Real-Time Stability Analysis and Control of Multiconverter Systems by Using MIMO-Identification Techniques

Tomi Roinila, *Member, IEEE*, Hessamaldin Abdollahi, *Student Member, IEEE*, Silvia Arrua, *Student Member, IEEE*, and Enrico Santi, *Senior Member, IEEE*

***Abstract*—DC distribution systems typically consist of several feedback-controlled switched-mode converters forming a complex power distribution system. Consequently, a number of issues related to stability arise due to interactions among multiple converter subsystems. Recent studies have presented methods such as passivity-based stability criterion, where the stability and other dynamic characteristics of an interconnected system can be effectively analyzed using bus-impedance measurement. Studies have presented online measurement techniques, where the bus impedance is obtained by combining together the measurements of input and output impedances of single converters in the system. Since the converters are coupled, the presented measurement techniques require several measurement cycles in order to sequentially measure the individual impedances to be combined to obtain the overall bus impedance. This paper presents a measurement technique based on injection of orthogonal binary sequences. Applying this method, all the impedances in the system can be simultaneously measured during one measurement cycle. Therefore, the overall measurement time of the bus impedance is reduced compared to conventional measurement techniques. Furthermore, the method guarantees that the system dynamics do not change between measurements, and therefore, the computed bus impedance is not distorted. Experimental results are presented and used to demonstrate the effectiveness of the proposed method in the design of a stabilizing controller for a notional dc system using positive feed-forward control.**

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

I. Introduction

DC POWER distribution systems are extensively used to power various electronic loads and processes. Such systems are considered as a feasible alternative to traditional ac systems due to the high performance, efficiency, and flexibility that power electronics offer. A great interest in developing these types of systems is found in various fields, including hybrid and electric vehicles, aircrafts, and electric ships [1], [2].

Manuscript received November 23, 2017; revised April 15, 2018; accepted July 5, 2018. Date of publication July 15, 2018; date of current version February 20, 2019. This work was supported in part by the Academy of Finland and in part by the Office of Naval Research under Grant N00014-16-1-2956. Recommended for publication by Associate Editor Prof. S. K. Mazumder. *(Corresponding author: Tomi Roinila.)*

T. Roinila is with the Department of Automation Science and Engineering, Tampere University of Technology, 33720 Tampere, Finland (e-mail: tomi.roinila@tut.fi).

H. Abdollahi, S. Arrua, and E. Santi are with the Department of Electrical Engineering, University of South Carolina, Columbia, SC 29208 USA (e-mail: abdollh@email.sc.edu; sarrua@email.sc.edu; santi@cec.sc.edu).

Color versions of one or more of the figures in this paper are available online at http://ieeexplore.ieee.org.

Digital Object Identifier 10.1109/TPEL.2018.2856532

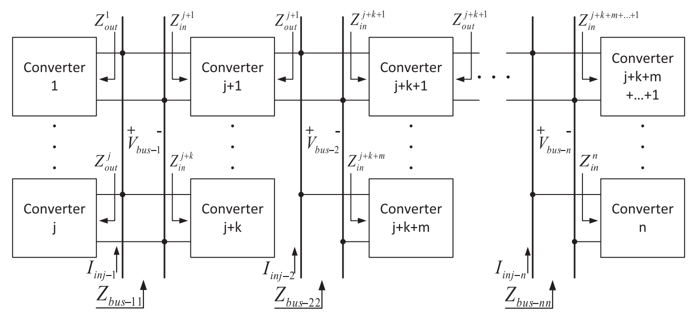

Fig. 1. Conceptual multibus system showing multiple interconnections [3].

Power-electronics-based DC-distribution systems consist of multiple converters creating a complex interconnected system. These systems are now being applied in several areas, including advanced automotive power systems, electric and hybrid-electric vehicles, telecommunication systems, as well as electric ship and electric aircraft power systems [4]–[6].

Consider the multibus power-electronics-enabled distribution architecture shown in Fig. 1. This system has n buses and contains a number of interconnected switching converters. Each of these interconnected converters typically has high-bandwidth feedback control. Converters that are standalone stable may exhibit a different dynamic behavior when interconnected and the small-signal stability may be compromised. This emergent behavior is due to interactions among the converter feedback loops through the dc bus interconnections [6]. Several stability criteria based on the equivalent bus impedances resulting from the converter interconnections have been proposed to evaluate the performance of a multiconverter system [7], [8]. Recently, the passivity-based stability criterion (PBSC) has been proposed, and the concept of an allowable impedance region (AIR) based on the Nyquist contour of the system bus impedance has been developed alongside the PBSC to ensure a good stability margin and dynamic performance [3], [9]. One of the advantages of the PBSC and AIR is that they can be applied based on bus-impedance measurements that do not require *a priori* knowledge of system parameters. The methods are well suited for online stability assessment and adaptive control tuning.

In order to cope with strong and fast-scale interactions in an interconnected power-electronics system, it is of high interest to adaptively perform the procedure of stability analysis and controller design. Because the bus impedance typically varies over time as a function of many parameters, the conventional control approach based on offline bus-impedance measurement of the interfaced converters is insufficient to guarantee stability. Therefore, accurate bus-impedance information acquired in real time is most desirable.

Recent studies have presented wideband methods suitable for fast and accurate online bus-impedance measurement of interconnected power-electronics systems [10]. In the methods, a broadband perturbation such as pseudo-random binary sequence (PRBS) is injected on top of the converter controller references or duty cycle using the existing converters in the system. The resulting voltage and current responses are measured at the output or input of the converters, and Fourier analysis is applied to obtain the impedances seen by single converters. The bus impedance is then computed as a combination of the measured impedances [10].

In a typical interconnected power-electronics system, the single converters are coupled at the dc bus. This means that multiple measurement cycles are required to obtain all the impedances needed in order to compute the bus impedance. In the case of three converters, the first converter is used as a perturbation source to obtain the impedance seen looking out from its terminals, which is the parallel combination of the impedances of the other two converters. Then, the second converter is used for perturbation, and finally the third one. As the number of converters increases, this single-input single-output method becomes tedious and time consuming. Furthermore, the operating conditions may change between the measurements.

This paper proposes the use of binary orthogonal sequences for simultaneous measurements of all the impedances of a multiconverter system. 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, all the impedances can be measured at the same time within one measurement cycle.

The proposed method has several considerable advantages over the methods using sequential perturbation of the individual converters. 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 impedance is measured with the system in the same conditions, which may not be the case if sequential perturbations 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.

The remainder of this paper is organized as follows. Section II reviews the theory behind the orthogonal binary sequences and their synthesis, and presents the Fourier technique required for obtaining the bus impedance from measured data. The section also reviews the methods for stability analysis and control design. Section III shows simulation examples and compares the proposed method to the previously presented single-input single-output method. Section IV presents experimental results based on a dc-power-distribution system and Section V a discussion of the proposed method. Finally, Section VI draws conclusions.

