Simultaneous Measurement of Bus Impedance and Control Loop Gains in Multi-Converter Systems

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***Abstract*—Power distribution systems are often dependent on the operation of a large number of power-electronics converters that are connected to a common bus. The converters may be standalone stable but the system may still exhibit stability issues due to interactions among multiple converter subsystems. Recent studies have presented methods such as passivity-based stability criterion, where the system stability can be monitored by using bus-impedance measurements. The method provides the dynamic performance of the complete system but does not reveal the effect of a single converter on system dynamics. Other studies have presented methods based on loop-gain measurements, where the system is analyzed through single converters. These methods provide more direct information on the operation of single converters and their stability margins compared to the bus-impedance approach but the loop gains do not provide direct information on the overall system operation and global stability. This paper proposes a method for simultaneously measuring the bus impedance and all the loop gains of a multi-converter system, thus providing an efficient tool to combine the two analysis methods. In the technique, several orthogonal broadband perturbations are simultaneously injected into the control loops of single converters. The resulting responses are measured from both sides of injection points and from the output voltages and currents of single converters. Then, cross-correlation and Fourier methods are applied to extract the spectral information of the measured responses for obtaining the bus impedance and the loop gains. The proposed technique allows a straightforward online method to fully characterize the stability of a multi-converter system. Experimental results are presented and used to demonstrate the effectiveness of the proposed method.**

***Index Terms*—Frequency response, signal design, spectral analysis, modeling, power system measurements.**

I. Introduction

Multi-converter power distribution systems have become increasingly important in powering various electronic loads and processes, including hybrid and electric vehicles [1], aircrafts [2], electric ships [3], and micro grids [4]. Such systems most often consist of a large number of power-electronics converters connected to the same bus, thus creating a complex interconnected systems.

Consider the power-electronics-based distribution architecture conceptually shown in Fig. 1. The system has p buses and contains a number of interconnected switching converters playing different roles. Some converters operate as a source and some converters as a load. Other converters operate as energy-storage interface converters, and are power-bidirectional, capable of acting both as a load and source [5]. Regardless of the operating mode, each converter usually has a high-bandwidth feedback control. Even though the converters have good stability margins in standalone mode, they may exhibit completely different dynamic behavior when interconnected. Therefore, due to interactions among the converter feedback loops through the bus interconnections, system stability may be compromised [6].

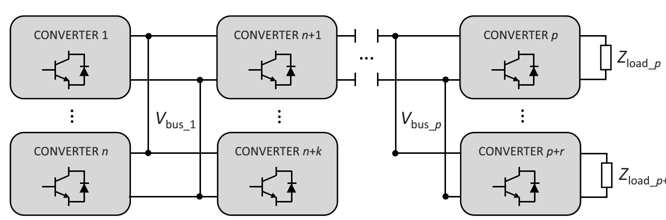

Fig. 1: Conceptual diagram of multibus system.

Recent studies have presented several methods to analyze the stability of a multi-converter system. Most of these methods are based either on the equivalent bus impedances resulting from the converter interconnections, or on the loop gains of single converters [7]–[11]. The authors in [7] and [8] proposed the passivity-based stability criterion (PBSC) which directly applies to the measured bus impedance. The concept of an allowable impedance region (AIR) was presented in [9] to be applied alongside the PBSC to guarantee sufficient stability margins and dynamic performance. The authors in [10] and [11] used different approach by directly measuring and analysing the loop gains of single converters. One of the advantages of all these methods is that they can be applied based on bus-impedance or loop-gain measurements which do not require a priori knowledge of the system parameters. In addition, these measurements can be performed during normal system operation by using the existing converters in the system, and, therefore, the methods are well suited for online stability assessment and adaptive control tuning.

Analyzing a multi-converter system either by a loop-gain approach or a bus-impedance approach has pros and cons. The loop-gain approach allows more direct information of the operation of a single converter and its stability margins. However, the method does not provide direct information of the overall system operation and global stability [10]. The bus-impedance approach, on the other hand, provides the dynamic performance of the complete system but does not reveal the effect of a single converter on system dynamics [12].

The present paper combines the loop-gain and bus-impedance approaches, and proposes a method for simultaneously obtaining the bus impedance and the loop gains of a multi-converter system. The method is based on orthogonal binary perturbations and cross-correlation technique [13]. In the method, each converter in a system applies an orthogonal injection simultaneously with the other converters. As the injections are orthogonal, that is, they have energy at different frequencies, the bus impedance and the loop gains can be measured at the same time within one measurement cycle even though the converters are coupled at the dc bus. Measuring both the bus impedance and loop gains is highly beneficial because together they produce the information of the dynamics of single converters and the complete system. In addition, consider a case where, for any reason, the bus impedance is not available at given time. This may happen when communication among converters is lost. For such a scenario, the loop gain can be used as a reliable alternative because any active converter can still measure its own loop gain and adaptively improve its own stability margins.

