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Abstract—This paper first derives a usable formula based on the parallel $R, L, C$ load and the conclusions from frequency shift islanding detection methods in current literature: the angle by which the total output current of the distributed resources (DR) units leads the point of common coupling (PCC) voltage must be conducted to have the same shifting direction as the load admittance angle during the variation of the frequency. On the basis of the formula and multi-DR operation, the scenarios in which the classic frequency shift methods are applied to energy storage converters are analyzed. The results indicate that the setting of the angle by which the energy storage converter current leads the PCC voltage may need to be modified when running state changes. It results in the problems that the classic methods are not applicable for non-UPF (unity power factor) control and have to distinguish between generation mode and consumption mode for UPF control. On account of the problems, a coping strategy, i.e. an improved method, is proposed. The analyses indicate that the improved method is applicable in every state. The last simulations and experiments confirm the preceding conclusions.

Index terms—consumption mode, energy storage converter, frequency shift, islanding detection, microgrid, multi-DR, reactive current perturbation

NOMENCLATURE

DR distributed resources

PCC point of common coupling

$R, L, C$ effective load resistance, inductance and capacitance

in an island

SFS Sandia Frequency Shift

SMS Slip-Mode Frequency Shift

UPF unity power factor

$f$ PCC frequency

$f_g$ nominal frequency of a power grid

$\mathbf{I}_c$ total currents vector of the DR units

$\mathbf{I}_{con}$ output current vector of the energy storage converter

$\mathbf{i}_{con}$ active current reference value

$I_A$ amplitude of the rated current of the energy storage converter

$\mathbf{I}_{inv}$ output current vector of the inverter

$i_{invq}$ projection of $\mathbf{I}_{inv}$ on the q-axis

$I_p$ gain of the perturbation

$i_{per}$ reactive current perturbation

$i_{qref}$ reactive current reference value

$P$ load active power (per-unit)

$P_{con}$ energy storage converter output active power

$P_{ql}$ load inductive reactive power (per-unit)

$P_{inv}$ inverter output active power

$Q_{con}$ energy storage converter output reactive power

$Q_l$ load quality factor

$Q_{inv}$ inverter output reactive power

$U_{PCC}$ voltage vector at PCC
θ₀ angle expected by control system

θ₀ reference angle by which the total output current of DR units leads the PCC voltage

θ_{con} angle by which \( \dot{i}_{con} \) leads \( \dot{U}_{PCC} \)

θₐ perturbing angle in the improved method

θ₇ perturbing angle in the classic methods

θ₈ load admittance angle

I. INTRODUCTION

Islanding detection has attracted much research since it was first introduced. The detection methods aimed at it include remote schemes and local schemes, the latter of which are divided into passive methods and active methods. The active methods have received more attention due to their advantages in expense and performance. Two famous ones are Sandia Frequency Shift (SFS) and Slip-Mode Frequency Shift (SMS), which belong to frequency shift methods and have been the classic active islanding detection methods up to the present day [1]-[6]. In addition, [7] and [8] proposed two methods based on the relationships between reactive power and frequency; [9] and [10] added a reactive power perturbation on the basis of SMS and SFS; [11] proposed a method based on a relationship between active power and voltage; [12] proposed the concept of perturbing reactive current, and [13]-[15] realized and tested it. Although new methods are constantly emerging, SFS and SMS are still being widely used. Hence, this paper focuses on these two classic methods.

The classic methods can function well in single-DR (distributed resources) operation. However, obviously, they are more commonly utilized in multi-DR operation where some problems may emerge. [16] shows the interactions between different frequency shift methods in multi-DR operation. [17] and [18] reveal the interactions between SFS methods and propose a technique to reduce the non-detection zone. However, the scenarios in consumption mode are rarely discussed [19][20].

On the basis of multi-DR operation, this paper analyzes different running states, including that in consumption mode. Through the analyses it can be found that the classic methods have significant problems on parameter setting, even without considering the interactions between them, which results in such methods not applicable for non-UPF (unity power factor) control and having to distinguish between generation mode and consumption mode for UPF control. This paper will center on the problems.