This paper is a revised and extended version of the work presented at the ECCE 2017 conference [11]

II. Theory and Methods

A. Stability Analysis and Control Design

The proposed identification technique has many applications; particularly, it can be implemented to measure the bus impedance of an interconnected power-electronics system. In this paper, the bus impedance measurement will be used for stability analysis and for the design of a stabilizing controller to provide an application of the proposed method.

Lack of stability or performance of an interconnected power-electronics system can be typically compensated by the design of a virtual damping network. The network can be actively inserted into the system bus with the objective of damping resonances or modifying the bus impedance to meet one of the several proposed stability criteria [12]. A possible way for introducing this active damping to the system is using positive feed-forward (PFF) control for the load converter in conjunction with negative feedback.

A recently proposed bus-impedance-based stability criterion is the PBSC, which requires modifying the bus impedance so that it appears passive [9]. The condition for passivity can be given as follows:

1) bus impedance $Z_{\text{bus}}(j\omega)$ contains no right-half-plane poles;
2) $Re\{Z_{\text{bus}}(j\omega)\} \geq 0, \forall\omega$.

The PBSC provides insight on the general stability of the system under study; however, it does not give information regarding transient performance. To overcome this limitation, the AIR has been proposed [10]. The AIR considers a simplified representative function of a system bus impedance to establish an allowed region in the s-domain, given in (1), for which the system will have desired dynamic performance. A minimum damping ratio ζ_{min} for oscillations is ensured if the magnitude of the system bus-impedance Nyquist contour is within the region established by

$$M(\alpha) = \frac{1}{2\zeta_{\text{min}}} e^{j\alpha} \quad \text{for} \quad -\frac{\pi}{2} \leq \alpha \leq \frac{\pi}{2}. \tag{1}$$

Based on the AIR, an appropriate damping impedance remains stable and has the desired transient response

$$Z_{\text{damp}} = Z_{\text{o-damp}} \frac{\frac{s^2}{\omega_0^2} + 2\zeta_{\text{damp}}\frac{s}{\omega_0} + 1}{\frac{s}{\omega_0}}. \tag{2}$$

In (2), ζ_{damp} has to be chosen large enough to minimize the potential for creating additional resonances. In general, $\zeta_{\text{damp}} = 1$ is considered a good choice. After obtaining the bus impedance, the design procedure for Z_{damp} can be summarized as follows:

1) determine the bus impedance resonant frequency ω_0;
2) obtain $|Z_{\text{bus}}(j\omega_0)|$ and $|Z_{\text{bus}}(j\omega_1)|$ for $\omega_1 \ll \omega_0$;
3) determine the characteristic impedance $Z_{\text{o-bus}} = |Z_{\text{bus}}(j\omega_1)|\frac{\omega_0}{\omega_1}$;
4) determine the damping ratio $\zeta_{\text{bus}} = \frac{Z_{\text{o-bus}}}{2|Z_{\text{bus}}(j\omega_0)|}$;

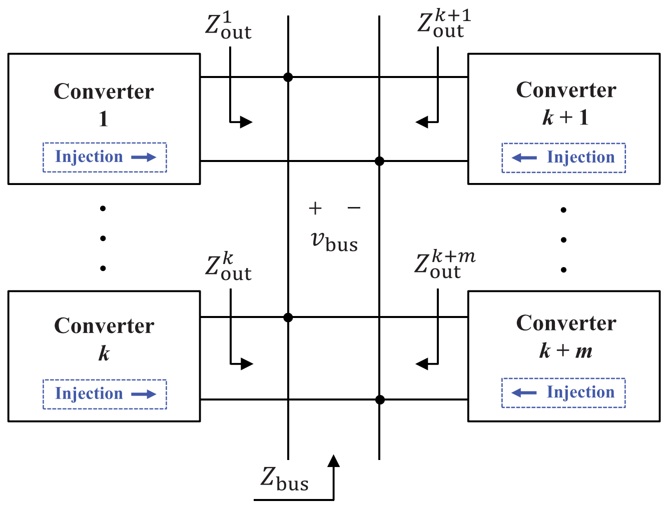

Fig. 2. Multiconverter system.

5) determine $Z_{\text{o-damp}} = [\frac{2}{Z_{\text{o-bus}}}(\frac{1}{|M|-K_m} - 2\zeta_{\text{bus}})]^{-1}$, where $K_m(0 \le K_m \le |M|)$.

The obtained damping impedance can be introduced into the system via PFF control of a load converter, i.e., of a converter having its input connected to the bus to be stabilized. The PFF method adds an input feedforward path to the controller with the objective of modifying the equivalent input impedance of the converter so that it can stabilize the bus. More details on this approach are found in [9] and [10].

Accurate knowledge of the bus impedance is critical for the success of the aforementioned controller-design techniques. Because the bus impedance typically varies over time as a function of many parameters, offline bus-impedance measurement followed by a custom design of the controllers is insufficient to guarantee the desired system dynamics. Therefore, using accurate bus-impedance information acquired in real time is the most desirable approach.

B. Bus-Impedance Measurement for Multiconverter Systems

A power-electronics-based multiconverter system can be considered a linear time-invariant system for small disturbances. Now, consider Fig. 2 depicting a multiconverter system which has k source converters and m load converters connected to a dc bus. The impedances seen by the source converters are denoted by $Z_{\text{out}}^1, \cdots, Z_{\text{out}}^k$, and the impedances seen by the load converters are denoted by $Z_{\text{out}}^{k+1}, \cdots, Z_{\text{out}}^{k+m}$. Note that Z_{out}^1 is the impedance seen by converter 1 and is the parallel combination of the impedances of all other converters connected to the bus. Injecting a perturbation from each converter one at a time, all these impedances can be measured and the bus impedance Z_{bus} obtained from [3]

$$\frac{1}{Z_{\text{bus}}(s)} = \frac{1}{k+m-1}\left\{\frac{1}{Z_{\text{out}}^1(s)} + \cdots + \frac{1}{Z_{\text{out}}^k(s)} + \frac{1}{Z_{\text{out}}^{k+1}(s)} + \cdots + \frac{1}{Z_{\text{out}}^{k+m}(s)}\right\}. \quad (3)$$

The factor $1/(k+m-1)$ is due to the fact that the impedance contributed by one converter is seen and measured by all the other $k+m-1$ converters.

Recent studies have used wideband-measurement techniques to obtain the bus impedance of a multiconverter system [10]. Using a single-input single-output approach, the converters must be perturbed one at a time. A broadband perturbation such as PRBS is injected on top of the converter controller references or duty cycle one converter at a time. The resulting voltage and current responses are measured at the bus, and Fourier analysis is applied to obtain the impedances seen by each converter. The bus impedance is then computed by using (3).

