Frequency-Domain Identification Based on Pseudorandom Sequences in Analysis and Control of DC Power Distribution Systems: A Review

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

***Abstract*—Frequency-domain identification based on wideband techniques has become a popular method in the analysis and control of various dc power distribution systems. In the method, a single converter or a system is perturbed by an external wideband voltage or current injection, the resulting voltage or current responses are measured, and Fourier analysis is applied to extract the spectral information of the measured variables. Most often, the system or converter input and output impedances and the loop gain are the quantities of interest. One class of perturbation signals, pseudorandom binary sequences, has become widely used because most of such signals can be generated using simple shift-register circuitry. As the signals are deterministic and binary, they are well suited to perform measurements on power-converter systems in real time, allowing fast response to system variations through, for example, adaptive controllers. This article reviews the pseudorandom binary sequences applied to dc power distribution systems and discusses their advantages as well as limitations. The conventional maximum-length binary sequence, inverse-repeat binary sequence, discrete-interval binary sequence, and orthogonal binary sequences are considered. Several experimental results from various dc power systems are presented and used to demonstrate the applicability of the discussed methods.**

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

I. Introduction

IN RECENT times dc power distribution systems have become extensively used to power various electronic loads and processes, including hybrid and electric vehicles [1], aircrafts and electric ships [2], battery-management systems [3], smart grids [4], and renewable-energy applications [5]. The proper functioning of those systems is often vital for the everyday life of society. Therefore, the stability, reliable operation, and power quality of the systems is of prime importance and the functioning has to be reliably verified both in the design and operational phase. This introduction discusses the use of pseudorandom binary signals for broadband excitation of power-electronics systems for online measurement of small-signal frequency-domain responses.

In the stability study of dc power distribution systems, one can distinguish between large- and small-signal stability [6]. Large-signal stability considers the effects of large perturbations and includes nonlinear effects. The behavior of nonlinear systems is significantly more complicated than that of linear systems. A popular method to study large-signal stability uses the theory introduced by Lyapunov [7]. In general, evaluating nonlinear stability is a difficult problem. For example, the evaluation of Lyapunov stability requires finding a so called Lyapunov function, but no general method to find such a function is available. Given the difficulties with large-signal stability, a common approach is to study a simpler problem, i.e., small-signal linearized stability [8]. A nonlinear system can be linearized around a given operating point, and linear theory can be applied to the resulting linearized system, providing small-signal stability information.

To address the small-signal stability issues in dc systems, it is common practice to perform frequency-domain stability analysis of an equivalent linearized model of the original system around the steady-state operating point [9], [10]. This stability analysis includes input and output impedances as well as the loop gain of the converters that are part of the system [11]. Rather than calculating these quantities based on the converter design and analytical models, they can be directly measured as frequency responses by using various identification methods [12]. One of the methods is to perturb the system by an external voltage or current injection, measuring the resulting voltage or current responses for the desired variables, and applying Fourier analysis to extract the spectral information.

One of the challenges in performing the frequency-domain characterization is that most power-converter systems typically generate an extraordinarily wide range of frequencies. For example, the control frequencies of a power supply can extend down as low as 0.01 Hz, and as high as several hundred kHz, depending on the switching frequency [10]. In the case of an interconnected system containing several subsystems and multiple power supplies, the number of generated frequencies may substantially increase. Another challenge is that most power-converter systems are strongly time varying; generators and loads can be connected

Manuscript received May 5, 2020; revised July 9, 2020; accepted September 8, 2020. Date of publication September 18, 2020; date of current version November 20, 2020. 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 (approved for public release by the US Office of Naval Research, DCN# 43-6468-20). Recommended for publication by Associate Editor J. Liu. *(Corresponding author: Tomi Roinila.)*

Tomi Roinila is with the Faculty of Information Technology and Communication Sciences, Tampere University, 33100 Tampere, Finland (e-mail: tomi.roinila@tuni.fi).

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

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

Digital Object Identifier 10.1109/TPEL.2020.3024624

This work is licensed under a Creative Commons Attribution 4.0 License. For more information, see https://creativecommons.org/licenses/by/4.0/

and disconnected, interface converters can operate at different operating points, systems can fail, and so on. Therefore, it is desirable to perform real-time measurements to monitor system stability and take corrective actions if needed. The ideal measurement technique would complete the measurement in a short time, allowing fast response to system variations. Additionally, it would be desirable to utilize existing power converters and sensors to perform measurements, rather than adding specialized equipment with associated extra cost and extra size and weight.