This paper is organized as follows. In section II, a usable formula for frequency shift methods is proposed. Section III analyzes several scenarios and finds the problems of the classic methods according to the formula. In view of the problems, a coping strategy, i.e. an improved method, is proposed in section IV. Section V and section VI verify the previous analyses by simulations and experiments, respectively. Section VII draws a conclusion for this paper.

II. A USABLE FORMULA FOR FREQUENCY SHIFT METHODS

Parallel \( R, L, C \) load is the test model in IEEE Std 1547.1-2005 [21]. Hence, it is the default load in this paper. Fig. 1 shows a diagram of the Multi-DR operation. In some areas, especially where a microgrid has been constructed, both generation facilities (e.g. inverters) and storage facilities (e.g. energy storage converters) are equipped [22][23], and this is the situation that will be discussed in this paper.

![Fig. 1. Multi-DR operation](image)

References [24] and [25] have indicated that if (1) is satisfied in an island condition, the frequency at the point of common coupling (PCC) will continuously change.

\[
d\theta_c/df > d\theta_L/df
\]

where \( \theta_c \) represents the reference angle by which the total output current of DR units (i.e. \( \dot{i}_c \)) leads the PCC voltage (i.e. \( \dot{U}_{PCC} \)), so that it is different from the actual angle in an island condition, and \( \theta_L \) represents the load admittance angle.

References [26] and [24] have pointed out that if the DR units reaches a new steady state in an island condition, (2), which is called the phase criterion, will be satisfied.

\[
\theta_c = \theta_L
\]

By uniting (1) and (2), (3) can be established on a steady state of an island, i.e. a necessary condition for the frequency stabilization.

\[
\begin{align*}
\theta_c &= \theta_L \\
\frac{d\theta_c}{df} &< \frac{d\theta_L}{df}
\end{align*}
\]

Frequency shift methods are there to make \( f \) deviate from the limits in an island condition. In (3), \( \theta_c \) can be controlled by DRs, thus, so long as \( \theta_c \) does not satisfy (3), \( f \) will continuously change up to deviating from the limits. Specifically, at least one of (1) and (4) must be ensured for a frequency shift method.

\[
\theta_c \neq \theta_L
\]

With regard to parallel \( R, L, C \) load, \( \theta_L \) is
\[ \theta_L = \arctan[R(2\pi fC - \frac{1}{2\pi fL})]. \]

The derivative of \( \theta_L \) is

\[ \frac{d\theta_L}{df} = \frac{2\pi RC + \frac{R}{2\pi fL^2}}{1 + R^2(2\pi fC - \frac{1}{2\pi fL})^2} \]

There is \( d\theta_L/df \geq 0 \). For satisfying (1), (5) is necessary.

\[ d\theta_L/df > 0 \quad (5) \]

For parallel \( R, L, C \) load, \( \theta_L \) may spontaneously move towards \( \theta_L \) when an island is present, otherwise \( f \) cannot tend to stabilization since (2) cannot be satisfied. Then if \( \theta_L \) is shifted in the same direction as \( \theta_L \) during \( f \) variation to meet (4), \( f \) will continuously change. This is an intuitive statement of why (5) is necessary. Although (5) cannot completely ensure (1), it points out the sign of \( d\theta_L/df \), which is important for the analyses below. As regards the size of \( d\theta_L/df \), [24] and [25] have presented the design criteria which aim at completely satisfying (1). Then, a usable formula can be derived: \( \theta_L \) must have the same shifting direction as \( \theta_L \) during the frequency variation. Due to \( d\theta_L/df \geq 0 \), (5) just reflects the formula.

III. THE CLASSIC FREQUENCY SHIFT METHODS APPLIED TO ENERGY STORAGE CONVERTERS ON THE BASIS OF THE USABLE FORMULA

This section will introduce the mentioned formula into the classic methods which are employed by the energy storage converter [1]. In power matching or near matching conditions islanding detection is difficult, thus it is more meaningful to analyze an islanding detection method in such conditions. The total active power of the DR units is appointed to be positive, so that the load power may be matched. The inverter operates in generation mode, whereas the energy storage converter can operate in generation mode or consumption mode. In fact, even if the inverter operates in consumption mode, the last conclusions can still be obtained as long as the total output active power of the DR units is positive. To simplify the analyses and stress a focal point, this paper assumes that only the energy storage converter takes charge of islanding detection, which will not affect the final conclusion.