For the case of multiple converters shown in Fig. 2, several measurement cycles are required to obtain all the input and output impedances when applying the conventional single-input single-output measurement techniques. As the number of input–output combinations increases, the overall measurement time may become large. In addition, the operating conditions may change between measurements, reducing measurement accuracy.

In this paper, orthogonal binary sequences are applied for simultaneous measurement of all the impedances in a multiconverter system. In the method, all converters apply an injection at the same time. Due to orthogonality, the injected energy lies at different frequencies for different injections, and hence, the cross coupling between converters is avoided. Consequently, only one measurement cycle is required to obtain all impedances. Therefore, the overall measurement time is reduced. Furthermore, the method guarantees that the system dynamics do not change between the measurements, and hence, the computed bus impedance is not distorted.

C. Orthogonal Binary Sequences

Previous studies have widely examined the synthesis of multi-input excitation sequences applicable to multiple-input-multiple-output (MIMO) systems [13]–[15]. Two approaches for generating such sequences are commonly used. The first one applies shifted versions of the same signal to excite the various inputs, and separates their effects using cross-correlation techniques [16]. The other approach applies uncorrelated orthogonal signals so that the effects of different inputs are decoupled [13]. The latter technique reduces the overall measurement time compared to the first approach, and also guarantees that the system operating conditions are not changed between the measurements. This paper utilizes this latter technique, using the set of orthogonal excitation sequences obtained by applying the technique presented in [13]. The technique is applied as follows.

1) A PRBS signal is generated using a shift-register circuitry with feedback [17].
2) The second signal is obtained by forming an *inverse-repeat binary sequence* (IRS) from the PRBS signal; 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 PRBS signal.

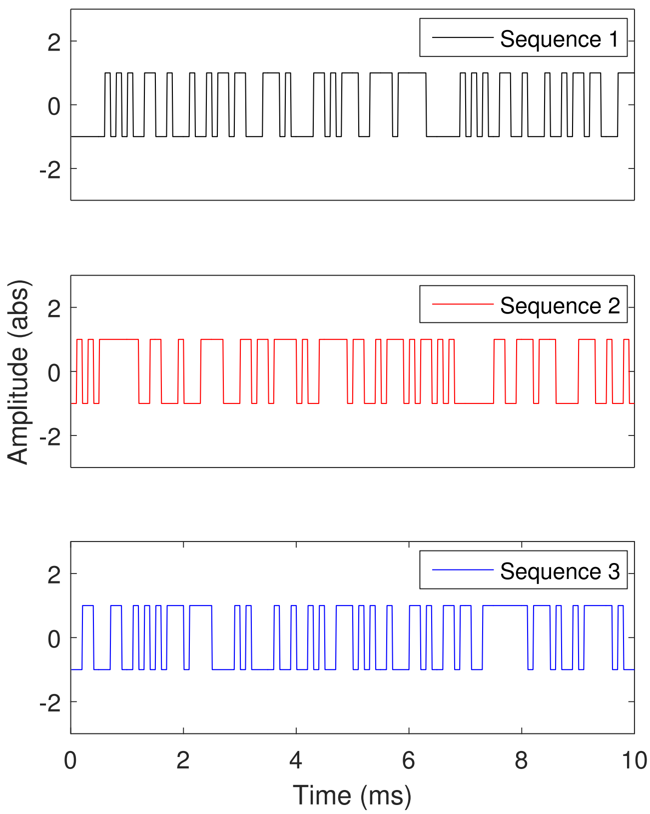

Fig. 3. Three orthogonal sequences in time domain.

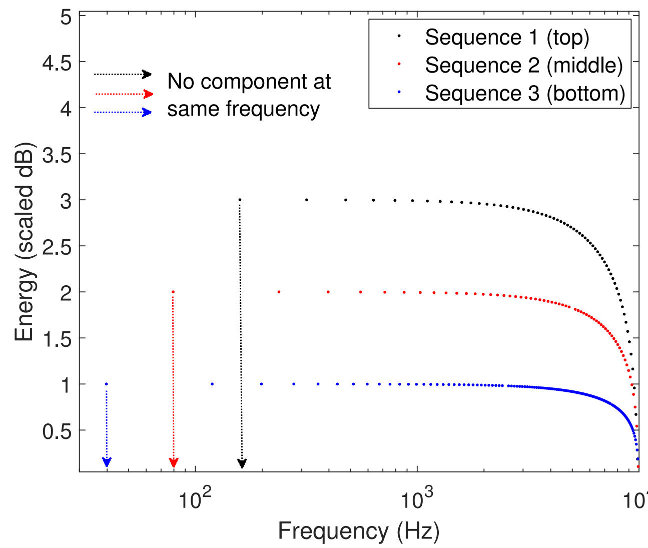

Fig. 4. Energy content of three orthogonal sequences.

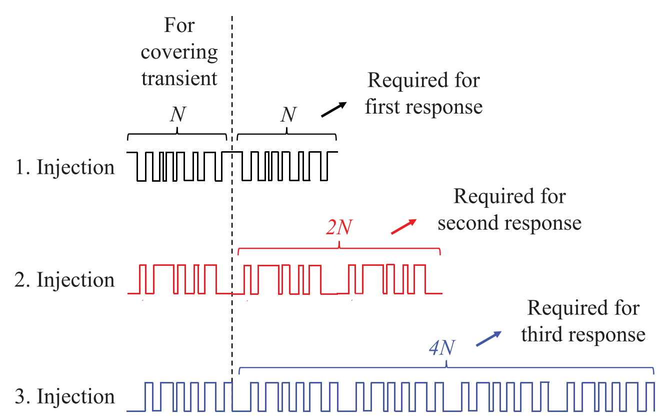

Fig. 5. Illustration of measurement time using simultaneous orthogonal PRBS injections.

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 PRBS signal, and so on.

A minor drawback of the technique is that the sequence length of the ith orthogonal sequence is doubled compared to the length of the $(i-1)$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 numerous single-input single-output measurements). A significant advantage of the proposed technique is that the signal-to-noise ratio 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 can be averaged over 2^{i-2} periods and so on.

Fig. 3 shows samples of three orthogonal binary sequences 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. Fig. 4 shows the power spectra of these sequences. The energy values are scaled to facilitate the illustration. The three signals have nonzero energy only at different frequencies, i.e., if one signal has nonzero 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.

It should be emphasized that when the abovementioned technique is applied, the second uncorrelated sequence is a form of inverse-repeat binary sequence (IRS) [18]. The IRS cancels out the effect of even-order nonlinearities, thus providing a more accurate estimate of the underlying linear dynamics. This property can provide significant benefit when choosing for the second sequence the input-output couple that suffers the strongest effect of nonlinearities.

