A dq-Domain Impedance Measurement Methodology for Three-Phase Converters in Distributed Energy Systems

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Received: 7 September 2018; Accepted: 9 October 2018; Published: 12 October 2018

Abstract: A distributed energy system (DES) using controlled power electronics converters delivers power to loads, via conventional, as well as a number of renewable, energy sources. However, stability concerns retard the integration of power electronics converters into an existing DES. Therefore, due to the high penetration of power converters, the overall network analysis of DES is becoming increasingly difficult. Impedance-based DES modeling emerged as an effective technique as it reduces the system into source and load subsystems and offers easier analysis of the dynamic interactions between them. These models can be obtained using either analytical calculations, simulations, or experimental measurements. In this work, firstly, a line-to-line current injection technique is used for the measurement of alternating current (AC) impedances. Since it requires repeated injections, a dq-domain impedance measurement methodology based upon a set of independent perturbations and measurements is proposed. The perturbation is injected via a sweep signal which is preprocessed by the digital signal processor (DSP) prior to injection. The dq reference frame is synchronized with the three-phase AC system using a low-bandwidth phase-locked loop (PLL). The close matching of impedance parameters measured in simulation using the proposed approach with those obtained using analytical expressions and the line-to-line current injection technique verifies the effectiveness of the approach. Furthermore, the method was also implemented experimentally, and the close matching of the results with the analytical and simulation results validates the overall modeling and measurement procedure.

Keywords: AC impedance; distributed energy system; shunt current injection; dq domain; measurement

1. Introduction

The ever increasing consumption and growing demand for the reliable supply of electrical energy led electrical engineers to conduct more research in the field of distributed energy systems (DEs). A distributed energy system delivers power to different electrical and electronic loads, via conventional, as well as a number of renewable, energy sources, e.g., solar energy, wind energy, bio mass, fuel cells, etc. With the availability of these resources comes the issue of their integration into the existing power distribution system. Thanks to the advancement in power electronics technology, this enabled the power distribution systems to supply various loads not only from the traditional utility grid, but also from modern alternative energy sources. The incorporation of a high number of electronic systems into DEs offers several advantages, i.e., high efficiency, high power factor, flexible control,
and robustness against variations in voltage and frequency [1]. Such DESs include more electric aircrafts (MEA), electric ships, hybrid electric vehicles (HEV), and micro- and nano-grids [2–5]. At the same time, it also introduces the risk of instability due to the interaction of various subsystems and the negative incremental impedance characteristic caused by the constant power load behavior of these subsystems [6]. A lot of research is being carried out in the area of designing advanced control systems to regulate DESs, which are being integrated into existing power systems [7–11]. Such integration occurs at the cost of increased complex interactions among the newly installed power electronic converters, leading to stability issues [12]. Individual subsystems comprising sources and loads, though stable while working in standalone mode, may become unstable when they are interconnected [12].

A priori evaluation of the stability would help avoid maneuvering the hardware set-up. The stability analysis of a power electronic system is usually carried out using small-signal models. The two types of small-signal methods are state-space-based and impedance-based analysis [13, 14]. The advantage of state-space-based analysis is its ability to decompose the dynamics of the system into different oscillation modes, enabling access to the stability of each mode using eigenvalues. However, for state-space models, complete knowledge about the system parameters is required [13]. Unfortunately, most of the electronic modules in modern DESs are from different vendors, and information about their design and parameters is often unavailable. Thus, in most cases, the designers do not have access to complete knowledge about the parameters of various modules.

An alternative method is impedance-based analysis, which requires the overall system to be decomposed into the equivalent source and load subsystems [15–19]. For a three-phase alternating current (AC) system, the small-signal stability analysis can be performed by applying the Nyquist criterion to the impedance ratio of source and load subsystems [20,21], as shown in Figure 1. For a direct current (DC) system, it is simply the ratio of the source subsystem’s output impedance and load subsystem’s input impedance. For three-phase systems, the impedances are expressed in the synchronous reference frame, i.e., the dq reference frame. In either case, to apply this criterion, it is required to measure the source subsystem’s output impedance \((Z_o)\) and load subsystem’s input impedance \((Z_i)\). The system is stable if the impedance ratio \((L(s))\) shown in Equation (1) does not encircle the point \((-1, 0)\).

\[
L(s) = \frac{Z_o}{Z_i}
\]  

(1)

Impedance-based stability analysis has some appealing properties. It considers the system as a black box, i.e., complete knowledge about the internal parameters of the system is not required as the measurement of impedance parameters are performed at external terminals only. Along with stability analysis, the impedance models of power electronics systems can also be used for control dynamics, harmonic resonance analysis, and electromagnetic interference (EMI) filter design [22–24]. Due to the complexity involved in modeling power converters, it is more practical to measure the impedances than to model them [25]. Therefore, it is of paramount significance to develop methods for impedance measurement of three-phase power electronic systems.