A. UPF Control

1) Generation mode

Fig. 2. shows a vector diagram of currents and voltage of the DR units in the d-q synchronous reference frame in an island condition.

According to (5), there is

\[ d\theta_L/d\theta_{\text{con}} \cdot d\theta_{\text{con}}/df > 0 \quad (6) \]

where \( \theta_{\text{con}} \) represents the angle by which \( \dot{I}_{\text{con}} \) leads \( \dot{U}_{\text{PCC}} \) and can be controlled by the energy storage converter.

As shown in Fig. 2, if \( \theta_{\text{con}} \) is slightly perturbed by implementing the classic methods, there is

\[ d\theta_L/d\theta_{\text{con}} > 0 \]

According to (6), the following relationship is required.

\[ d\theta_{\text{con}}/df > 0 \quad (7) \]

In other words, for the classic methods, in order to comply with the mentioned formula \( \theta_{\text{con}} \) must be set as (7).

2) Consumption mode

As shown in Fig. 3, in the same way, if \( \theta_{\text{con}} \) is slightly perturbed, there is

\[ d\theta_L/d\theta_{\text{con}} < 0 \]

According to (6), the following relationship is required.

\[ d\theta_{\text{con}}/df < 0 \quad (8) \]

Thus, \( \theta_{\text{con}} \) must be set as (8).

B. Non-UPF Control

With the increase of the penetration of distributed generation, some further capabilities are required, such as providing an ancillary service, which needs dispatching reactive power. Accordingly, the DR units may be utilized to satisfy the reactive power requirement [27]-[32]. The following part will analyze the DR units operating in non-UPF control.

1) Generation mode

Fig. 4 shows two vector diagrams in an island condition. The classic methods, in fact, carry out an inverse Givens transformation of the reference currents, shown as (9) [1]. If \( f \)
varies, the phase of $I_{\text{con}}$ will change while the amplitude will not, so that the end point of $I_{\text{c}}$ will slip on the arc shown in Fig. 4 when $f$ varies.

$$\begin{pmatrix} i_d^* \\ i_q^* \end{pmatrix} = \begin{pmatrix} \cos \theta_t & -\sin \theta_t \\ \sin \theta_t & \cos \theta_t \end{pmatrix} \begin{pmatrix} i_{\text{ref}} \\ i_{\text{qref}} \end{pmatrix}$$  \hspace{1cm} (9)

Fig. 4. Vector diagrams in generation mode and non-UPF control. (a) $|i_{\text{invq}}| > I_{\text{con}}$, (b) $|i_{\text{invq}}| \leq I_{\text{con}} \leq I_{\text{inv}}$.

Fig. 4(a) shows the scenario that $|i_{\text{invq}}| > I_{\text{con}}$, where $i_{\text{invq}}$ is the projection of $I_{\text{inv}}$ on the $q$-axis. Point $B$ is the tangent point on the circle relative to the origin (the same as below).

When the end point of $I_{\text{c}}$ is on $AB$, there is

$$d\theta_c/d\theta_{\text{con}} < 0$$

According to (6), it can be derived that $\theta_{\text{con}}$ must be set as (8).

When the end point of $I_{\text{c}}$ is on $BC$, as above, $\theta_{\text{con}}$ must be set as (7).

The scenario shown in Fig. 4(b) can be analyzed in the same way. The conclusions are summarized in Table I.

<table>
<thead>
<tr>
<th>$\theta_{\text{con}}$</th>
<th>Fig. 4(a)</th>
<th>Fig. 4(b)</th>
<th>Fig. 5(a)</th>
<th>Fig. 5(b)</th>
<th>Fig. 5(c)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Set as (7) BC Entire arc</td>
<td>$B_1C$ Entire arc</td>
<td>$B_1C$</td>
<td>Entire arc (on the right of the $q$-axis)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Set as (8) AB</td>
<td>$B_2C$</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

2) Consumption mode

Fig. 5 shows three vector diagrams in an island condition.