Fig. 5 illustrates the measurement time required for simultaneous measurements of multiple responses. The figure shows an example where three orthogonal injections are simultaneously applied. Assuming that the system transient period is equal to the length of the first injection (N), the total measurement time to obtain all three frequency responses would be $5N$. As the injections are periodic sequences, the data acquisition can be started at any point as long as full periods are acquired. Applying single injections of length N sequentially to the three converters, the total measurement time to obtain all three responses would be $6N$ ($3N$ for the transients and $3N$ for the responses). An additional advantage of using multiple simultaneous injections is that during the measurement time period of

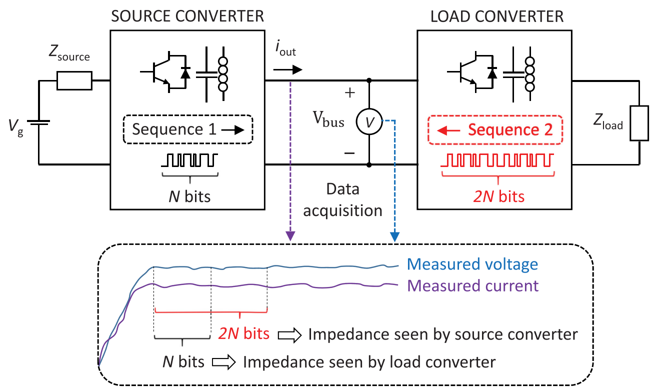

Fig. 6. Measurement principle of bus impedance.

$5N$, the first response can be averaged over four injection periods and the second response over two injection periods, after discarding the transient period of length N at the beginning.

D. Orthogonal Sequences in Bus-Impedance Measurement

Considering a multiconverter system, one must compute the impedances seen by each converter in order to obtain the bus impedance, as shown in (3). In such a measurement, the impedance of each converter is computed by utilizing the same point for voltage measurement. Therefore, it may be somewhat confusing how several impedances can be simultaneously obtained by using only a single voltage/current measurement. Fig. 6 shows a conceptual diagram of a two-converter single-phase system and its bus-impedance measurement. In the system, two orthogonal sequences of lengths N and $2N$ are applied, and only one voltage and current are measured. In the setup, N-bit-long samples of the measured voltage and one current provide the data required for measuring the impedance seen by the load converter, and $2N$-bit-long samples of the voltage and current provide the data required for measuring the impedance seen by the source converter. The data sequences for obtaining the impedances overlap, but each sequence is analyzed at different frequencies as shown in Fig. 7. As the data length required for obtaining the second impedance is twice compared to the data length required for obtaining the first impedance, one may average the data required for measuring the first impedance without increasing the overall measurement time. Notice also that since the orthogonal sequences are periodic, the measurements can be initiated at an arbitrary time, as long as full data cycles (N, $2N$, $4N$, etc.) are collected. Therefore, synchronization among converters is not required.

E. Frequency-Response Computation

Several techniques can be used to compute the impedances of a multiconverter system once the measurement data is acquired. One method is to use cross correlation between the measured bus voltage and converter current to obtain the impulse-response function of the impedance, after which Fourier transform is applied to compute the frequency response [19], [20]. An alternative to the cross-correlation technique is to use directly a

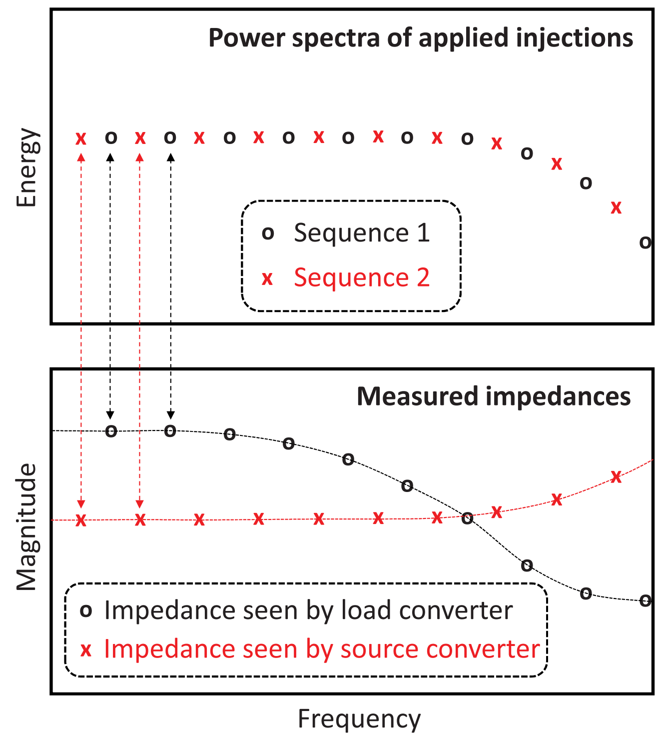

Fig. 7. Obtaining simultaneously several impedances.

frequency-domain computation, that is, the measured data sequences are first transformed into the frequency domain, after which the frequency responses are computed by using cross spectrum between the input and output spectra [21].

In this work, a logarithmic averaging procedure is applied [22]. Assuming a perturbation is injected through each converter (see Fig. 2), it can be shown that impedance $Z^i_{\text{out}}(j\omega)$ can be computed by applying logarithmic averaging as

$$Z^i_{\text{out}}(j\omega) = \left(\prod_{n=1}^{P} \frac{V_{\text{bus}}(j\omega)}{I_i(j\omega)}\right)^{1/P} \quad (4)$$

where $(i = 1, 2, \cdots, k, \cdots, k+m)$, V_{bus} denotes the Fourier-transformed bus voltage, I_i is the Fourier-transformed output (or input) current of ith converter, and P denotes the number of injected excitation periods. In the method, the measurements of voltage and current are segmented and Fourier-transformed, after which (4) is applied. The method is particularly useful in practice because it tends to cancel out the effect of noise from both the input and output sides [23].

III. Simulation Study

Three buck converters were connected together in the MATLAB/Simulink simulator environment in accordance with Fig. 8. Three orthogonal binary sequences were designed. The first sequence had 4095 bits, the second 8190 bits, and the third 16380 bits. Each sequence was generated at 20 kHz. The injection amplitudes were selected such that the measured bus voltage and converter currents did not exceed their nominal values by more than 5 %. The perturbations were simultaneously

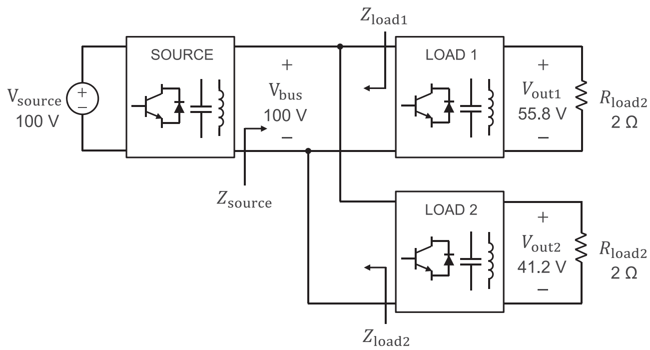

Fig. 8. System under test.