The converter small-signal model can be straightforwardly estimated by injecting sinusoidal current/voltage into the system, and performing Fourier analysis at steady state using the measured current and/or voltage responses. Using sine sweeps provides the highest possible signal-to-noise ratio (SNR), and, hence, the most reliable and accurate frequency-response estimate. However, the sine sweeps are not well suited for online measurements due to long measurement time. Another problem in using sine sweeps is that the signal generator used for implementing the sine sweeps needs to be able to produce a large number of different signal levels (infinite number in the case of ideal sine sweeps). This effectively prevents the implementation of the method in practical low-cost applications.

An attractive alternative to sine sweeps is to apply an excitation signal that has carefully designed time-domain properties and a broadband spectrum [13]. The excitation signal with a broadband spectrum has energy at several frequencies, thus allowing to measure a frequency response simultaneously at several frequencies. Hence, instead of injecting sine signals frequency-by-frequency, all the necessary frequency-response information can be captured within one measurement, thus, drastically reducing the measurement time.

The signals having a broadband spectrum are generally divided into binary [14], near binary [15], and nonbinary sequences [16], each having many attractive properties. Considering power-electronics systems, periodic binary sequences are highly acceptable alternatives in many cases for obtaining the converter small-signal model. First, as the sequences are binary, they are very easy to implement even with a low-cost application system whose output can only generate a small number of signal levels. This is obviously not the case for example with sinusoidal sequences, which have infinite number of signal levels. Second, the binary sequences have the lowest possible peak factor, which means that the signal energy is very high in relation to the signal time-domain amplitude [17]. This is particularly useful when analyzing systems that are sensitive to varying external signals. Third, the spectral-energy distribution of the periodic binary sequences is largely controllable, which makes the signals well scalable to different applications. This is not the case for a number of other types of perturbations such as impulse.

Recent studies have widely recognized the potential and effectiveness of different broadband binary sequences in stability analysis of dc power distribution systems. One of the most popular signals has been the maximum-length pseudorandom binary sequence (MLBS) [18]–[41]. The sequence is periodic, easy to implement, and has a largely controllable spectral energy distribution. The inverse-repeat binary sequence (IRS) was introduced for stability analysis of converter systems that are affected by strong nonlinearities [42]. The IRS is modified from the conventional MLBS such that the energy of every other harmonics is suppressed. Applying the IRS minimizes the effect of second-order nonlinearities in the system, thus providing more accurate estimate of the system linear dynamics. Discrete-interval binary sequence (DIBS) is another class of pseudorandom sequences in which the power spectrum can be specified by the user [43]. The DIBS is a computer optimized signal where the goal of the optimization is to force as much power as possible into the specified harmonic frequencies without increasing the signal time-domain amplitude. For larger systems containing several converters, orthogonal pseudorandom binary sequences have been applied [44], [45]. These sequences make it possible to simultaneously measure several (coupled) frequency responses, thus reducing the overall measurement time and guaranteeing constant system operating conditions during the measurements.

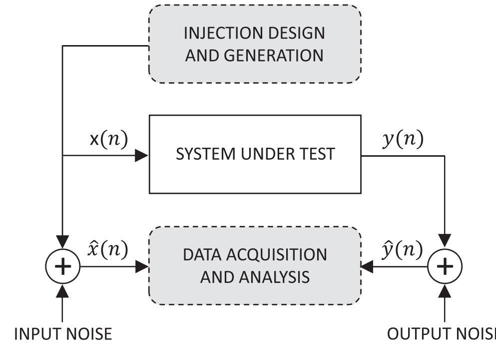


Fig. 1. Typical measurement setup.

This article will provide a comprehensive review of the pseudorandom sequences applied in the dynamic analysis of dc power distribution systems. The theory behind the synthesis of the sequences is presented, and a number of experimental results are shown to demonstrate the applicability of the methods. The article focuses only on periodic binary sequences as they have an exceptional combination of properties that are well suited to model power-electronics systems. It is emphasized, however, that there exist several other, efficient, broadband measurement methods.

The remainder of this article is organized as follows. Section II provides the basic theory of wideband identification of power-converter systems. Sections III, IV, V, and VI review and provide examples of the pseudorandom sequences applied in power-converter systems; the MLBS, IRS, DIBS, and orthogonal binary sequences (OBS) are considered, respectively. Finally, Section VII concludes this article.