For DC-based DEs, measurement techniques of various frequency response parameters, including impedance parameters, are well established and widely reported in the literature [26,27]. However, for three-phase AC systems, the measurement methods for impedance parameters are not
intuitive due to the time-varying nature of the operating point. The impedance measurement methods for AC systems can be broadly categorized into two types, i.e., with an external source and without an external source. The method which requires an external source is implemented via shunt current or series voltage injection, utilizing three-phase injection or line-to-line injection [28–30]. This method has relatively high accuracy, but requires a longer signal sweep time and, therefore, is not suitable for systems connected to the grid where impedance is rapidly changing. The second category includes methods which do not require an external source. It includes the operating point shift method, but this method is not considered practical for systems which are connected to the grid [31]. The noise injection method proposed in Reference [32] is considered easier to implement, but is based on some cumbersome computations. The pulse injection method discussed in Reference [33] requires fewer calculations, but is less accurate.

The main drawback of the abovementioned shunt current or series voltage injection techniques is that they require perturbation signals to be injected for one frequency at a time. In order to obtain the impedance over a wide frequency range, the process must be repeated several times. Each time, the perturbation signal of a particular frequency is injected into the system, and the corresponding voltage and current signals are recorded. These recorded signals are then processed to calculate the impedance value at each frequency point. As a result, the whole process takes a long time to complete the injection and then the calculation of impedance over the entire frequency range. It is also possible that the operating point of the system may change during the tedious procedure, leading to erroneous results.

Therefore, an approach is required in which the impedance parameters can be measured in a short period of time. Furthermore, the process should not require repetition for different frequency points and the measurements should be taken such that the impedance parameters are valid over the entire operating range. In this work, an AC impedance measurement technique in the synchronous $dq$ reference frame is presented for three-phase AC systems. Most of the power electronics converters used in DESs employ $dq$-reference-frame-based control techniques [7–11]. Thus, if the impedance parameters are also described in the $dq$ domain, it would result in close relation to the control in the $dq$ reference frame. Furthermore, the characteristics of the $dq$-domain impedances would be similar to DC systems, as the AC voltages and currents are transformed into DC components. Hence, the small-signal stability analysis can be performed by applying the Nyquist criterion to the ratio of impedances for source and load subsystems. The impedance measurement methodology is based on a set of independent perturbations, and measurements are performed in the $dq$ reference frame. The perturbation is injected via a sweep signal which is preprocessed by the digital signal processor (DSP) prior to injection. The DSP is programmed to add the perturbation to either the $d$- or $q$-channel for the measurement of a particular impedance parameter. The $dq$ reference frame is synchronized with the three-phase AC system using a low-bandwidth phase-locked loop (PLL).

The proposed method was compared with the conventional shunt-current-injection-based method. Comparison of the impedance parameters measured via simulation using the proposed approach with those obtained via analytical expressions and the line-to-line current injection technique reveal their close matching, and hence, verify its effectiveness. Furthermore, the proposed approach was also implemented experimentally, and the results match with the ones measured via simulation, thereby validating the overall modeling and measurement procedure.

The paper is organized as follows: Section 2 explains the shunt-current-injection-based impedance measurement technique. The proposed impedance measurement methodology is presented in Section 3. Section 4 describes the practical impedance measurement set-up for the proposed approach. Section 5 presents the simulation and experimental results for the proposed approach and also compares them with the analytical and shunt-current-injection-based technique. Finally, Section 6 concludes the paper.
2. Impedance Measurement Methodology Using Shunt Current Injection Approach

The general diagram of the impedance measurement methodology based on the shunt current line-to-line injection technique is shown in Figure 2, while the practical injection circuit for the three-phase AC–AC network’s impedance measurement is shown in Figure 3.

![General diagram for impedance measurement using the line-to-line current injection.](image)

**Figure 2.** General diagram for impedance measurement using the line-to-line current injection.

![Three-phase alternating current (AC–AC network’s impedance measurement set-up.](image)

**Figure 3.** Three-phase alternating current (AC–AC network’s impedance measurement set-up.

In Figures 2 and 3, the symbols are defined as follows:

- \( Z_o \) is the source subsystem’s output impedance;
- \( Y_i \) is the load subsystem’s input admittance;
- \( v_x \) is the three-phase source voltage;
- \( R_x \) is the resistor;
- \( L_x \) is the inductor;
- \( R_{inj} \) is the injection resistor;
- \( L_{inj} \) is the injection inductor;
- \( A, B \) is the power metal-oxide-semiconductor field-effect transistor (MOSFET).

Here, \( x \in (a, b, c) \), and the subscripts \( a, b, \) and \( c \) represent the parameters associated with the three phases.

The parameters of the three-phase RL network are given in Table 1.

| Parameter | Source Voltage \((v_{\text{rms}})\) | Source Frequency \((f)\) | Load Resistor \((R)\) | Load Inductor \((L)\) | Injection Resistor \((R_{\text{inj}})\) | Injection Inductor \((L_{\text{inj}})\) |
|-----------|---------------------------------|-----------------|-----------------|-----------------|----------------|-----------------|
| Value     | 115 V                           | 400 Hz          | 13 Ω            | 297 μH          | 100 Ω          | 1 mH            |
The chopper circuit, shown in Figure 3, was used for the line-to-line shunt current injection, consisting of a resistor $R_{mj}$ and inductor $L_{mj}$ in series with a bidirectional switch. Practically, line-to-line current is injected in any two of the three lines a, b, and c by switching the power MOSFETs (Motorola IRF 540, 150 W, 27 Ampere, 100 V) $A$ and $B$ alternatively, with 50% duty ratio, to introduce impedance variation at the interface junction. This causes the current injection into the system at the switching frequency.