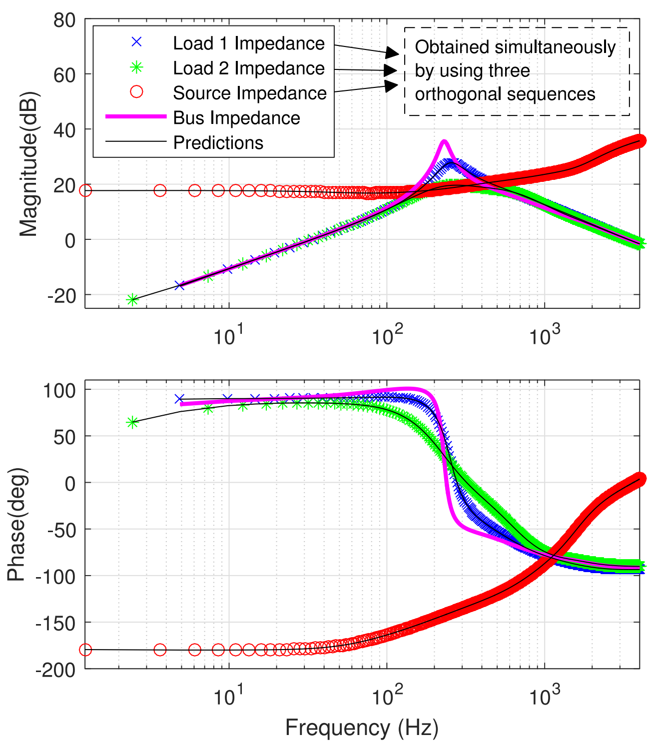

Fig. 9. Impedances Z_{load1}, Z_{load2}, and Z_{source} of Fig. 8 measured using orthogonal sequences (simulation).

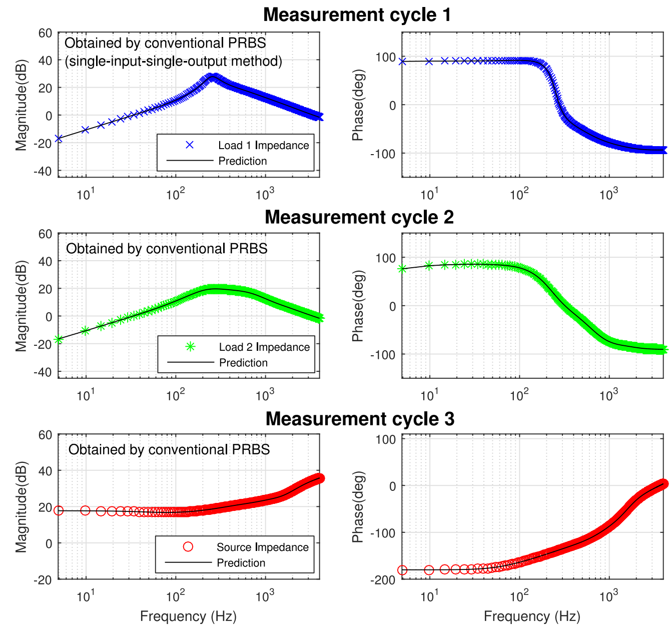

Fig. 10. Impedances Z_{load1}, Z_{load2}, and Z_{source} of Fig. 8 measured using single-input single-output method (simulation).

injected on top of the controller reference of each converter. The resulting bus voltage and currents were measured; after this, (4) was applied and the bus impedance was computed by using (3).

Fig. 9 shows the three impedances measured using the proposed technique. The calculated bus impedance obtained applying (3) to the measured impedances is shown as a magenta solid line. The references (black solid lines) are obtained by applying single sine sweeps to each converter (one at a time). As Fig. 9 shows, the input and output impedances (and hence the bus impedance) are accurately measured in a wide frequency band during a single measurement cycle.

As a comparison, the impedances were also measured by a conventional single-input single-output method [10]. In the measurement, a PRBS injection was applied from each converter one at a time. Fig. 10 shows the measured impedances when a 4095-bit-length PRBS was applied with a generation frequency of 20 kHz. As expected, the single-input single-output method calculates the impedances with the same accuracy as the orthogonal sequences. However, the latter technique requires three separate measurement cycles in order to obtain the impedances. Therefore, the overall measurement time is increased. In addition, the latter method does not guarantee that the system operating conditions remain same between the measurements.

IV. Experimental Verification

The dc-power-distribution system depicted in Fig. 11 was constructed in the laboratory using custom designed IGBT-based switching converters. The system consists of a source buck converter supplying a voltage source inverter feeding a resistive load; both converters switch at 20 kHz and operate under feedback control using an inner current loop and outer voltage loop PI control strategy. The digital control is implemented using a dSPACE DS1104 DSP-based control platform.

Two orthogonal binary sequences were designed and added to the controller references. The first sequence had 4095 bits and the second 8190 bits. Each sequence was generated at 20 kHz. The injection amplitudes were selected such that the measured bus voltage and converter currents did not deviate from their nominal values by more than 5% (see Fig. 13). This required a 10% injection signal amplitude. The first sequence was injected with 10 periods and the second sequence with 5 periods. Therefore, the total injection time was approximately 2 s. The resulting bus voltage and converter currents were measured; after this, (4) was applied. The bus impedance was then computed using (3).

Fig. 12 shows a sample of the output voltage of the source converter with and without the injection. The voltage during