The proposed measurement method has several considerable advantages. This approach ensures that the bus impedance and loop gains are measured with the system in the same conditions, which may not be the case if sequential perturbations or separate experiments are applied. As the injections are binary, the sequences are very easy to implement even with a low-cost controller, whose output can only cope with a small number of signal levels. Therefore, the method does not require complex external data-acquisition devices but the injections and measurements can be performed by using the existing converters in the system. It is also emphasized, that the proposed method is highly versatile, and can be applied not only for multi-converter systems but also for a wide range of other power-electronics applications such as grid-connected systems.

The remainder of the paper is organized as follows. Section II reviews the theory behind the cross-correlation technique and orthogonal perturbation sequences used for bus-impedance and loop-gain measurements. Section III shows simulation examples and compares the proposed method to the previously presented single-input-single-output method. Section IV demonstrates the versatility of the proposed method and presents experimental results based on a grid-connected power-distribution system. Finally, Section V draws conclusions.

II. Theory and Methods

Fig. 2 shows a conceptual identification setup of a multi-converter system where each converter, represented by an impulse-response function $g_1(t), g_2(t), ..., g_n(t)$, is to be identified. The identification may involve input- and/or output-impedance measurements or loop-gain measurements. In a conventional identification process each converter is sequentially perturbed by an excitation signal $x_1(t), x_2(t), ..., x_n(t)$, producing the corresponding output response $y_1(t), y_2(t), ..., y_n(t)$. As the converters are most often interconnected and coupled, the superposition theorem dictates that in the identification process, when measuring the impulse-response function of one converter, no perturbation can be applied to other converters.

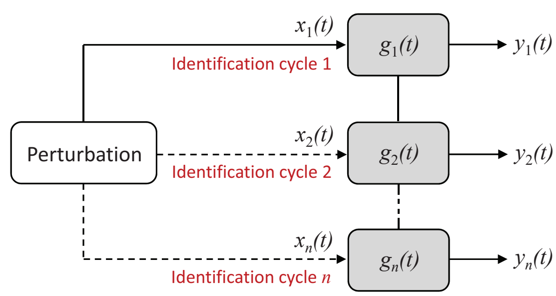

Fig. 2: Identification of MIMO system by using sequential perturbations.

Assuming the multi-converter system is linear for small disturbances, the sampled output can be described as

$$y_i(m) = \sum_{k=1}^{N} g_i(k)x_i(m-k) \tag{1}$$

where N is the length of the sampled output signal, and $i = 1, 2, ..., N$. Assuming the excitation resembles white noise, the cross-correlation between $x_i(m)$ and $y_i(m)$ can be shown to be [14]

$$R_{x_i y_i}(m) = \alpha g_i(m) \tag{2}$$

where α denotes the variance of $x_i(m)$. Hence, the cross-correlation between the measured input and output signals yields the system impulse response. The response can be converted to the frequency domain and represented as a frequency-response function by applying the Fourier transform. Therefore, the frequency response is obtained as

$$G(j\omega) = \frac{1}{\alpha}\mathcal{F}[R_{u_i y_i}(m)] \tag{3}$$

where $\mathcal{F}$ denotes the Fourier transform.

The only requirement for (3) is that the perturbation resembles white noise, that is, the autocorrelation of the perturbation must be a delta function. The method based on (3) has been applied in a number of applications of power-electronics converters and systems [15]–[18]. One of the most applied perturbations has been the maximum-length binary sequence (MLBS) which is a periodic broadband sequence having only two different signal levels. The sequence has a largely controllable spectral-energy content, and, due to the binary form, the sequence is very easy to implement compared to signals of non-binary form.

A. Orthogonal binary perturbations

Measuring the system-characterizing frequency responses from a system depicted in Fig. 2 may become tedious as the number of required frequency responses increases. In such a case, one may apply a method based on orthogonal perturbations. In the method, several orthogonal injections are simultaneously injected into the system. As the injections are orthogonal, that is, they have energy at different frequencies, several frequency responses can be measured at the same time within one measurement cycle. The technique has several considerable advantages over the methods using sequential perturbation, This approach not only saves overall experimentation time, because the system has to be allowed to settle to a dynamic steady state only once, but also ensures that each frequency response is measured under the same system operating conditions, which may not be the case if sequential perturbations are applied.