The four AC impedance measurement parameters, i.e., $Z_{dd}$, $Z_{dq}$, $Z_{qd}$, and $Z_{qq}$, are as shown in Equation (2). To measure $Z_{dd}$ and $Z_{dq}$, perturbation frequency is injected in $i_q$ while $i_d$ set to zero. On the other hand, to measure $Z_{dq}$ and $Z_{qq}$ at $\omega_p$, perturbation frequency is injected in $i_q$ while $i_d$ is set to zero.

$$\begin{align*}
Z_{dd}(\omega_p) &= \frac{v_d}{i_d}, i_q = 0; \\
Z_{dq}(\omega_p) &= \frac{v_d}{i_q}, i_q = 0; \\
Z_{qd}(\omega_p) &= \frac{v_q}{i_d}, i_q = 0; \\
Z_{qq}(\omega_p) &= \frac{v_q}{i_q}, i_d = 0.
\end{align*}$$

(2)

The algorithm developed and implemented using the MATLAB software package (R2016b, Mathworks, Natick, MA, USA) [34], shown in Figure 4, was used for the measurement of impedance parameters. In the first step, for calculating a specific parameter at frequency $\omega_p$, two linearly independent frequency signals were injected at $\omega = [\omega_p \pm \omega_g]$, where $\omega_g$ is the frequency of the three-phase voltage source in rad/s ($\omega_g = 2\pi f$). Then, the time-domain voltage values of the three-phase voltage ($v_u$, $v_b$, $v_c$) and current ($i_u$, $i_b$, $i_c$) signals were extracted, which were used for the transformation of three-phase voltage and current signals into a $dq$-synchronous reference frame. Then, fast Fourier transform (FFT) was performed to extract the $dq$-domain values of voltage ($v_d$, $v_q$) and current ($i_d$, $i_q$) at the injected frequency $\omega$, and the impedance parameters shown in Equation (3) were computed.

$$\begin{bmatrix}
dv_d \\
dv_q
\end{bmatrix} =
\begin{bmatrix}
Z_{dd} & Z_{dq} \\
Z_{qd} & Z_{qq}
\end{bmatrix}
\begin{bmatrix}
di_d \\
di_q
\end{bmatrix},$$

(3)

where $Z_{dd}$ is the $d$-axis impedance parameter with perturbation in the $d$-axis, $Z_{dq}$ is the $d$-axis impedance parameter with perturbation in the $q$-axis, $Z_{qd}$ is the $q$-axis impedance parameter with perturbation in the $d$-axis, and $Z_{qq}$ is the $q$-axis impedance parameter with perturbation in the $q$-axis.

![Figure 4. Algorithm for impedance measurements implemented using MATLAB.](image-url)

To avoid frequency overlapping, which may affect the results, multiples of the fundamental frequency were not injected. This technique has a drawback of injecting considerable harmonics, but they are mathematically removed by the FFT process.
The four impedance parameters obtained using the algorithm described above were compared with those obtained using the analytical expression given in Equation (4). Equation (4) represents a passive load consisting of resistance ($R$) and inductance ($L$). The symbol $\omega_g$ represents the angular frequency of the system.

$$Z_{ana} = \begin{bmatrix} R + j\omega_g L & -\omega_g L \\ \omega_g L & R + j\omega_g L \end{bmatrix}.$$  \hspace{1cm} (4)

Figure 5 shows the comparison of frequency responses obtained using the analytical expression given in Equation (3) for the four impedance parameters and those obtained using the measurement methodology described. It can be seen that all four parameters match pretty well for the simulated system. The difference appearing for the phase plot of $Z_{dq}$ is due to the fact that these two parameters were measured using the perturbation from cross-channels (i.e., for perturbation in the $d$-axis and measurement at the $q$-axis, and vice versa).

**Figure 5.** Comparison of $Z$-parameters for simulated resistor/inductor ($RL$) network using the shunt current injection approach with analytical results.

3. Impedance Measurement Methodology in the $dq$-Domain

The impedance measurements of a three-phase AC–AC system using the proposed method were performed in the $dq$-domain. For an AC–AC network, there are four unknown impedance parameters, as shown in the Equation (3); therefore, we needed four equations to solve them.

In synchronous reference frame, the impedance matrix is written as

$$\begin{bmatrix} v_d \\ v_q \end{bmatrix} = \begin{bmatrix} Z_{dd} & Z_{dq} \\ Z_{qd} & Z_{qq} \end{bmatrix} \begin{bmatrix} i_d \\ i_q \end{bmatrix},$$ \hspace{1cm} (5)
with a source voltage of \( v_k \), and a source current of \( i_k \), where \( k \in (d, q) \), and the subscripts \( d \) and \( q \) denote the parameters associated with the \( d \)-axis and \( q \)-axis, respectively.