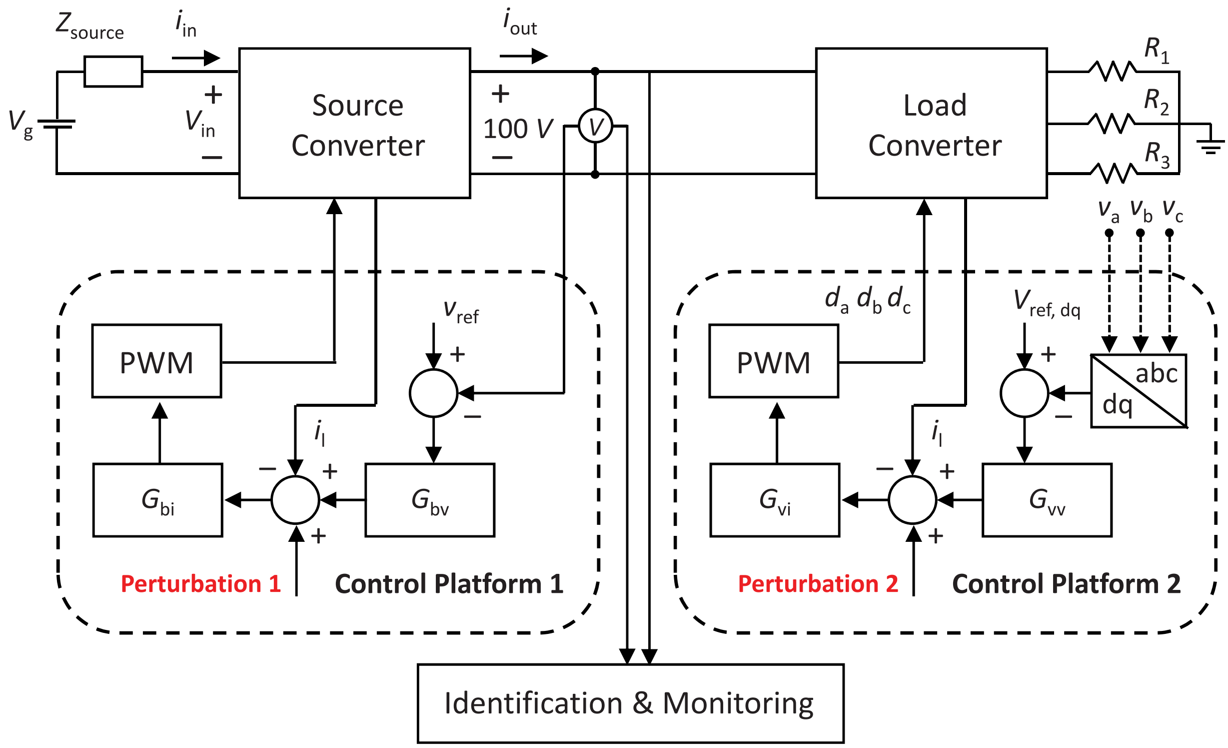

Fig. 11. System under test.

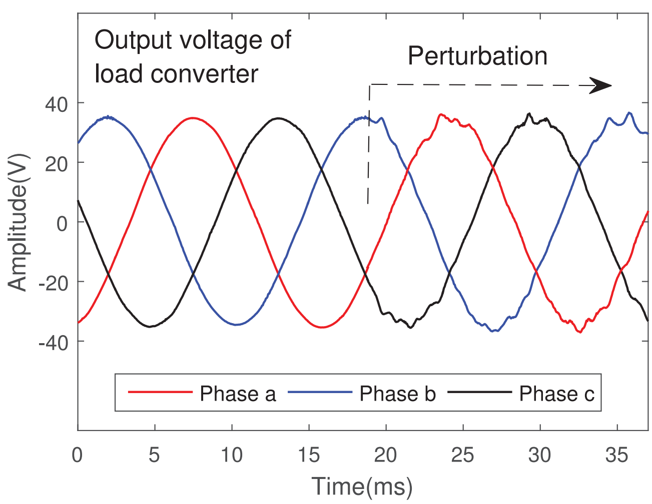

Fig. 12. Sample of perturbed and nonperturbed output voltage of the load converter.

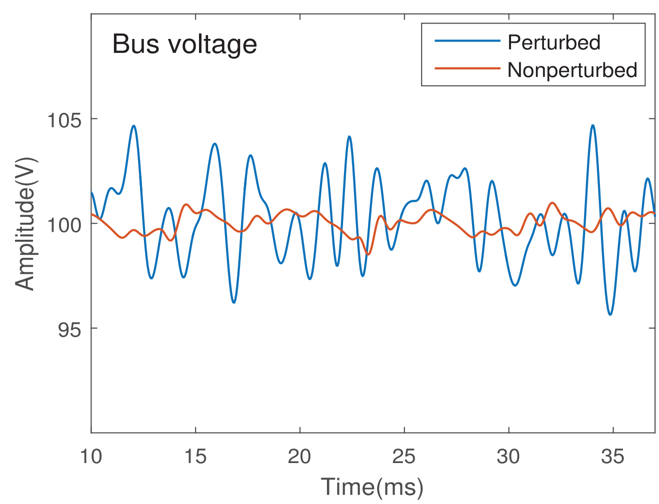

Fig. 13. Sample of perturbed and nonperturbed bus voltage.

the injection exceeds the nominal voltage value only by approximately 5%, and therefore, the system operates well within the defined limits. Fig. 13 shows similar behavior for the bus voltage.

Fig. 14 shows the measured input and output impedance and the computed bus impedance. As the figure shows, the impedances are correctly obtained over a wide frequency range (during a single measurement cycle) and match the references quite well. The references are obtained using single PRBS injections, that is, the converter impedances are separately measured using the conventional PRBS method. The figure shows that the bus impedance (magenta solid line) closely follows the output impedance of the source buck converter except at the resonance frequency. This is expected as the output impedance of the buck converter is much smaller than the input impedance of the voltage-source inverter and dominates in the parallel combination. At the resonant frequency, the situation is different: the input and output impedances have comparable amplitude, and the bus impedance shows a peak at this frequency as a result of interaction of the two parallel impedances. The phase of the bus

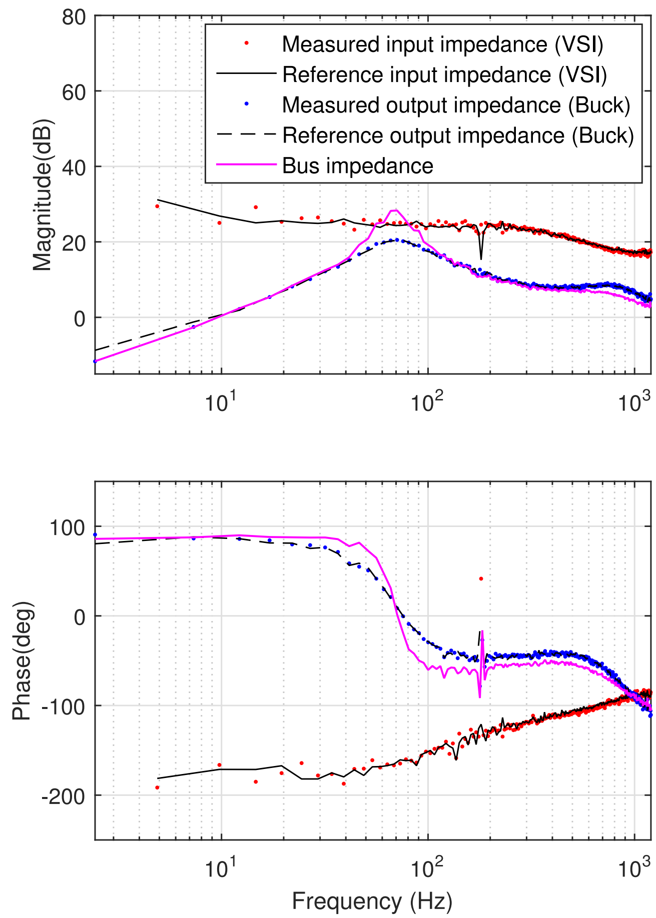

Fig. 14. Measured load and source impedances using orthogonal sequences and computed bus impedance.