II. Wideband Identification of Power-Converter Systems

A dc power-converter system can be considered a linear time-invariant system for small disturbances. According to basic control theory, this type of system can be fully characterized by its impulse response, which can be transformed into frequency domain and represented by a frequency-response function.

Fig. 1 shows a typical measurement setup where the system under test is to be identified. The system is perturbed by the excitation $x(n)$, which yields the corresponding output response

$y(n)$. The measured input and output signal $\hat{x}(n)$ and $\hat{y}(n)$ are corrupted by input noise and output noise, respectively. The noise signals are assumed to resemble white noise and are uncorrelated with $x(n)$ and $y(n)$. All of the signals are assumed to be zero mean sequences. In noisy environments, the logarithmic averaging procedure [12] is often applied to compute the frequency response of the system under test as

$$G_{\log}(j\omega) = \left(\prod_{k=1}^{P} \frac{\hat{Y}_k(j\omega)}{\hat{X}_k(j\omega)} \right)^{1/P} \quad (1)$$

where $\hat{X}(j\omega)$ and $\hat{Y}(j\omega)$ are Fourier-transformed input and output sequences (measured), respectively, and P denotes the number of injected excitation periods. In the method, the measurements from both input and output sides are segmented and Fourier transformed after which (1) is applied. The method tends to cancel out the effect of uncorrelated noise from both input and output sides, so that the frequency response is obtained more accurately compared to conventional cross-correlation techniques [12].

The perturbation design plays a very important role in obtaining the desired frequency response through the experiment described in Fig. 1. An optimal design leads to maximally informative experiments, that is, experiments that extract the maximum amount of information, and reduces operational costs associated with the identification procedure. In practice, there are several challenges and questions regarding the perturbation design, including the following.

1) As most converter systems are characterized in a wide frequency band, the perturbation should have an adequately rich spectral-energy content distributed as evenly as possible.
2) In the case of noisy systems, it would be necessary either to average the measurements over a long period of time, or to increase the injection amplitude. In the latter case, the assumption of linearity may no longer be valid. Therefore, one should apply a perturbation that makes it possible to minimize the effects of nonlinearities.
3) The perturbation should be easily implementable. It would be desirable to utilize existing converters in a system and their sensors to perform the perturbation injection, rather than adding specialized equipment with associated extra cost and extra size and weight. Therefore, the number of different signal levels in the perturbation should be as small as possible.
4) There is always a treadoff between the measurement accuracy and measurement time. Therefore, it is critical to define the minimum accuracy and measurement time required for a specific application.

For a linear-system identification, a binary signal most often offers the best possible choice in terms of maximizing signal power within time-domain-amplitude constraints [46]. Another major advantage of binary sequences over other types of signals, such as sinusoids, is that they can be implemented with a low-cost system whose output can only generate a small number of signal levels. The following sections will review the synthesis and applications of the four most widely used binary perturbations in converter systems: MLBS, IRS, DIBS, and OBS are considered.

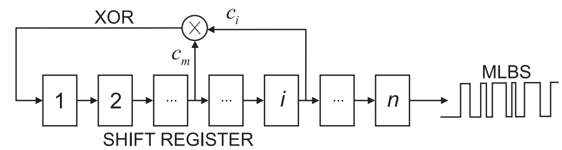


Fig. 2. n-bit shift register with XOR feedback for MLBS generation.

TABLE I
MAXIMUM-LENGTH BINARY SEQUENCE FROM A FOUR-STAGE SHIFT REGISTER

Shift	Stage 1	Stage 2	Stage 3	Stage 4
1	0	0	0	1
2	1	0	0	0
3	1	1	0	0
4	1	1	1	0
5	1	1	1	1
6	0	1	1	1
7	1	0	1	1
8	0	1	0	1
9	1	0	1	0
10	1	1	0	1
11	0	1	1	0
12	0	0	1	1
13	1	0	0	1
14	0	1	0	0
15	0	0	1	0
16	0	0	0	1

III. MAXIMUM-LENGTH BINARY SEQUENCE

Pseudorandom binary sequence (PRBS) is a periodic broadband signal with the following properties.