Previous studies have widely examined the synthesis of orthogonal injection sequences applicable to MIMO systems [13]. One of the most popular approaches has been a method based on Hadamard modulation [19]. In the method, a set of orthogonal excitation sequences are obtained as follows:

1) Generate a conventional MLBS by using a shift-register circuitry with feedback.
2) The second signal is obtained by forming an inverse-repeat sequence from the MLBS; that is, by adding, modulo 2, the sequence 0 1 0 1 0 1... to the first sequence.
3) The third sequence is obtained by adding, modulo 2, the sequence 0 0 1 1 0 0 1 1... to the original MLBS.
4) The fourth sequence is obtained by adding, modulo 2, the sequence 0 0 0 0 1 1 1 1 0 0 0 0 1 1 1 1... to the original MLBS, and so on.

A minor drawback of the technique is that the sequence length of the i^{th} orthogonal sequence is doubled compared to the length of the $(i-1)^{\text{th}}$ sequence. This feature means that the total time for the measurement may become substantially longer than in a single-input single-output measurement (although definitely still shorter than separate single-input single-output measurements). A significant advantage of the proposed technique is that the signal-to-noise ratio (SNR) can be improved. Since each signal is deterministic, averaging can be applied and signal-to-noise ratio increased such that the response of the first sequence is averaged over 2^{i-1} periods, the response of the second sequence over 2^{i-2} periods and so on.

Fig. 3 shows samples of three orthogonal binary sequences in the time and frequency domain obtained by the presented method. The first sequence is produced by a 6-bit-length shift register. All of the sequences are generated at 10 kHz. The energy values are scaled to facilitate the illustration. The three signals have non-zero energy only at different frequencies, that is, if one signal has non-zero energy at a certain frequency, the other two signals have zero energy at that frequency. The energies of all sequences drop to zero at the generation frequency and its harmonics. The design parameters of the sequences include the signal lengths and their generation frequencies, the signal amplitudes, and the number of injection periods. These parameters can be designed based on the requirements of the frequency resolution, measurement time and SNR.

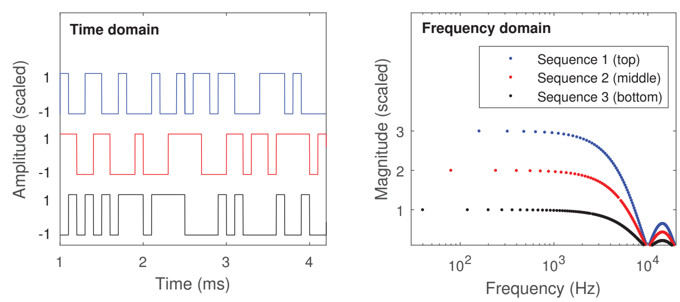

Fig. 3: Samples of three orthogonal sequences in the time and frequency domain.

III. Simulation Approach

Three switching converters (one source and two load converters) were connected together in Matlab/Simulink environment. Fig. 4 shows the system and the measurement setup for obtaining the bus impedance and loop gains. In the figure, $G_{\text{v\_s}}$ and $G_{\text{i\_s}}$ denote the voltage and current controllers of the source converter, and $G_{\text{v\_L1}}$, $G_{\text{i\_L1}}$, $G_{\text{v\_L2}}$, and $G_{\text{i\_L2}}$ are the corresponding controllers of the load converters. The main parameter values are given in Table I.

Three orthogonal binary sequences were designed. The first sequence had 1023 bits, the second 2046 bits, and the third 4092 bits. Each sequence was generated at 20 kHz. The injection amplitudes were selected such that the measured variables did not exceed their nominal values by more than 5 %. The perturbations were simultaneously injected on top of the inputs of the converter's voltage controllers. The voltages from both sides of the injection points, the output currents of each converter, and the bus voltage were simultaneously