### 3.1. Measurements of \( Z_{dd} \) and \( Z_{dq} \)

The first equation from Equation (5) can also be written as

\[
\begin{align*}
\nu_d &= Z_{dd}i_d + Z_{dq}i_q. 
\end{align*}
\]

(6)

It can be rearranged to

\[
\begin{align*}
1 &= Z_{dd} \frac{i_d}{\nu_d} + Z_{dq} \frac{i_q}{\nu_d}. 
\end{align*}
\]

(7)

This equation contains two measurement parameters, which can be obtained by applying two independent perturbations. The subscripts “1” and “2” represent two independent perturbations, injected to the \( d \)- and \( q \)-axis, respectively.

\[
\begin{align*}
\begin{cases}
1 &= Z_{dd} \left( \frac{i_d}{\nu_d} \right)_1 + Z_{dq} \left( \frac{i_q}{\nu_d} \right)_1, \\
1 &= Z_{dd} \left( \frac{i_d}{\nu_d} \right)_2 + Z_{dq} \left( \frac{i_q}{\nu_d} \right)_2.
\end{cases}
\end{align*}
\]

(8)

It can be written as

\[
\begin{align*}
\begin{bmatrix}
1 \\
1 
\end{bmatrix} &= \begin{bmatrix}
\left( \frac{i_d}{\nu_d} \right)_1 & \left( \frac{i_q}{\nu_d} \right)_1 \\
\left( \frac{i_d}{\nu_d} \right)_2 & \left( \frac{i_q}{\nu_d} \right)_2 
\end{bmatrix} \begin{bmatrix}
Z_{dd} \\
Z_{dq}
\end{bmatrix},
\end{align*}
\]

(9)

and finally,

\[
\begin{align*}
\begin{bmatrix}
Z_{dd} \\
Z_{dq}
\end{bmatrix} &= \text{inv} \begin{bmatrix}
\left( \frac{i_d}{\nu_d} \right)_1 & \left( \frac{i_q}{\nu_d} \right)_1 \\
\left( \frac{i_d}{\nu_d} \right)_2 & \left( \frac{i_q}{\nu_d} \right)_2 
\end{bmatrix} \begin{bmatrix}
1 \\
1
\end{bmatrix},
\end{align*}
\]

(10a)

or

\[
Z_1 = M_1^{-1} \mathbf{1}.
\]

(10b)

In Equation (10b), the bold font indicates vector quantities.

Upon expanding Equation (10a) to further clarify the need for two independent perturbations, we have

\[
\begin{align*}
\begin{bmatrix}
Z_{dd} \\
Z_{dq}
\end{bmatrix} &= \frac{1}{\left( \frac{i_d}{\nu_d} \right)_1 \left( \frac{i_q}{\nu_d} \right)_2 - \left( \frac{i_d}{\nu_d} \right)_2 \left( \frac{i_q}{\nu_d} \right)_1} \begin{bmatrix}
\left( \frac{i_d}{\nu_d} \right)_2 & -\left( \frac{i_q}{\nu_d} \right)_2 \\
-\left( \frac{i_d}{\nu_d} \right)_1 & \left( \frac{i_q}{\nu_d} \right)_1
\end{bmatrix} \begin{bmatrix}
1 \\
1
\end{bmatrix};
\end{align*}
\]

\[
Z_{dd} = \frac{\left( \frac{i_d}{\nu_d} \right)_2 - \left( \frac{i_q}{\nu_d} \right)_1}{\left( \frac{i_d}{\nu_d} \right)_2 \left( \frac{i_q}{\nu_d} \right)_1 - \left( \frac{i_d}{\nu_d} \right)_1 \left( \frac{i_q}{\nu_d} \right)_2}, \quad Z_{dq} = \frac{\left( \frac{i_d}{\nu_d} \right)_1 + \left( \frac{i_q}{\nu_d} \right)_2}{\left( \frac{i_d}{\nu_d} \right)_1 \left( \frac{i_q}{\nu_d} \right)_2 - \left( \frac{i_d}{\nu_d} \right)_2 \left( \frac{i_q}{\nu_d} \right)_1}.
\]

It shows that a set of two independent perturbations, i.e., \( M_1 \), will enable us to measure the subset \( Z_1 \).

### 3.2. Measurements of \( Z_{qd} \) and \( Z_{qq} \)

The second equation from Equation (5) can also be written as

\[
\begin{align*}
\nu_q &= Z_{qd}i_d + Z_{qq}i_q. 
\end{align*}
\]

(11)

By applying the same procedure as for Equation (6), we have

\[
\begin{align*}
\begin{bmatrix}
Z_{qd} \\
Z_{qq}
\end{bmatrix} &= \text{inv} \begin{bmatrix}
\left( \frac{i_d}{\nu_q} \right)_1 & \left( \frac{i_q}{\nu_q} \right)_1 \\
\left( \frac{i_d}{\nu_q} \right)_2 & \left( \frac{i_q}{\nu_q} \right)_2 
\end{bmatrix} \begin{bmatrix}
1 \\
1
\end{bmatrix},
\end{align*}
\]

(12a)
or

\[ Z_2 = M_2^{-1}1. \]  

(12b)

It shows that a set of two independent perturbations, i.e., \( M_2 \), will enable us to measure the subset \( Z_2 \).