As above, the conclusions are also summarized in Table I.

Fig. 5. Vector diagram in consumption mode and non-UPF control. (a) $|i_{\text{invq}}| > I_{\text{con}}$, (b) $|i_{\text{invq}}| \leq I_{\text{con}} \leq I_{\text{inv}}$, (c) $I_{\text{inv}} < I_{\text{con}}$.

For the classic methods, it can be seen from the above analyses that in non-UPF control the setting requirements of $\theta_{\text{con}}$ are not consistent, which requires the energy storage converter to get the location of the end point of $I_{\text{c}}$. Unfortunately, due to the randomness of the occurrence time and region of the island, it is impossible to satisfy the requirement for any local system. That is the problem. Consequently, the classic methods are practicable only in UPF control, and even then, the energy storage converter has to distinguish between generation mode and consumption mode. The next subsection will contribute a modified scheme for consumption mode.

C. A Modified Schemes for $d\theta_{\text{con}}/df < 0$

According to the previous conclusions, once the classic frequency shift methods are employed in consumption mode and UPF control, $\theta_{\text{con}}$ must be set as $d\theta_{\text{con}}/df < 0$. The modified schemes to satisfy $d\theta_{\text{con}}/df < 0$ are demonstrated below.

For the classic methods, $\theta_{\text{con}}$ can also be represented as [1][33]

$$\theta_{\text{con}} = \theta_0 + \theta_f$$

where $\theta_0$ represents the angle expected by the control system.
and is independent of \( f \), whereas the perturbing angle \( \theta_\text{f} \) is a function of \( f \). Then the relationship below can be derived.

\[
d\theta_\text{cool}/df = d\theta/df
\]

Therefore, \( d\theta/df > 0 \) must be maintained in generation mode, and in consumption mode \( d\theta_\text{cool}/df < 0 \) can be realized by modifying \( \theta_\text{f} \) as the negative value of its equivalent in generation mode, i.e. \( -\theta_\text{f} \).

### IV. COPING STRATEGY—AN IMPROVED METHOD

#### A. The Principles and Applications of the Improved Method

Compared with the classic methods, the improved method replaces phase angle perturbation with reactive current perturbation. Its implementation scheme is shown in Fig. 6.

![Fig. 6. Block diagrams of the improved method. (a) Constant power control. (b) Constant current control](image)

The reactive current perturbation in Fig. 6 is

\[
i_{\text{per}} = I_p \tan \theta_\text{d}
\]

where \( \theta_\text{d} \) represents the perturbing angle and is related to \( f \). To decouple the active and reactive current control and enhance the effectiveness of the perturbation, \( I_p \) can be set as below:

Constant power control,

\[
I_p = I_{\text{IA}}
\]

Constant current control,

\[
I_p = I_{\text{IA}}
\]

where \( I_{\text{IA}} \) and \( i_{\text{def}} \) represent the amplitude of the rated current of the energy storage converter and the active current reference value, respectively.

In contrast with the classic methods, the improved method does not perturb the active current, and there is little coupling between the active and reactive current control. In addition, the improved method transforms the phase angle perturbation (i.e. \( \theta_\text{d} \)) into its equivalent reactive current perturbation (i.e. \( i_{\text{per}} \)), by which the parameter of the classic methods can be referred, e.g. setting \( \theta_\text{d}=\theta_\text{f} \). At this point it is simpler than some similar methods [13]-[15]. Next, the scenarios for which this method is applied to the energy storage converter will be analyzed.

If the improved method is employed in UPF control, the conclusions are the same as that in section III-A. In non-UPF control, as shown in Fig. 4 and Fig. 5, if \( f \) varies, the phase of \( \dot{I}_\text{con} \) will change while the projection of \( \dot{I}_\text{con} \) on the d-axis (i.e. active current) will not, so that the end point of \( \dot{I}_\text{c} \) will slip on the lines parallel to the q-axis when \( f \) varies.