1) The signal has two levels, and it can switch level only at certain event points $t = 0, \Delta t, 2\Delta t, ...$
2) The change of signal level is predetermined, so that the PRBS is deterministic and experiments are repeatable.
3) The sequence is periodic with period $T = N\Delta t$, where N is an odd integer.
4) Within one period, there are $(N + 1)/2$ intervals when the signal is at one level and $(N - 1)/2$ intervals when it is at the other.

A PRBS is based on a sequence of length N. The most commonly used signals are based on maximum-length sequences. Such sequences exist for $N = 2^n - 1$, where n is an integer. The reason for their popularity is that they can be generated using feedback shift register circuits, as shown in Fig. 2.

Table I shows an example of an output from a shift register circuit for generating an MLBS of length $2^4 - 1 = 15$. The feedback is generated from stages 1 and 4. All four columns in Table I produce the same MLBS. The register can be started with any number other than 0, 0, 0, 0. In the example, the register is started from 0, 0, 0, 1. Each binary number from 0, 0, 0, 1 to 1, 1, 1, 1 appears exactly once (the sequence starts repeating after 15 cycles). This is a general result for all maximum-length binary sequences [47]. In practice, the values 0 and 1 are mapped to -1 and +1 to produce a symmetrical MLBS with an average close to zero.

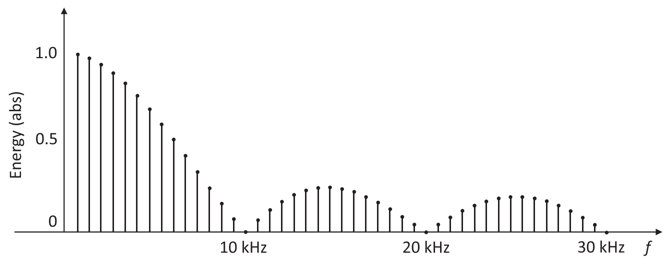


Fig. 3. Power spectrum of 15-bit-length MLBS generated at 10 kHz.

It should be emphasized that the selection of the feedback connections (stages) is important. Very few of the possible connections result in sequence of the maximum length of $2^n - 1$ (some sequences can be produced from several different stages). An example of one possible feedback configuration for each n in the range $2 \leq n \leq 100$ can be found in [47].

Fig. 3 shows the form of the power spectrum of the MLBS shown in Table I. The sequence is generated at 10 kHz and has signal levels ± 1 V. The energy values are scaled between zero and one. The power spectrum has an envelope and drops to zero at the generation frequency and its harmonics. The spectrum is given by

$$\Phi_{\text{MLBS}}(q) = \frac{a^2(N+1)}{N^2}\frac{\sin^2(\pi q/N)}{(\pi q/N)^2}, \quad q = \pm 1, \pm 2, \ldots \quad (2)$$

where q denotes the sequence number of the spectral line, a is the signal amplitude, and N is the signal length.

The MLBS x has the lowest possible peak factor $|x|_{\text{peak}}/x_{\text{rms}} = 1$ regardless of its length. Hence, the sequence is well suited for sensitive systems, which require small-amplitude perturbation. Due to the deterministic nature of the sequence, the signal can be repeated and injected precisely and the SNR can be increased by synchronous averaging of the response periods. Using the averaging, the effect of noise is reduced by a factor of $1/\sqrt{P}$, where P is the number of applied injections periods [12].

A. Literature Review: Utilizing the MLBS

The potential of the MLBS for switched-mode converters was studied for the first time in [18] and [19]. In these papers, digitally controlled converters were considered, and the MLBS and cross-correlation techniques were applied to measure the converter control-to-output transfer function. The methods were improved in [20]–[22], and solutions for integrating the methods into an existing system were presented.

Barkley and Santi [26], [27] proposed several additional improvements to the MLBS-based measurements of dc-power converters; a windowing technique was applied to reduce the effect of noise, and a novel data-manipulation technique was proposed to improve the frequency-response estimates at high frequencies. Issues in high-frequency measurements were further considered in [28], which concluded that, in order to achieve high accuracy at high frequencies, the injection must be redesigned so that most of the injection spectral energy lies at high frequencies. A method to design such a signal was proposed by introducing a blue-noise filtered signal. The work also considered practical restrictions of frequency-response measurements, such as the implementation using a finite-resolution analog-to-digital converter.

Further improvements to the measurement technique based on the MLBS were presented in [29]; the aliasing effect of the pulsewidth modulation was considered, and a circular cross-correlation method was proposed. This work was extended in [30], which presented a systematic approach to design the MLBS for switched-mode power supplies and introduced a fuzzy-based statistical tool to analyze the measured frequency responses.