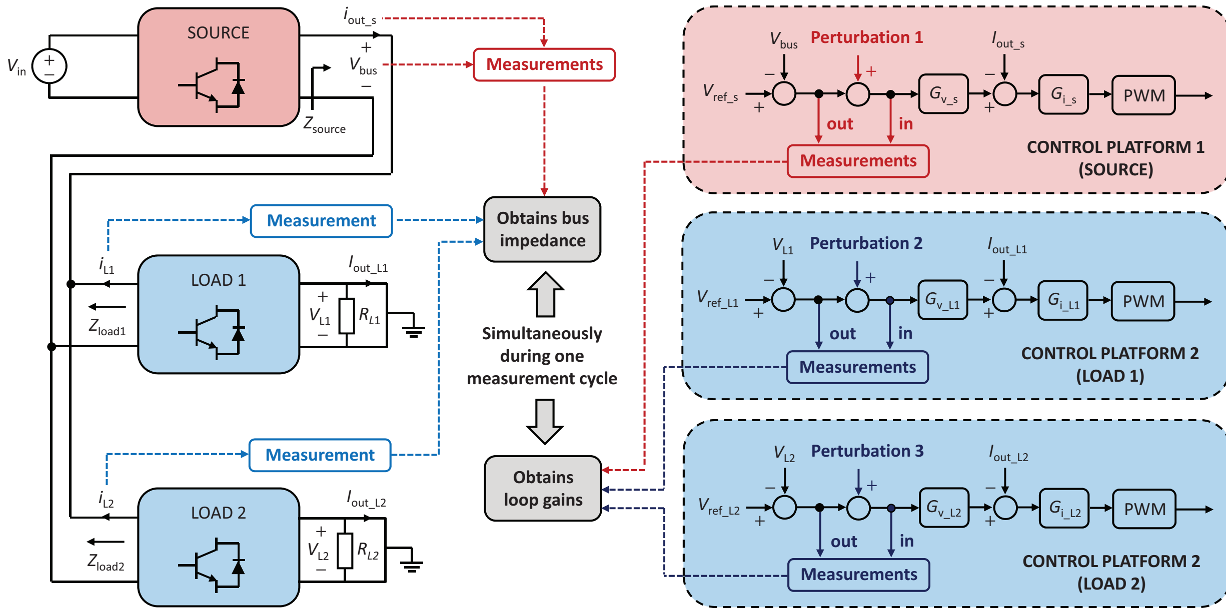

Fig. 4: Schematic diagram for measuring (simultaneously) the bus impedance and loop gains for a multi-converter system.

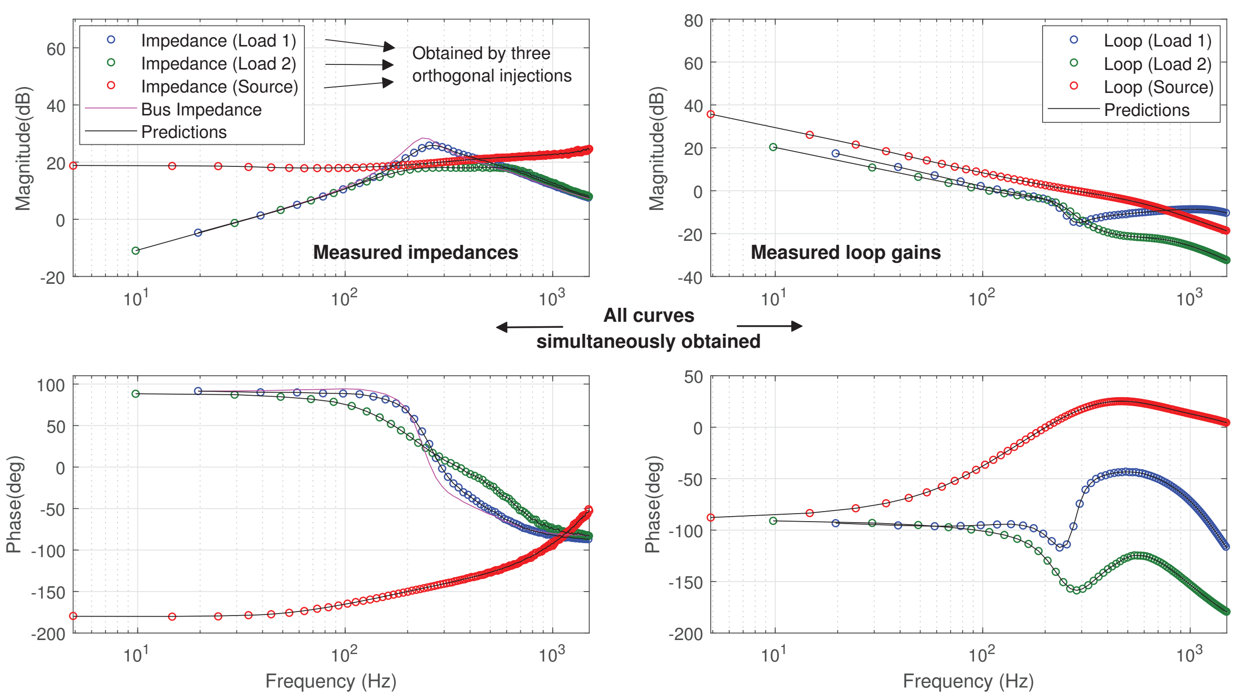

Fig. 5: Measured impedances and loop gains.

measured, and (3) was applied to each of the six input-output couple.