As shown in Fig. 4, in generation mode the relationship below is always established.

\[
d\theta_\text{c}/df > 0
\]

According to (6), \( \theta_\text{con} \) must be set as (7).

As shown in Fig. 5, in consumption mode, as above, \( \theta_\text{con} \) must be set as (8).

The specific conclusions on the setting of \( \theta_\text{con} \) are summed up in Table II.

<table>
<thead>
<tr>
<th>Conditions</th>
<th>UPF control</th>
<th>Non-UPF control</th>
</tr>
</thead>
<tbody>
<tr>
<td>Generation mode, the classic methods</td>
<td>( d\theta_\text{cool}/df &gt; 0 ) or ( d\theta_\text{cool}/df &lt; 0 ) (Depend on ( I_c ))</td>
<td>( d\theta_\text{cool}/df &lt; 0 ) or ( d\theta_\text{cool}/df &gt; 0 ) (Depend on ( I_c ))</td>
</tr>
<tr>
<td>Consumption mode, the classic methods</td>
<td>( d\theta_\text{cool}/df &lt; 0 ) or ( d\theta_\text{cool}/df &lt; 0 ) (Depend on ( I_c ))</td>
<td>( d\theta_\text{cool}/df &lt; 0 ) or ( d\theta_\text{cool}/df &gt; 0 ) (Depend on ( I_c ))</td>
</tr>
<tr>
<td>Generation mode, the improved method</td>
<td>( d\theta_\text{cool}/df &gt; 0 )</td>
<td>( d\theta_\text{cool}/df &lt; 0 )</td>
</tr>
<tr>
<td>Consumption mode, the improved method</td>
<td>( d\theta_\text{cool}/df &lt; 0 )</td>
<td>( d\theta_\text{cool}/df &lt; 0 )</td>
</tr>
</tbody>
</table>

#### B. The Specific Scheme Aiming at the Setting of \( d\theta_\text{con}/df \)

For the improved method there is
\[
d\theta_{\text{con}}/df = d\theta_{\text{con}}/d(i_{\text{qref}}+i_{\text{per}}) \cdot di_{\text{per}}/df \quad (11)
\]

where \(i_{\text{qref}}\) and \(i_{\text{qref}}+i_{\text{per}}\) represent the reactive current reference value and the projection of \(I_{\text{con}}\) on the q-axis (i.e. reactive current), respectively. Since \(i_{\text{qref}}\) is independent of \(f\), (11) can also be written as

\[
d\theta_{\text{con}}/df = d\theta_{\text{con}}/d(i_{\text{qref}}+i_{\text{per}}) \cdot di_{\text{per}}/df. \quad (12)
\]

As shown in Fig. 2 and Fig. 4, in generation mode there is

\[
d\theta_{\text{con}}/df = d\theta_{\text{con}}/d(i_{\text{qref}}+i_{\text{per}}) > 0.
\]

According to (12), it can be derived that

\[
d\theta_{\text{con}}/df > 0 \iff di_{\text{per}}/df > 0.
\]

In the same way, as shown in Fig. 3 and Fig. 5, in consumption mode there is

\[
d\theta_{\text{con}}/df < 0 \iff di_{\text{per}}/df > 0.
\]

Thus, (13) must be satisfied whether in generation mode or in consumption mode.

\[
di_{\text{per}}/df > 0 \quad (13)
\]

According to (10), (13) is equivalent to (14).

\[
d\theta_{f}/df > 0 \quad (14)
\]

Therefore, the setting of \(\theta_{\text{con}}\) can be achieved as long as (14) is satisfied and there is no need to distinguish the running states. In other words, the improved method proposed in this paper is applicable in every state. Compared with the mentioned classic methods, the improved method has obvious advantages.

V. SIMULATIONS

The simulations performed on Matlab/Simulink are based on a 220 V/50 Hz single-phase source. The simulation circuit is shown in Fig. 7, where there is a 9 kVA energy storage converter and an inverter connected to the source. Only the energy storage converter implements the islanding detection method. SFS and the improved method will be employed in the following simulations and experiments.