The frequency-response measurements obtained by the MLBS have been extensively used for the analysis and control of dc-power-electronics systems in past studies. Adaptive control strategies were proposed in [23]. The work applied the measurement methods to estimate the converter control-to-output frequency response, which was used to adjust the converter digital compensator to achieve the desired closed-loop dynamic behavior. Shirazi *et al.* [24] applied the same methods; they considered digitally controlled point-of-load converters with a wide range of capacitive loads and presented techniques to adjust the converter PID controller in real time. The work was further improved in [25], which applied the methods to several different converter types. These papers provided first examples of converter automated offline system design, and for online adaptive control.

The work in [29] applied the MLBS to measure the converter closed-loop output impedance. It was stated that the output impedance can be directly used to verify the stability of a converter loaded by an arbitrary load. As the output impedance can be externally measured from the converter output without interfering with the converter internal circuitry (no need for breaking feedback loops or performing loop injection), this approach provided a convenient method to analyze system stability.

Adaptive control strategies based on converter parametric identification were considered in [31]. The converter control-to-output frequency response was first measured by the MLBS, after which a fitting algorithm was applied to obtain a parametric model. The model was then used to adjust the converter digital controller. Similar methods were applied to medium-voltage dc power distribution systems in [32]. Riccobono *et al.* [33] had a more general approach, and presented an MLBS-based online technique to obtain the converter parameterized model.

Riccobono and Santi [34] applied the MLBS to the stability analysis of a dc power-distribution system for the all-electric ship. They applied a so called passivity-based stability criterion to assess the system overall stability. The MLBS was utilized to measure the dc bus impedance required for the criterion. A similar approach was applied in [35], which extended the methods to a multibus case. The MLBS was also utilized in [36] and [37], which presented an allowable-impedance-region concept to more effectively analyze the dynamic performance of a dc system.

A kilowatt-scale dc system was considered in [38] and [39], and a power hardware-in-the-loop (PHIL) platform utilizing the MLBS was implemented. These papers focused on stability

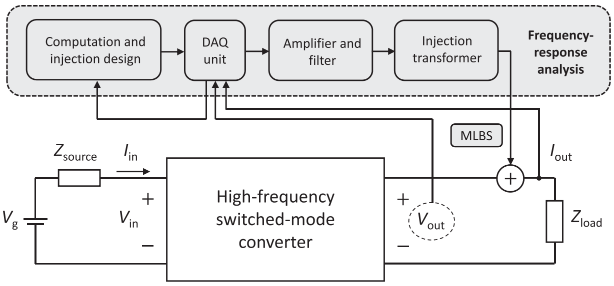


Fig. 4. Conceptual diagram of the measurement system used to measure converter output impedance.

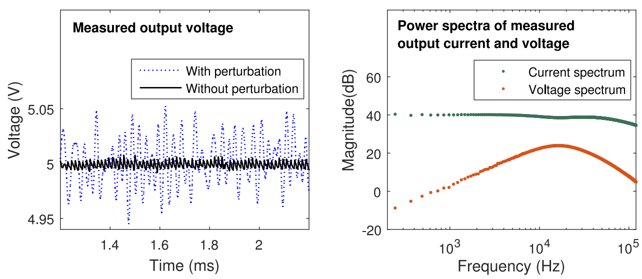


Fig. 5. Samples of perturbed and nonperturbed output voltage, and the power spectra of the measured output current and voltage.

issues of the PHIL power interface control algorithms, and provided steps to design a high accuracy and highly stable PHIL test platform for dc power system simulation. The results were later applied in [40] to stability analysis on a scaled 1.5-kW medium-voltage dc-distribution system consisting of three converters interconnected at a common bus.

Roinila *et al.* [41] presented adaptive-control techniques based on indirect measurement of the converter controller loop. In the method, the converter control-to-output frequency response was first measured online by using the MLBS. Then, the controller loop gain was computed based on the measured control-to-output response. A loop-shaping technique was then utilized for adaptive control design to obtain desired stability margins. The advantage of the presented method compared to previously presented techniques was that the loop-gain measurement did not require opening the feedback loop.

B. Experiment Example: Applying MLBS

Fig. 4 shows a conceptual measurement setup used for measuring the output impedance from a high-frequency switched-mode buck converter [29]. The setup was implemented by using NI PCI-6115 data-acquisition unit and a linear amplifier. The converter input voltage V_g was 12 V and the output voltage V_{out} 5 V.