A set of two independent perturbations is required to be injected for each subset (\( Z_1 \) and \( Z_2 \)) of the impedance measurements.

3.3. Perturbations for \( Z_{dd} \) and \( Z_{dq} \)

To measure the first impedance subset \( Z_1 \) given in Equation (10), firstly, a certain magnitude perturbation \( \alpha \) is injected into only the \( d \)-axis with the \( q \)-axis magnitude as zero, i.e.,

\[ P_d = \alpha, \quad P_q = 0. \]

(13)

where \( \alpha \) is the magnitude of the injected signal and its value depends on the system under test.

The measurements are made for \( \left( \frac{i_d}{v_d} \right)_1 \) and \( \left( \frac{i_q}{v_d} \right)_1 \).

In the second case, a certain magnitude perturbation is injected into only \( q \)-axis with the \( d \)-axis magnitude as zero, i.e.,

\[ P_d = 0, \quad P_q = \alpha. \]

(14)

The measurements are made for \( \left( \frac{i_d}{v_q} \right)_2 \) and \( \left( \frac{i_q}{v_q} \right)_2 \).

3.4. Perturbations for \( Z_{qd} \) and \( Z_{qq} \)

To measure the second impedance subset \( Z_2 \) given in Equation (12), firstly, a certain magnitude perturbation is injected into only the \( d \)-axis with the \( q \)-axis magnitude as zero, i.e.,

\[ P_d = \alpha, \quad P_q = 0. \]

(15)

The measurements are made for \( \left( \frac{i_d}{v_q} \right)_1 \) and \( \left( \frac{i_q}{v_q} \right)_1 \).

In the second case, a certain magnitude perturbation is injected into only the \( q \)-axis with the \( d \)-axis magnitude as zero, i.e.,

\[ P_d = 0, \quad P_q = \alpha. \]

(16)

The measurements are made for \( \left( \frac{i_d}{v_q} \right)_2 \) and \( \left( \frac{i_q}{v_q} \right)_2 \).

The \( dq \) transformation results in an equivalent DC system with two coupled channels. The perturbation injected into one channel results in a response from the same channel and also the cross-coupled channel.

4. Impedance Measurement Set-Up

4.1. Measurement Set-Up

The three-phase AC–AC network’s impedance measurement set-up is shown in Figure 6. The main parts of the system include a network analyzer or frequency response analyzer (FRA) and a digital signal processor (DSP).

For the impedance measurement, according to the methodology discussed above, the three-phase input voltage (\( v_{abc} \)) is required to be perturbed. For this purpose, the small-signal perturbation \( (P_x) \) was added in series to each phase of the input ac voltage. The small-signal perturbation generated by the source of FRA was firstly given to the DSP. The DSP was programmed to perform the function of adding the perturbation to either the \( d \)- or \( q \)-channel of the source voltage. The addition of perturbation to the \( d \)- or \( q \)-axis of the source voltage depends on the impedance parameter being measured. The system’s voltages and currents (which include the effect of perturbations already added) were measured using...
voltage and current sensors and were supplied to the DSP. The DSP transformed the measured AC signals to the \(dq\) domain. After the transformation, the respective \(dq\)-domain voltages \((v_d, v_q)\) were applied to reference channel (CHR) and the \(dq\)-domain currents \((i_d, i_q)\) were applied to the measurement channel (CHT) of the FRA for the frequency response measurements.

![Figure 6. Z-parameter measurement set-up for the three-phase AC–AC network.](image)

In Figure 6, the symbols are defined as follows:

- \(v_x\) is the three-phase source voltage;
- \(i_x\) is the three-phase source current;
- \(P_x\) is the perturbation signal;
- \(R_x\) is the resistor;
- \(L_x\) is the inductor;
- \(v_{dx}\) is the \(dq\)-domain voltage;
- \(i_{dx}\) is the \(dq\)-domain current.

Here, \(x \in \{a, b, c\}\), and the subscripts \(a, b, c\) represent the parameters associated with the three phases. Also \(k \in \{d, q\}\), and the subscripts \(d, q\) represent the parameters associated with the \(d\)- and \(q\)-axis, respectively.

### 4.2. Phase-Locked Loop

The measurement of various parameters for the three-phase AC system was performed in a synchronous \(dq\) reference frame, achieved by employing a phase-locked loop (PLL) [35]. In the \(dq\) reference frame, an alignment is chosen to define the frame. In this work, the \(dq\) frame was aligned with the \(d\)-axis, such that the \(q\)-axis component was zero.

The block diagram of the synchronous reference frame PLL is shown in Figure 7. By applying Clarke’s and Park’s transformation to the source voltage \((v_{abc})\), the error signal \((v_{d})\) was obtained. The error signal was constrained to zero to obtain the estimated source frequency \((\omega_{PLL})\), where \((\omega_k)\) is the actual source frequency. The angle of the PLL \((\theta)\) was calculated by integrating \(\omega_{PLL}\).