<table>
<thead>
<tr>
<th>Cases</th>
<th>(P_{\text{con}}) (W)</th>
<th>(Q_{\text{con}}) (Var)</th>
<th>(P_{\text{inv}}) (W)</th>
<th>(Q_{\text{inv}}) (Var)</th>
<th>Corresponding state</th>
</tr>
</thead>
<tbody>
<tr>
<td>UPF, generation mode</td>
<td>2500</td>
<td>0</td>
<td>2500</td>
<td>0</td>
<td>Fig. 2</td>
</tr>
<tr>
<td>UPF, consumption mode</td>
<td>-2500</td>
<td>0</td>
<td>7500</td>
<td>0</td>
<td>Fig. 3</td>
</tr>
<tr>
<td>Non-UPF, generation mode</td>
<td>2000</td>
<td>2000</td>
<td>3000</td>
<td>4000</td>
<td>BC of Fig. 4(a)</td>
</tr>
<tr>
<td>(The 1st group)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Non-UPF, consumption mode</td>
<td>-5000</td>
<td>1000</td>
<td>10000</td>
<td>5000</td>
<td>B1, B2 of Fig. 5(b)</td>
</tr>
<tr>
<td>(The 1st group)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
**Non-UPF, generation mode** (The 2nd group)

| 1000 | -3000 | 4000 | 9000 | AB of Fig. 4(a) |

**Non-UPF, consumption mode** (The 2nd group)

| -1000 | 5000  | 6000 | 1000 | BC of Fig. 5(b) |

\( P_{con} \) and \( Q_{con} \) represent the energy storage converter active power and reactive power, respectively, while \( P_{inv} \) and \( Q_{inv} \) represent the inverter active power and reactive power, respectively.

### A. UPF Control

Load parameters: \( R = 9.68 \Omega, L = 12.3 \text{ mH}, C = 0.822 \text{ mF} \).

The results are shown in Fig. 8, where curves \( f_1 - f_3 \) and \( f_4 - f_6 \) are obtained in generation mode and consumption mode, respectively. \( f_1 \) and \( f_4 \) correspond to the improved method; \( f_2 \) and \( f_5 \) correspond to the SFS method with \( \frac{d}{df} \theta_{con} > 0 \), whereas \( f_3 \) and \( f_6 \) correspond to \( \frac{d}{df} \theta_{con} < 0 \) (the same below).

**Fig. 8.** Frequency waveforms in UPF control.

\( f_1 \): the improved method in generation mode; \( f_2 \): SFS in generation mode with \( \frac{d}{df} \theta_{con} > 0 \); \( f_3 \): SFS in generation mode with \( \frac{d}{df} \theta_{con} < 0 \); \( f_4 \): the improved method in consumption mode; \( f_5 \): SFS in consumption mode with \( \frac{d}{df} \theta_{con} > 0 \); \( f_6 \): SFS in consumption mode with \( \frac{d}{df} \theta_{con} < 0 \) (the same as below).

### B. Non-UPF Control

Load parameters: \( R = 9.68 \Omega, L = 9.72 \text{ mH}, C = 0.648 \text{ mF} \).

The results of the 1st group cases and the 2nd group cases are shown in Fig. 9 and Fig. 10, respectively.

**Fig. 9.** The 1st group frequency waveforms in non-UPF control.

**Fig. 10.** The 2nd group frequency waveforms in non-UPF control.

The above simulations confirm the statements in Table II, and demonstrate the universality of the improved method.

### C. IEEE Std 1547.1 Testing for the Improved Method

To further evaluate the improved method, this subsection shows six cases with longer trip times, listed in Table IV, which are based on IEEE Std 1547.1. The differences with the above simulations are that only the energy storage converter operates (i.e. single-DR operation) and the island condition is present at 0.35 s.