A 4095-bit-length MLBS was generated at 500 kHz. An averaging over 10 injection periods was applied, and thus, the total injection time was approximately 0.08 s. The injection amplitude was set such that the converter output voltage did not vary more than 5% of its nominal voltage. An MLBS series injection was performed at the output of the converter to measure the converter output impedance. Fig. 5 shows samples of perturbed and nonperturbed output voltage in the time domain, and the power spectra of the measured current and voltage. It can be seen that the voltage spectral power decreases at both low and high frequencies. This is expected given the parallel L-C output impedance characteristics of the converter.

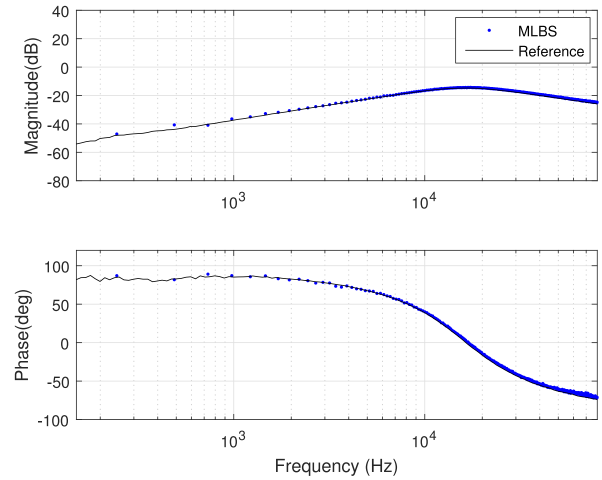


Fig. 6. Measured output impedance by using MLBS injection.

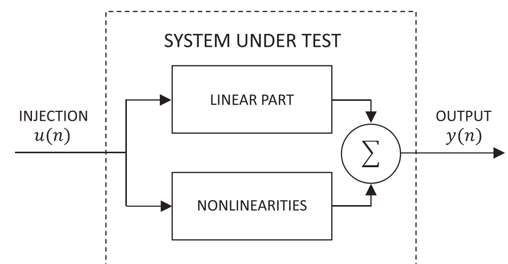


Fig. 7. System with linear and nonlinear components.

Fig. 6 shows the computed output impedance of the converter. The impedance was also measured using a Venable 3120 network analyzer under the same operating conditions (reference). As the figure shows, the impedance obtained by the MLBS highly accurately follows the reference in a wide range of frequencies. The total measurement time of the response using the MLBS was less than one second, including the injection. The measurement time using the network analyzer was approximately 1.5 min, about a thousand times longer than the MLBS total injection time.

IV. Inverse-Repeat Binary Sequence

A power-converter system often suffers from many different nonlinearities such as switching effects, nonlinear inductances and capacitances, and electromagnetic couplings among components. In some cases, the effect of these nonlinearities may be very strong causing difficulties in accurately measuring the converter linear dynamics.

Fig. 7 shows a conceptual diagram of a converter system in which both the linear and nonlinear components of the system under test are considered. The nonlinearities could be further separated into even- and odd-order nonlinearities [48]. Basically, a system exhibiting nonlinearities can be modeled in two ways. One method is to identify the system including all of its nonlinearities [48]. The other way is to identify only the linear portion of the model, which requires that the nonlinearities are suppressed. The latter technique is useful for power-electronics systems because usually the converter design is based on the linear model, which makes the nonlinear part not of interest. One method of minimizing the effect of nonlinearities is to apply the IRS, which is generated by considering two periods of the MLBS and toggling every other digit of the two-period sequence. The IRS effectively suppresses the most dominant nonlinearities from the system output, as shown in the following.