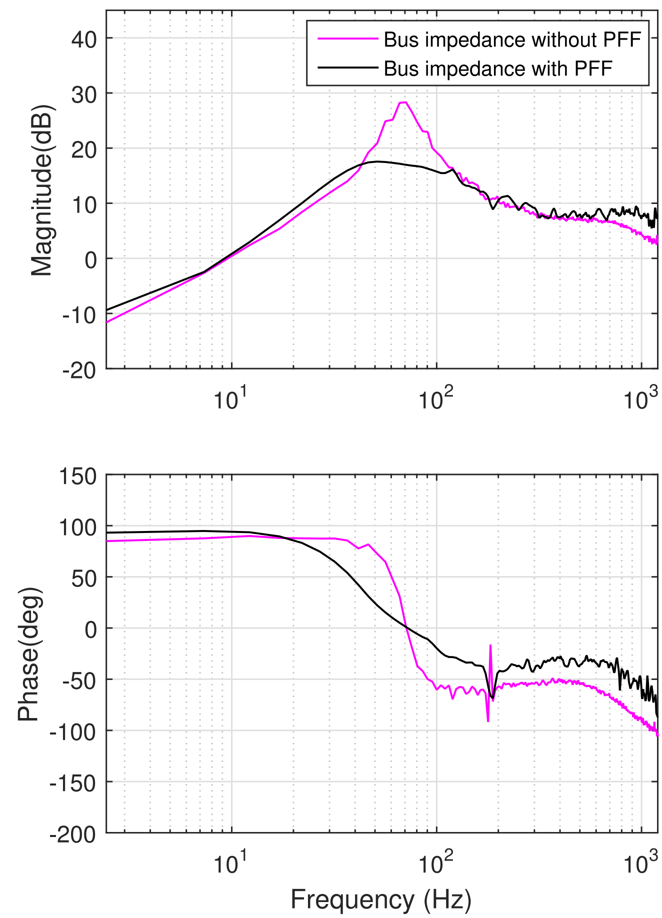

Fig. 15. Bus impedance with and without positive feedforward controller.

impedance stays within ±90 degrees in a wide frequency range. Therefore, since the impedance is passive, the system is stable. Due to the large peak at the resonance, however, the transient behavior of the system is not well damped.

A. Control Design

The control design method based on AIR presented in Section II was applied and a PFF controller was designed based on the online measurements. The same orthogonal injections were applied, and the bus impedance was measured with the PFF controller. Fig. 15 shows the measured bus impedance with and without the controller. As the figure shows, the magnitude at the resonance frequency is reduced by approximately 10 dB, which indicates improved transient behavior of the system.

Fig. 16 shows the step response in the bus voltage before and after adding the PFF controller. The step is introduced in the output voltage reference of the load converter. As the figure shows, in the absence of the PFF controller the bus voltage response is oscillatory and the system is lightly damped. The PFF controller introduces extra damping and the bus voltage response becomes better behaved.

V. DISCUSSION

This paper has clearly shown the advantages of using orthogonal binary injections to perform accurate and fast bus-impedance measurement of multiconverter systems. Applying the proposed method, only one measurement cycle is required to obtain all the impedances in a system. This not only reduces the overall measurement time, but also guarantees that the operating conditions of single converters do not change between measurements. The method makes it possible to simultaneously measure an arbitrary number of converter impedances.

Comparing the proposed method to conventional techniques, such as methods based on injection of single sinusoids, there are certain drawbacks that need to be discussed. First, the possible nonlinearities should be carefully considered. As most converter systems are nonlinear, injecting a signal with a given frequency will generate energy at multiple additional frequencies in response to it. In the proposed method, by injecting multiple frequencies at the same time, although the input sequences are orthogonal and do not overlap on their spectral content, the responses of the subsystems may overlap due to their nonlinearity. Therefore, if the system under test shows strong nonlinearities, the measured responses may be strongly distorted.

One method to study the effect of nonlinearities is to apply an excitation with given frequencies, and measure the response

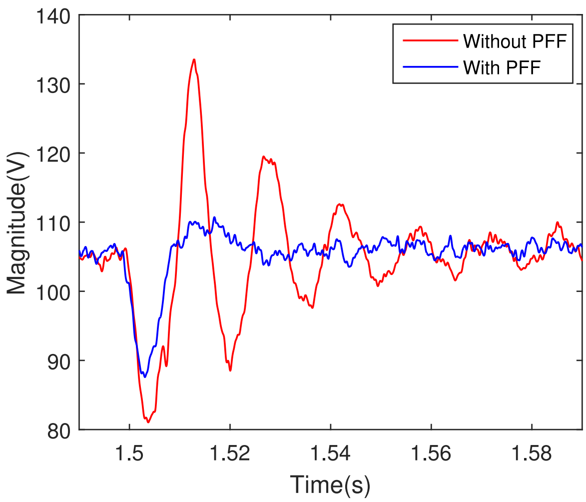

Fig. 16. Step response with and without positive feedforward controller.

at frequencies which do not appear in the excitation signal. As most systems are highly sensitive to the injection amplitude, possible nonlinearities can be minimized by reducing the injection amplitude and increasing the number of injection periods to decrease the noise floor through averaging. Another method to reduce the effect of nonlinear distortions is to select more appropriate injections such as ternary sequences [24]. A ternary sequence is a broadband perturbation that has three levels and an average close to zero. The sequence can be designed to have harmonic multiples of two (2, 4, 6,...) suppressed or harmonic multiples of two and three (2, 3, 4, 6, 8, 9,...) suppressed. Using appropriately designed set of periodic ternary signals, the linear component of each converter impedance can be identified, eliminating errors from even-order nonlinear distortions, and minimizing errors from noise and odd-order nonlinear distortions. This will be one of the topics of future work.

VI. Conclusion

Bus impedance is an important quantity for stability analysis and control design of interconnected systems that consist of multiple power converters. This paper presented the use of orthogonal binary sequences to be used for fast bus-impedance measurement of interconnected multiconverter systems. Applying the orthogonal sequences, the bus impedance can be measured with a single measurement sequence. Compared to conventional single-input single-output techniques, this method not only reduces overall measurement time but also guarantees that the operating conditions of the system remain constant during the experiments. An added advantage is that the signal-to-noise ratio of the measurements can be improved through averaging. Experimental measurements based on an interconnected dc-power-distribution system were presented to demonstrate the effectiveness of the proposed method.

References

[1] D. Tan, "Emerging system applications and technological trends in power electronics: Power electronics is increasingly cutting across traditional boundaries," *IEEE Power Electron. Mag.*, vol. 2, no. 2, pp. 38–47, Jun. 2015.

[2] A. Riccobono *et al.*, "On the stability of shipboard dc power distribution systems-online impedance-based methods," *IEEE Electrification Mag.*, vol. 5, pp. 55–67, Sep. 2017.