Fig. 5 shows the three impedances and the three loop gains measured using the proposed technique. The figure also shows the calculated bus impedance obtained by [8]

$$\frac{1}{Z_{\text{bus}}(s)} = \frac{1}{2}\left\{\frac{1}{Z_{\text{source}}(s)} + \frac{1}{Z_{\text{load1}}(s)} + \frac{1}{Z_{\text{load2}}(s)}\right\} \quad (4)$$

The references (black solid lines) are obtained by sequential measurements using the conventional MLBS (one at a time). As the figure shows, the impedances and the loop gains are accurately measured in a wide frequency band during a single measurement cycle. The responses in Fig. 5 indicate a stable system operation. All the controllers have more than 70 degrees of phase margin.

Fig. 5 shows that the bus impedance exhibits a peak resonance in the mid-frequency range. The frequency and the

TABLE I: Simulation parameters.

Converter	Parameter	Value	Perturbation
Source	V_{in} V_{ref_s}	200 V 100 V	Length: 1023 bits Amplitude: 0.05 V
Load 1	R_{L1} V_{ref_L1}	10 Ω 56 V	Length: 2046 bits Amplitude: 0.05 V
Load 2	R_{L2} V_{ref_L2}	2 Ω 41 V	Length: 4092 bits Amplitude: 0.05 V

TABLE II: Electrical parameters.

v_{dc}^{ref}	v_{g}^{ref}	f_{SW}	f_{grid}	L_1	L_2	C_f	R_f
410 V	120 V	8 kHz	60 Hz	2.5 mH	0.6 mH	10 μF	1.8 Ω

magnitude of this resonance as well as other post-calculated characteristics of the bus impedance are usually applied for a stability assessment based on the PBSC and AIR [8]. However, in the case of multiple source converters, the bus impedance may exhibit several resonances. In such a case, other methods are required to determine the converter that produces the highest peak resonance. In order to determine the resonance, loop-gain measurements of single converters can be used. The loop gains provide the phase margins of different source converters, and the converter having the lowest margin is usually responsible for the highest peak in the bus impedance. Therefore, more efficient damping of the bus impedance (that is, higher overall system stability) is achieved by adjusting the controller gains of the converter that has the lowest phase margin.

IV. Experimental Verification

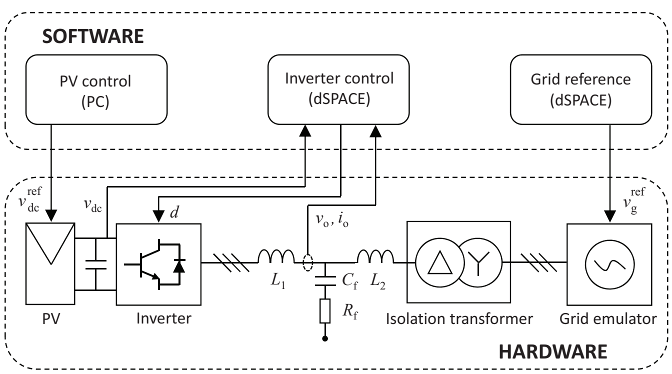

Fig. 6: System under study.

In order to demonstrate the versatility of the proposed method, several frequency responses were simultaneously measured from a grid-connected three-phase system. Fig. 6 shows the system under study. A 3 kW three-phase photovoltaic inverter is connected to a grid emulator through an LCL-filter and isolation transformer. The grid impedance is composed of a series-connected three-phase inductance (4.0 mH). The inverter is fed by an electric photovoltaic emulator, and the grid is emulated using a three-phase linear amplifier, which can sink all of the generated power. The inverter utilizes a conventional dq-domain current control and a cascaded dc-voltage control. The electrical parameters are shown in Table II.