![Figure 7. Structure of the synchronous reference frame phase-locked loop.](image)

The role of the PLL is to make the measurement parameters rotationally invariant; otherwise, different alignments of the \(dq\) reference frame will result in different measurements. This is due to the fact that the injection of perturbation results in sinusoidal fluctuations in the line voltage. These perturbations
also pass through the PLL, resulting in sinusoidal fluctuations in the line frequency, because any signal other than the fundamental frequency affects the output of the PLL [30]. During the measurement process, it is assumed that the dq reference frame is at constant frequency. This assumption would become invalid if the PLL keeps changing its output. In order to keep the output of the PLL constant, the bandwidth of the PLL is reduced to be significantly lower than the lowest perturbation frequency. This ensures that the injection perturbation has no effect on the PLL output. In this work, the bandwidth perturbation), while the proportional (\(k_p\)) and integral (\(k_i\)) gains were \(k_p = 0.5\) and \(k_i = 31.4\), respectively.

5. Impedance Measurement Results

5.1. Simulation Results

The simulation model of the three-phase RL network was built in the SABER circuit simulation software (4.0, Synopsys, CA, USA) [36], whose schematic circuit is shown in Figure 8a. Figure 8b shows the implementation of the proposed measurement set-up in SABER, according to the measurement methodology described in Section 4.1. One of the advantages of using SABER is that the network analyzer block emulates the operation of the frequency response analyzer as used subsequently in the experiment.

![Schematic Circuit](image)

**Figure 8.** Generalized (a) and Saber schematic circuit (b) for the three-phase RL network.

The parameters of the three-phase RL network are given in Table 2.

| Parameter | Source Voltage (\(v_{rms}\)) | Source Frequency (\(f\)) | Load Resistor (\(R\)) | Load Inductor (\(L\)) |
|-----------|-----------------------------|--------------------------|-----------------------|-----------------------|
| Value     | 115 V                       | 400 Hz                   | 13 \(\Omega\)         | 297 \(\mu H\)         |

As per the methodology described in Section 3, a set of two independent perturbations was applied for each subset of the impedance parameters, resulting in four frequency responses for each,
which were subsequently identified and are shown in Figure 9a,b. Once the required frequency response measurement and identification were done, then Equations (10) and (12) were used to calculate the impedance matrix given in Equation (4).

Figure 10 shows the comparison of frequency responses obtained using the analytical expression given in Equation (3) for the four impedance parameters and those obtained using the measurement methodology described. It can be seen that all four parameters match pretty well for the simulated system.
5.2. Experimental Results

The three-phase RL network was also investigated experimentally, and Table 3 shows the parameters used in the experiment for the three-phase RL network. The experimental validation of the described impedance measurement methodology was carried out using a prototype which is a scaled-down version of the simulation model. The various components used were designed for low power levels; therefore, a three-phase source voltage of 20 V was applied.

| Parameter     | Source Voltage ($v_{\text{rms}}$) | Source Frequency (f) | Load Resistor (R) | Load Inductor (L) |
|---------------|-----------------------------------|----------------------|------------------|-------------------|
| Value         | 20 V                              | 400 Hz               | 13 Ω             | 297 μH            |

Table 3. Experimental parameters for the three-phase RL network.

As per the methodology described in Section 3, a set of two independent perturbations was applied for each subset of impedance parameters, resulting in four frequency responses for each, which were subsequently identified. Just as was done for the simulated RL network, once the required frequency response measurement and identification were done, Equations (10) and (12) were then used to calculate the impedance matrix shown in Equation (4). Figure 11 shows the comparison of impedance parameters obtained experimentally with those obtained analytically and via simulation.

The slight mismatch of the experimental result with the simulation for one of the two cross-coupling parameters, i.e., $Z_{qd}$, was due to the fact that the value of the $q$-channel signal was relatively very small and the resulting impedance levels were too low to be sensed by the network analyzer.
Author Contributions: M.S., H.A., and S.K. conceived and designed the experiments. M.S., H.A., and H.L. performed the experiments, analyzed the data, and implemented the methodology via software simulations. M.S. and H.A. wrote the original draft of the paper. H.Z. and B.M.K. provided technical feedback, and reviewed and edited the manuscript. D.K. and J.Y. supervised the whole research work.

Funding: This research received no external funding.

Conflicts of Interest: The authors declare no conflicts of interest.

Figure 11. Comparison of analytical and measured Z-parameters for simulated and experimental RL networks.