Consider the system shown in Fig. 7. The sampled output signal $y(n)$ can be represented as a Volterra series expansion [49] as

$$y(n) = \sum_{k=0}^{M} h_1(k)u(n-k) + \sum_{k_1=0}^{M}\sum_{k_2=0}^{M} h_2(k_1,k_2)u(n-k_1)u(n-k_2) + \cdots + \sum_{k_1=0}^{M} .. \sum_{k_i=0}^{M} h_i(k_1,.,k_i)u(n-k_1)..u(n-k_i) \tag{3}$$

where $u(k)$ is the sampled input signal and M is the length of the sampled data. Each of the convolutions contains a kernel, either linear (h_1), or nonlinear ($h_2, \ldots, h_i$). If the system is assumed to be linear it can be described by the first convolution only. Applying correlation relationship [50] to (3), the cross-correlation function $\phi_{uy}(n)$ between $u(n)$ and $y(n)$ can be expressed as

$$\phi_{uy}(n) = \sum_{k=0}^{M} h_1(k)\phi_{uu}(n-k) + \sum_{k_1=0}^{M}\sum_{k_2=0}^{M} h_2(k_1,k_2)\phi_{uu}(n-k_1)\phi_{uu}(n-k_2) + \cdots + \sum_{k_1=0}^{M} .. \sum_{k_i=0}^{M} h_i(k_1,.,k_i)\phi_{uu}(n-k_1)..\phi_{uu}(n-k_i) \tag{4}$$

where $\phi_{uu}(n-k)$ is the autocorrelation function of $u(n)$. $\phi_{uu}(n-k_1)..\phi_{uu}(n-k_i)$ represents the ith order autocorrelation function of $u(n)$, and can be expressed as

$$\phi_{uu}(n)_i = \sum_{k_1,..,k_i}^{M} u(n)u(n-k_1)..u(n-k_i). \tag{5}$$

Because, the IRS is repeating and antisymmetric, $u(n)$ satisfies the condition

$$u(n) = -u(n+S/2) \tag{6}$$

where S is the length of the doubled MLBS. Due to (6), all the even-order kernels cancel out from (4), which can be seen by

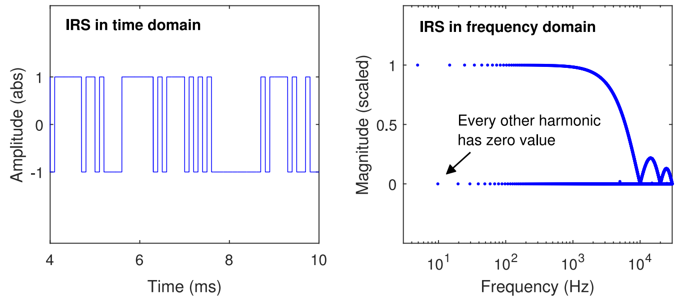


Fig. 8. Sample of IRS in the time and frequency domain.

rewriting the second-order autocorrelation function in (5), as

$$\phi_{uu}(n)_2 = \sum_{k_{1,2}=0}^{S} u(n)u(n-k_1)u(n-k_2) = \sum_{k_{1,2}=0}^{S/2} u(n)u(n-k_1)u(n-k_2) + \sum_{k_{1,2}=S/2}^{S} u(n)u(n-k_1)u(n-k_2). \tag{7}$$

Due to the antisymmetric property of the IRS, the two components in (7) are equal and opposite. The same applies for the higher even-order autocorrelation functions as well. Therefore, all the even-order kernels cancel out from (4) leaving only the linear term and terms involving odd-order kernels. Consequently, the system linear part can be obtained more accurately. The contributions of the higher order kernels on the output are usually of negligible amplitude compared to the contributions of the lower order kernels [51]. Hence, the nonlinear effect caused by the second-order kernel may be assumed to be dominant.

The IRS is periodic with a period of $2N\Delta t$, where N is the period length of the MLBS used for generating the IRS, and Δt denotes the clock cycle of the sequence. Assuming the signal length is adequately long and the generation frequency high enough, the spectral and autocorrelation properties of the IRS are close to the corresponding properties of pure white noise. Fig. 8 shows a sample of a 2046-bit-length IRS generated at 10 kHz. The spectrum is very close to the spectrum of the MLBS but every other harmonic has zero value.

It is somewhat surprising that the IRS has not gained much popularity in the analysis of power-converter systems. Roinila *et al.* [42] applied the IRS to the dynamic analysis of a self-oscillating buck–boost-based battery charger. The results confirmed that the IRS produces highly accurate frequency responses under strong nonlinearities where the conventional MLBS does not work properly.