Two orthogonal binary sequences were designed in order to simultaneously measure the inverter's voltage-controller loop gain, the inverter output admittance, and the grid impedance. The first sequence had 2047 bits and the second 4094 bits. Each sequence was generated at 4 kHz. The injection amplitudes were selected so that the measured voltages and currents did not exceed their nominal values by more than 5%. The first sequence was injected on top of the inverter's voltage-controller reference with 100 periods and the second sequence on top of the reference voltage (q-component) of the grid emulator with 50 periods (because the length of the second sequence is twice compared to the first sequence). Therefore, the total injection time was approximately 51 s. Fig. 7 shows a conceptual diagram of the measurement setup.

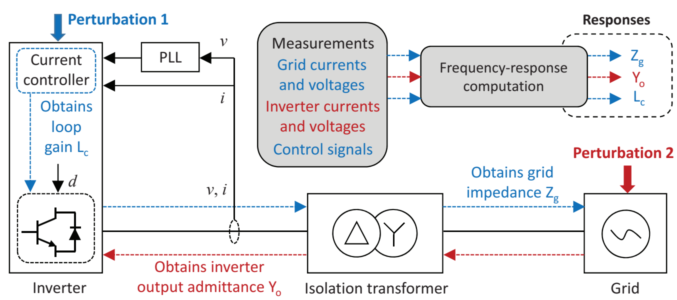

Fig. 7: Conceptual diagram of the measurement setup.

The data acquisition and post processing were performed as follows.

- Loop gain: the voltages from both sides of the injection point were measured after which (3) was applied. The measurements were averaged over 100 injection periods.
- Inverter output admittance: the inverter output voltages and currents were measured and transformed into the dq domain after which (3) was applied. The measurements were averaged over 50 injection periods.
- Grid impedance: the output voltages and currents of the grid emulator were measured and transformed into the dq domain after which (3) was applied. The measurements were averaged over 100 injection periods.

Fig. 8 shows the measured grid impedance, voltage-controller loop gain, and inverter output admittance. The grid impedance and the loop gain are obtained by Perturbation 1, and the inverter output admittance by Perturbation 2. In this example, only the q-components are shown for the grid impedance and for the inverter output admittance. The d-components were measured as well and they showed similar behavior. As the figure shows, the frequency responses are consistently obtained in a wide frequency range with a relatively low variance. The orthogonality of the perturbations can be observed as the inverter output admittance is obtained at different frequencies compared to the other two responses.

The frequency responses shown in Fig. 8 confirm a stable operation of the system with a controller's phase margin of approximately 35 degrees.

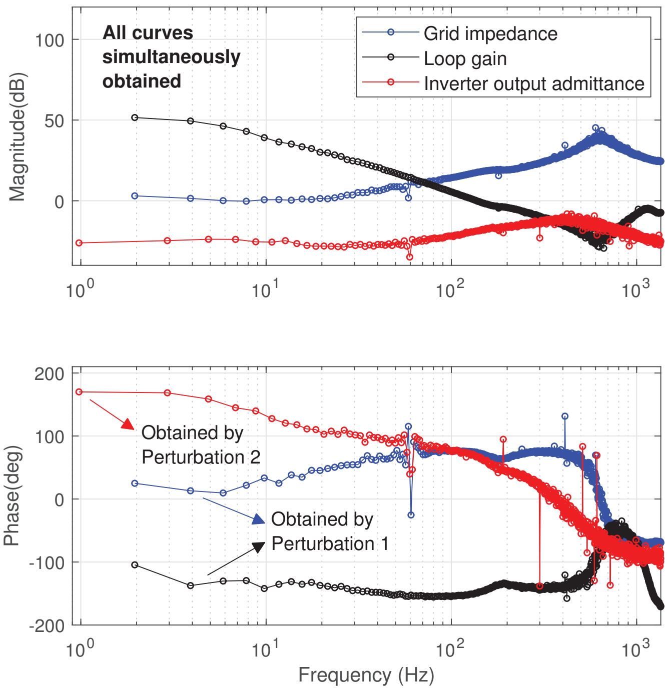

Fig. 8: Measured q-components of grid impedance, voltage-controller loop gain and inverter output admittance.

V. Conclusion

Bus impedance and loop gains are important quantities for stability analysis and control design of interconnected systems that consist of multiple power converters. This paper has presented a method based on cross-correlation technique and orthogonal binary sequences to simultaneously measure the bus impedance and loop gains of interconnected multi-converter system. Applying the proposed method, the bus impedance and the loop gains can be measured within a single measurement cycle, therefore guaranteeing constant operating conditions during the experiments. Due to the binary form of the perturbations, the method is well implementable even by using a low-cost signal generator. Experimental measurements based on a grid-connected converter were presented to demonstrate the effectiveness and versatility of the proposed method.

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