<table>
<thead>
<tr>
<th>Cases</th>
<th>( P(%) )</th>
<th>( P_{sl}(%) )</th>
<th>( R(\Omega) )</th>
<th>( L(\text{mH}) )</th>
<th>( C(\text{mF}) )</th>
<th>( Q_f )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>100</td>
<td>100</td>
<td>5.38</td>
<td>6.85</td>
<td>1.48</td>
<td>2.5</td>
</tr>
<tr>
<td>2</td>
<td>100</td>
<td>99</td>
<td>5.38</td>
<td>6.92</td>
<td>1.48</td>
<td>2.49</td>
</tr>
<tr>
<td>3</td>
<td>100</td>
<td>101</td>
<td>5.38</td>
<td>6.78</td>
<td>1.48</td>
<td>2.51</td>
</tr>
<tr>
<td>4</td>
<td>33</td>
<td>100</td>
<td>16.13</td>
<td>20.54</td>
<td>0.4933</td>
<td>2.5</td>
</tr>
<tr>
<td>5</td>
<td>66</td>
<td>100</td>
<td>8.067</td>
<td>10.27</td>
<td>0.9866</td>
<td>2.5</td>
</tr>
<tr>
<td>6</td>
<td>66</td>
<td>99</td>
<td>8.067</td>
<td>10.37</td>
<td>0.9866</td>
<td>2.49</td>
</tr>
</tbody>
</table>

\( P \) and \( P_{sl} \) represent the active load power and inductive reactive power, respectively; while \( R, L, C \) and \( Q_f \) represent load and quality factor, respectively.

The results shown in Fig. 11 indicate that the frequency can deviate from the limits within 0.45 s, which qualifies for anti-islanding.
VI. EXPERIMENTS

The experimental platform consists of a 5 kVA three-phase energy storage converter and a 5 kVA three-phase inverter, both of which are connected to a 190 V/50 Hz power interface. The configurations of the platform are similar to that of the simulation model above. The parameters of the islanding detection methods are set as below:

\[
\theta_l = [0.01+0.2(f_f-g)]\pi/2, \text{ for } d\theta_{con}/df > 0 \\
\theta_l = -[0.01+0.2(f_f-g)]\pi/2, \text{ for } d\theta_{con}/df < 0 \\
\theta_d = [0.01+0.2(f_f-g)]\pi/2 \\
I_{iA} = 21 \text{ A}
\]

To compare with the above simulations as well as to be not verbose, two cases shown in Table V are tested.

**TABLE V**

<table>
<thead>
<tr>
<th>Test Cases in the Experiments</th>
<th>Cases</th>
<th>(P_{con}) (W)</th>
<th>(Q_{con}) (Var)</th>
<th>(P_{inv}) (W)</th>
<th>(Q_{inv}) (Var)</th>
<th>Corresponding state</th>
</tr>
</thead>
<tbody>
<tr>
<td>UPF, consumption mode</td>
<td>-1300</td>
<td>0</td>
<td>2600</td>
<td>0</td>
<td>Fig. 3</td>
<td></td>
</tr>
<tr>
<td>Non-UPF, generation mode</td>
<td>700</td>
<td>-1300</td>
<td>1300</td>
<td>2600</td>
<td>AB of Fig. 4(a)</td>
<td></td>
</tr>
</tbody>
</table>

Fig. 12 shows the results in consumption mode and UPF control, and Fig. 13 shows the results in generation mode and non-UPF control.
Accordingly, all the waveforms from the experiments are consistent with those from the simulations, which further strengthens the preceding conclusions.

VII. CONCLUSION

Through summarizing the conclusions in present literature, for frequency shift islanding detection methods a usable formula has been derived: the angle by which the total output current of the DR units leads the PCC voltage must be conducted to have the same shifting direction as the load admittance angle during the frequency variation. By introducing the formula into the classic frequency shift methods which is applied to the energy storage converter operating in multi-DR operations, it is found that the setting requirements of the angle by which the energy storage converter current leads the PCC voltage are inconsistent. As a result, the classic methods are applicable only in UPF control and have to distinguish between generation mode and consumption mode. For overcoming the shortcomings, an improved method applicable in every state has been proposed.

In generation mode, the operating characteristics of energy storage converters are similar to that of inverters. Therefore, the conclusions on frequency shift methods, which are based on energy storage converters in generation mode, are tenable for inverters as well. The modified schemes of the other frequency shift methods can be derived from the proposed usable formula if needed.

REFERENCES


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