[3] J. Siegers, S. Arrua, and E. Santi, "Stabilizing controller design for multibus MVdc distribution systems using a passivity based stability criterion and positive feed-forward control," *IEEE J. Emer. Sel. Topics Power Electron.*, vol. 5, pp. 14–27, Mar. 2017.

[4] D. Clayton, S. Sudhoff, and G. Grater, "Electric ship drive and power system," in *Proc. Conf. Rec. 24th Int. Power Modulator Symp.*, 2000, pp. 85–88.

[5] A. Emadi and M. Ehsani, "Multi-converter power electronic systems: Definition and applications," in *Proc. IEEE Power Electron. Specialists Conf.*, 2001, pp. 1230–1236.

[6] A. Emadi, A. Khaligh, C. Rivetta, and G. Williamson, "Constant power loads and negative impedance instability in automotive systems: definition, modeling, stability, and control of power electronic converters and motor drives," *IEEE Trans. Veh. Technol.*, vol. 55, no. 4, pp. 1112–1125, Jul. 2006.

[7] R. D. Middlebrook, "Input filter considerations in design and application of switching regulators," in *Proc. IEEE Ind. Appl. Soc. Annu. Meeting*, 1976, pp. 366–382.

[8] C. Wildrick, F. Lee, B. Cho, and B. Choi, "A method of defining the load impedance specification for a stable distributed power system," *IEEE Trans. Power Electron.*, vol. 10, no. 3, pp. 280–285, May. 1995.

[9] A. Riccobono and E. Santi, "A novel passivity-base stability criterion (PBSC) for switching converter DC distribution systems," in *Proc. IEEE Appl. Power Electron. Conf. Expo.*, 2012, pp. 2560–2567.

[10] J. Siegers, S. Arrua, and E. Santi, "Allowable bus impedance region for MVDC distribution systems and stabilizing controller design using positive feed-forward control," in *Proc. IEEE Energy Convers. Congr. Expo.*, 2016, pp. 1–8.

[11] T. Roinila, H. Abdollahi, S. Arrua, and E. Santi, "Online measurement of bus impedance of interconnected power electronic systems: Applying orthogonal sequences," in *Proc. IEEE Energy Convers. Congr. Expo.*, 2017, pp. 5783–5788.

[12] A. Riccobono and E. Santi, "Comprehensive review of stability criteria for DC power distribution systems," *IEEE Trans. Ind. Appl.*, vol. 50, no. 5, pp. 3525–3535, Sep./Oct. 2014.

[13] K. Godfrey, *Perturbation Signals for System Identification*. Hertfordshire, U.K.: Prentice Hall, 1993.

[14] T. Roinila, T. Messo, and E. Santi, "MIMO-identification techniques for rapid impedance-based stability assessment of three phase systems in DQ domain," *IEEE Trans. Power Electron.*, vol. 33, no. 5, pp. 4015–4022, May 2018.

[15] R. Luhtala, T. Roinila, and T. Messo, "Implementation of real-time impedance-based stability assessment of grid-connected systems using mimo-identification techniques," *IEEE Trans. Ind. Appl.*, 2018, to be published, doi: 10.1109/TIA.2018.2826998.

[16] L. Yao, J. Zhao, and J. Qian, "An improved pseudo-random binary sequence design for multivariable system identification," in *Proc. IEEE World Congr. Intell. Control Autom.*, 2006, pp. 1768–1772.

[17] W. D. T. Davies, *System Identification for Self-Adaptive Control.* John Wiley & Sons Ltd, 1970.

[18] T. Roinila, M. Vilkko, and T. Suntio, "Frequency-response measurement of switched-mode power supplies in the presence of nonlinear distortions," *IEEE Trans. Power Electron.*, vol. 25, pp. 2179–2187, Aug. 2010.

[19] B. Miao, R. Zane, and D. Maksimovic, "System identification of power converters with digital control through cross-correlation methods," *IEEE Trans. Power Electron.*, vol. 20, no. 5, pp. 1093–1099, Sep. 2005.

[20] T. Roinila, T. Helin, M. Vilkko, T. Suntio, and H. Koivisto, "Circular correlation based identification of switching power converter with uncertainty analysis using fuzzy density approach," *Simul. Modelling Practice Theory*, vol. 17, pp. 1043–1058, 2009.

[21] L. Ljung, *System Identification: Theory for the User*. Upper Saddle River, NJ, USA: Prentice Hall PTR, 1999.

[22] T. Roinila, M. Vilkko, and J. Sun, "Broadband methods for online grid impedance measurement," in *Proc. IEEE Energy Convers. Congr. Expo.*, 2013, pp. 3003–3010.

[23] T. Roinila, M. Vilkko, and J. Sun, “Online grid impedance measurement using discrete-interval binary sequence injection,” *IEEE J. Emer. Sel. Topics Power Electron.*, vol. 2, pp. 985–993, Dec. 2014.

[24] T. Roinila and T. Messo, “Online grid-impedance measurement using ternary-sequence injection,” *IEEE Trans. Ind. Appl.*, 2018, to be published, doi: 10.1109/TIA.2018.2825938.

Tomi Roinila (M’10) received the M.Sc. (Tech.) and Dr.Tech. degrees in automation and control engineering from the Tampere University of Technology (TUT), in Finland, in 2006 and 2010, respectively. He is currently an Academy Research Fellow at TUT. His main research interests include modeling and control of grid-connected power-electronics systems, and modeling of multiconverter systems.

Hessamaldin Abdollahi (S’14) received the B.Sc. degree in electrical and electronic engineering from Qazvin Azad University, Qazvin, Iran, in 2011, and the M.S. degree in electrical engineering from Politecnico di Milano, Milano, Italy, in 2015. He is currently working toward the Ph.D. degree at the Department of Electrical Engineering, University of South Carolina, Columbia, SC, USA. His main research interests include design and control of power converters, stability analysis, and control of multiconverter power distribution systems.

Silvia Arrua (S’15) received the bachelor’s degree in electromechanical engineering from the National University of Asuncion, Paraguay, in 2012, and the M.S. degree in electrical engineering from the University of South Carolina, Columbia, SC, USA, in 2016, where she is currently working toward the Ph.D. degree in electrical engineering. Her current research interests include system identification and modeling and control and stability analysis of power converter systems.

Enrico Santi (S’91–M’93–SM’01) received the bachelor’s degree from the University of Padua, Italy, in 1988, and the Ph.D. degree from Caltech in 1994, both in electrical engineering. Since 1998, he has been with the Department of Electrical Engineering, University of South Carolina, Columbia, SC, USA, where he is currently an Associate Professor. He has authored or coauthored over 150 papers on power electronics and modeling and simulation in international journals and conference proceedings. His research interests include switched-mode power converters, advanced modeling and simulation of power systems, modeling and simulation of semiconductor power devices, and control of power electronic systems.