](Fig 12. Neural network as a black-box featuring the non-linear relationship between the multivariate input variables and multi-variate responses)

BASIC CONCEPTS OF ANNS

Now we will briefly discuss the basic concepts of ANNs. It is wise to keep in mind that in the phrase 'neural network' the emphasise is on the word 'network' rather than on the word 'neural'. The meaning of this remark is that the way how the 'artificial neurons' are connected or networked together is much more important than the way how each neuron performs its simple operation for which it is designed for.

Artificial neuron is supposed to mimic the action of a biological neuron, i.e., to accept many different signals, $x_i$, from many neighbouring neurons and to process them in a pre-defined simple way. Depending on the outcome of this processing, the neuron $j$ decides either to fire an output signal $y_j$ or not. The output signal (if it is triggered) can be either 0 or 1, or can have any real value between 0 and 1 (Fig. 2) depending on whether we are dealing with 'binary' or with 'real valued' artificial neurons, respectively.

The first function is a linear combination of the input variables, $x_1 , x_2, ... x_i, ... x_m$, multiplied with the coefficients, $w_{ji}$, called 'weights', while the second function serves as a 'transfer function' because it 'transfers' the signal(s) through the neuron's axon to the other neurons' dendrites. Here, we shall show now how the output, $y_j$, on the $j$-th neuron is calculated. First, the net input is calculated according to equation:

$$Net_j = \sum_{i=1}^{m} w_{ji}x_i$$  \hspace{1cm} (22)

$$y_j = \text{out}_j = \frac{1}{1 + \exp[-a_j(Net_j + \theta_j)]}$$ \hspace{1cm} (23)

The weights $w_{ji}$ in the artificial neurons are the analogues to the real neural synapse strengths between the axons firing the signals.

![Image](Figure 13. Comparison between the biological and artificial neuron. The circle mimicking the neuron's cell body represents simple mathematical procedure that makes one output signal $y_j$ from the set input signals represented by the multi-variate vector $X$.)

Some possible forms for the transfer function are plotted in Figure 3. It is important to understand that the form of the transfer function, once it is chosen, is used for all neurons in the network, regardless of where they are placed or how they are connected with other neurons. What changes during the learning or training is not the function, but the weights and the function parameters that control the position of the threshold value, $q_j$, and the slope of the transfer function.
Figure 14. Three different transfer functions: a threshold (a), a sigmoidal (b) and a radial function (c). The parameter $q_j$ in all three functions decides the $Net_j$ value around which the neuron is most selective. The other parameter, $a_j$ seen in equations (1) and (2) affects the slope of the transfer function (not applicable in case a).

$$u_j = a_j(Net_j + \theta_j) = \sum_{i=1}^{n} a_i w_{ij} x_i + a_j \theta_j$$  (24)

$$= a_i w_{ijx_1} + a_j w_{ijx_2} + \cdots + a_j w_{ijx_i} + \cdots + a_j w_{ijx_m} + a_j \theta_j$$  (25)

Therefore, Figure 4 shows actually a 2-layer and a 3-layer networks with the input layer being inactive. The reader should be careful when reading the literature on ANNs because authors sometimes actually refer to the above ANNs as to the twoand three-layer ones. We shall regard only the active layer of neurons as actual layer and will therefore name this networks as one and two-layer ANNs.

Figure 15. One-layer (left) and two-layer (right) ANNs. The ANNs shown can be applied to solve a 3-variable input 4-responses output problem.

APPLICATIONS

In a short introduction to the ANNs in which only few most often used architectures and techniques have been briefly discussed, it is not possible to give even an overview on the possibilities the ANNs are offering to the chemists. The number of scientific papers using ANNs in various areas and for solving different problems in chemistry is growing rapidly (1,2). In this paragraph only one example (11) in which error-back-propagation and Kohonen ANN techniques will be used. Because the counter-propagation method is similar to that of Kohonen, it will not be discussed here. The reader can than choose the explained techniques at his or hers own needs.

For making good prediction about classes a training set that will cover the measurement space as evenly as possible is needed. Therefore, we have selected from each labelled (tagged) neuron only one object (analysed oil sample). The reasoning was the following: if two different objects excite the same neuron, they must be extremely similar, hence it is no use to employ both of them for making a model. For such purpose it is better to select those objects that excite as many different neurons as possible. After making selection of 237 objects we supplement them with 13 more samples from different origins to approximately balance the presence of oils from all regions. In this way 250 oil samples were selected for the training set. The rest of 322 objects was used as a test set.

V. VERIFICATION RESULTS

Simulated results have been obtained from a single-phase low voltage microgrid. To emulate the behavior of six kilometers feeder with distributed parameters, a DG unit with an LCL filter is connected to PCC through a ladder network with six identical LC filter units.

A. Single DG Unit Grid-Tied Operation

Fig. 16. Harmonic voltage amplification during a single DG unit islanding operation (without damping) [from upper to lower: (a) PCC voltage (THD = 15.2%); (b) node 1 voltage (THD = 14.7%); (c) node 3 voltage (THD = 11.9%); (d) node 5 voltage (THD = 10.5%); and (e) DG unit filter capacitor voltage (THD = 1.6%)].

TABLE V

<table>
<thead>
<tr>
<th>Harmonic SPECTRUM OF AN ISLANDING MICROGRID WITHOUT ACTIVE DAMPING</th>
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<tbody>
<tr>
<td>Harmonic</td>
</tr>
<tr>
<td>----------</td>
</tr>
<tr>
<td>3rd harmonic</td>
</tr>
<tr>
<td>5th harmonic</td>
</tr>
<tr>
<td>7th harmonic</td>
</tr>
<tr>
<td>9th harmonic</td>
</tr>
<tr>
<td>11th harmonic</td>
</tr>
<tr>
<td>13th harmonic</td>
</tr>
</tbody>
</table>
B. Single DG Unit Islanding Operation

In addition to grid-connected operation, the performance of a single DG unit in islanding operation is also investigated. In this case, the PCC load is a single-phase diode rectifier and it is supplied by the DG unit through long feeder. When the conventional VCM without damping is adopted, the performance of the system is obtained in Fig. 12. Similar to the grid-tied operation, the voltage waveforms at PCC, nodes 1, 3, and 5, and DG unit filter capacitor are shown from channels (a) to (e), respectively.

C. Multiple DG Units Grid-Tied Operation

To verify the circulating harmonic current between multiple DG units, two grid-connected DG units at the same power rating are placed at the receiving end of the feeder.

VI. CONCLUSION

In this paper, the impacts of voltage-controlled and current-controlled distributed generation (DG) units to microgrid resonance propagation are compared. To actively mitigate the resonance using DG units, an enhanced DG unit component of the proposed nonlinear virtual impedance is employed to compensate the impact of dg unit LCL filter grid-side inductor. The resistive element is responsible for active damping. With properly controlled dg equivalent harmonic impedance at chosen harmonic frequencies, the proposed method can even eliminate the harmonic circulating current among multiple dg units with mismatched output filter parameters. Here we are using the fuzzy controller compared to other controllers due to its accurate performance. Comprehensive simulations are conducted to substantiate the validity of the proposed method.

REFERENCES


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