6. Conclusions

The trend of electrification in power systems for aircrafts, ships, vehicles, and commercial, as well as residential, services led the way for an increasing number of power electronics converters being incorporated into these systems. Though this arrangement offers several advantages, it also brings the issue of stability. To address the stability issues, such models are required to be developed which do not require prior information about system parameters, and which consume a short measurement time. The state-space-based stability analysis methods have a shortcoming that they require detailed knowledge about system parameters, which is often not the case with modules employed in modern DESs from different vendors. Methods such as line-to-line current injection require a perturbation injection for each frequency point, and therefore, are not suitable for systems where impedance is rapidly changing. In this work, an impedance measurement methodology was presented based on measurements in a synchronous dq reference frame. Compared to the other injection-based techniques, it considers the system as a black box and requires fewer perturbations and a shorter time for measurement of parameters over a wide frequency range. The simulation and experimental results of the presented methodology were compared with analytical and line-to-line current injection techniques, and their close match validates the modeling and measurement procedures.
References

1. Wen, B.; Burgos, R.; Boroyevich, D.; Mattavelli, P.; Shen, Z. AC Stability Analysis and dq Frame Impedance Specifications in Power-Electronics-Based Distributed Power Systems. *IEEE J. Emerg. Sel. Top. Power Electron.* 2017, 5, 1455–1465. [CrossRef]
2. Bose, B.K. Global Energy Scenario and Impact of Power Electronics in 21st Century. *IEEE Trans. Ind. Electron.* 2013, 60, 2638–2651. [CrossRef]
3. Nefedov, E.; Sierla, S.; Vyatkin, V. Internet of Energy Approach for Sustainable Use of Electric Vehicles as Energy Storage of Prosumer Buildings. *Energies* 2018, 11, 2165. [CrossRef]
4. Harighi, T.; Bayindir, R.; Padmanaban, S.; Mihet-Popa, L.; Hossain, E. An Overview of Energy Scenarios, Storage Systems and the Infrastructure for Vehicle-to-Grid Technology. *Energies* 2018, 11, 2174. [CrossRef]
5. Saponara, S.; Ciarpi, G. IC Design and Measurement of an Inductorless 48V DC/DC Converter in Low-Cost CMOS Technology Facing Harsh Environments. *IEEE Trans. Circuits Syst. II* 2018, 65, 380–393. [CrossRef]
6. Aldhaheri, A.; Etemadi, A. Impedance Decoupling in DC Distributed Systems to Maintain Stability and Dynamic Performance. *Energies* 2017, 10, 470. [CrossRef]
7. Mehrasa, M.; Adabi, M.E.; Pouremsaeil, E.; Adabi, J.; Jorgensen, B.N. Direct Lyapunov Control (DLC) Technique for Distributed Generation (DG) Technology. *Electr. Eng.* 2014, 96, 309–321. [CrossRef]
8. Mehrasa, M.; Pouremsaeil, E.; Shamsodin, T.; Vechiu, I.; Catalao, J.P.S. Novel Control Strategy for Modular Multilevel Converters Based on Differential Flatness Theory. *IEEE J. Emerg. Sel. Top. Power Electron.* 2018, 6, 888–897. [CrossRef]
9. Mehrasa, M.; Sharifzadeh, M.; Sheikholeslami, A.; Pouremsaeil, E.; Catalao, J.P.S.; Al-Haddad, K. A Control based on Upper and Lower’s Arms Modulation Functions of MMC in HVDC Applications. In Proceedings of the IEEE International Conference on Industrial Technology (ICIT), Lyon, France, 20–22 February 2018.
10. Miceli, R.; Schettino, G.; Viola, F. A Novel Computational Approach for Harmonic Mitigation in PV Systems with Single-Phase Five-Level CHBMI. *Energies* 2018, 11, 2100. [CrossRef]
11. Polanco Vasquez, L.O.; Carreño Meneses, C.A.; Pizano Martinez, A.; López Redondo, J.; Pérez García, M.; Álvarez Hervás, J.D. Optimal Energy Management within a Microgrid: A Comparative Study. *Energies* 2018, 11, 2167. [CrossRef]
12. Liu, F.; Liu, J.; Zhang, H.; Xue, D.; Dou, Q. Comprehensive study about stability issues of multi-module distributed system. In Proceedings of the International Power Electronics Conference (IPEC), Hiroshima, Japan, 18–21 May 2014.
13. Rygg, A.; Molinas, M. Apparent Impedance Analysis: A Small-Signal Method for Stability Analysis of Power Electronic-Based Systems. *IEEE J. Emerg. Sel. Top. Power Electron.* 2017, 5, 1474–1486. [CrossRef]
14. Jaksic, M.; Shen, Z.; Cvetkovic, I.; Boroyevich, D.; Burgos, R.; DiMarino, C.; Chen, F. Medium-Voltage Impedance Measurement Unit for Assessing the System Stability of Electric Ships. *IEEE Trans. Energy Convers.* 2017, 32, 829–841. [CrossRef]
15. Lissandron, S.; Santa, I.D.; Mattavelli, P.; Wen, B. Experimental validation for impedance-based small-signal stability analysis of single phase interconnected power systems with grid-feeding inverters. *IEEE J. Emerg. Sel. Top. Power Electron.* 2016, 4, 103–115. [CrossRef]
16. Amin, M.; Ardal, A.; Molinas, M. Self-synchronization of wind farm in an MMC-based HVDC system: A stability investigation. *IEEE Trans. Energy Convers.* 2017, 32, 458–470. [CrossRef]
17. Liu, Z.; Liu, J.; Bao, W.; Zhao, Y. Infinity-norm of Impedance-based Stability Criterion for Three-phase AC Distributed Power Systems with Constant Power Loads. *IEEE Trans. Power Electron.* 2015, 30, 3030–3043. [CrossRef]
18. Suntio, T.; Viinamaki, J.; Jokipii, J.; Mesko, T.; Kuperman, A. Dynamic Characterization of Power Electronic Interfaces. *IEEE J. Emerg. Sel. Top. Power Electron.* 2014, 2, 949–961. [CrossRef]
19. Sun, J. Small-signal Methods for AC Distributed Power Systems—A Review. *IEEE Trans. Power Electron.* 2009, 24, 2545–2554.
20. Wen, B.; Boroyevich, D.; Mattavelli, P.; Zhiyu, S.; Burgos, R. Experimental verification of the generalized Nyquist stability criterion for balanced three-phase ac systems in the presence of constant power loads. In Proceedings of the IEEE Energy Conversion Congress and Exposition (ECCE), Raleigh, NC, USA, 15–20 September 2012.
21. Rygg, A.; Molinas, M.; Zhang, C.; Cai, X. A modified sequence domain impedance definition and its equivalence to the dq-domain impedance definition for the stability analysis of AC power electronic systems. *IEEE J. Emerg. Sel. Top. Power Electron.* 2016, 4, 1383–1396. [CrossRef]

22. Cao, W.; Ma, Y.; Wang, F. Sequence-impedance-based harmonic stability analysis and controller parameter design of three-phase inverter based multi bus AC power systems. *IEEE Trans. Power Electron.* 2016, 32, 7674–7693. [CrossRef]

23. Xu, L.; Fan, L.; Miao, Z. DC impedance-model-based resonance analysis of a VSC–HVDC system. *IEEE Trans. Power Deliv.* 2015, 30, 1221–1230. [CrossRef]

24. Tarateeraseth, V.; See, K.-Y.; Canavero, F.G.; Chang, R.W.-Y. Systematic Electromagnetic Interference Filter Design Based on Information from in-Circuit Impedance Measurements. *IEEE Trans. Electromagn. Compat.* 2010, 52, 588–598. [CrossRef]

25. Liu, Z.; Liu, J.; Hou, X.; Dou, Q.; Xue, D.; Liu, T. Output impedance modeling and stability prediction of three-phase paralleled inverters with master-slave sharing scheme based on terminal characteristics of individual inverters. *IEEE Trans. Power Electron.* 2016, 31, 5306–5320. [CrossRef]

26. Ali, H.; Zheng, X.; Wu, X.; Khan, S.; Saad, M. Frequency response measurements of dc-dc buck converter. In Proceedings of the 28th Annual IEEE Applied Power Electronics Conference and Exposition (APEC), Long Beach, CA, USA, 17–21 March 2013.

27. Zheng, X.; Ali, H.; Wu, X.; Zaman, H.; Khan, S. Non-Linear Behavioral Modeling for DC-DC Converters and Dynamic Analysis of Distributed Energy Systems. *Energies* 2017, 10, 63. [CrossRef]

28. Shen, Z.; Jaksic, M.; Mattavelli, P.; Boroyevich, D.; Verhulst, J.; Belkhayat, M. Design and implementation of three-phase AC impedance measurement unit (IMU) with series and shunt injection. In Proceedings of the 28th Annual IEEE Applied Power Electronics Conference and Exposition (APEC), Long Beach, CA, USA, 17–21 March 2013.

29. Huang, J.; Corzine, K.A.; Belkhayat, M. Small-Signal Impedance Measurement of Power-Electronics-Based AC Power Systems Using Line-to-Line Current Injection. *IEEE Trans. Power Electron.* 2009, 24, 445–455. [CrossRef]

30. Francis, G.; Burgos, R.; Boroyevich, D.; Wang, F.; Karimi, K. An algorithm and implementation system for measuring impedance in the d-q domain. In Proceedings of the IEEE Energy Conversion Congress and Exposition (ECCE), Phoenix, Arizona, AZ, USA, 17–22 September 2011.

31. Gu, H.; Guo, X.; Wang, D.; Wu, W. Real-time grid impedance estimation technique for grid connected power converters. In Proceedings of the IEEE International Symposium on Industrial Electronics, Hangzhou, China, 28–31 May 2012.

32. Martin, D.; Santi, E.; Barkley, A. Wide bandwidth system identification of AC system impedances by applying perturbations to an existing converter. In Proceedings of the Energy Conversion Congress and Exposition, Phoenix, AZ, USA, 17–22 September 2011.

33. Dou, Q.; Liu, Z.; Liu, J.; Boa, W. A novel impedance measurement method for three-phase power electronic systems. In Proceedings of the 9th International Conference on Power Electronics and ECCE Asia (ICPE-ECCE Asia), Seoul, Korea, 1–5 June 2015.

34. MathWorks. Available online: http://www.mathworks.com (accessed on 3 September 2017).

35. Arricibita, D.; Marroya, L.; Barrios, E.L. Simple and robust PLL algorithm for accurate phase tracking under grid disturbances. In Proceedings of the IEEE 18th Workshop on Control and Modeling of Power Electronics (COMPEL), Stanford, CA, USA, 9–12 July 2017.

36. Saber Sketch. Available online: https://www.synopsys.com/verification/virtual-prototyping/saber.html (accessed on 14 August 2017).

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