There exist various methods for nonlinear identification of power-converter systems [52]–[54]. The most popular methods are based on the Wiener and Hammerstein modeling strategies, which are very useful when the system nonlinearities are more of static nature [55]. In these methods, the system is modeled by a linear part approximating the system dynamics and a nonlinear

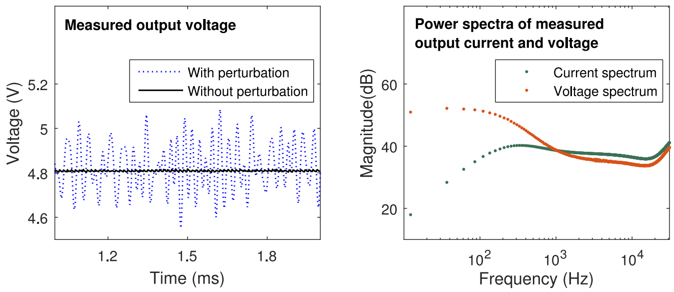


Fig. 9. Samples of perturbed and non-perturbed output voltage, and the power spectra of the measured output current and voltage.

part representing the static nonlinearities in the system. The IRS is well applicable with these methods as the sequence can be efficiently used to obtain the system linear part.

A. Experiment Example: Applying IRS

The frequency response of the output impedance from a commercial (Nokia AC-5E) buck–boost-based battery charger (5.0 V_{dc}/800 mA) was measured in accordance with the measurement setup shown in Fig. 4. The converter operated at the boundary of continuous and discontinuous conduction mode and utilized peak-current-mode control (self-oscillating control). Therefore, the circuit had a variable switching frequency [56], and was more sensitive to nonlinear effects compared to the previous experiment example. Another source of nonlinearity is found from the digital-to-analog converter of the data-acquisition unit. The system under study is presented in more detail in [42].

An 8190-bit-length IRS was generated at 100 kHz. An averaging over 10 injection periods was applied, and thus, the total injection time was approximately 0.20 s. The injection amplitude was set to 0.3 A. The designed IRS was injected into the output current, which was measured together with the output voltage. The converter was assumed to operate at an approximately constant operating point during the injection. Fig. 9 shows samples of perturbed and nonperturbed output voltage in the time domain, and the power spectra of the measured output current and voltage.

Fig. 10 shows the computed output impedance of the converter. The impedance was also measured by the conventional MLBS having the same signal parameters as the IRS, and by a Venable 3120 network analyzer (reference). The impedance obtained by the IRS highly accurately follows the reference in a wide range of frequencies. The measurement inaccuracy with the MLBS is the justification for the use of the IRS for excitation and it can be explained by the behavior of the electrolytic capacitor of the boundary-mode buck–boost converter. The output impedance of the converter is the impedance of the electrolytic capacitor with its equivalent series resistance causing a zero at a few kHz. The capacitor current is approximately a square wave due to the boundary mode operation. The voltage ripple dominant component changes shape around the zero frequency from a triangle (capacitive) at low frequencies to a square (resistive) at higher frequencies. This results in a change in the voltage harmonic content. This change in harmonic content strongly

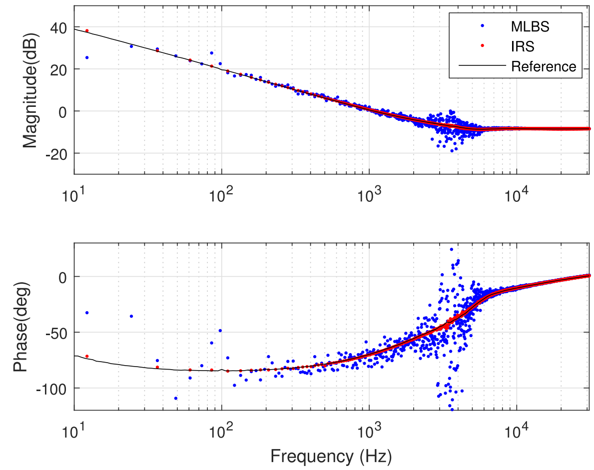


Fig. 10. Measured output impedance by using MLBS and IRS injections.

affects the MLBS measurement, but its effect is significantly reduced for the IRS measurement, as expected, showing the advantage gained using the IRS.

V. Discrete-Interval Binary Sequence

DIBS is a class of pseudorandom sequences, which is often referred to as a binary multifrequency signal [57]. The DIBS is a computer-optimized signal where the goal of the optimization is to force as much power as possible into the specified harmonic frequencies without increasing the signal time-domain amplitude. The frequency resolution is, hence, weakened but otherwise the DIBS has the same attractive properties of the conventional MLBS. There also exist many optimized broadband excitations of nonbinary form such as multisine [12]. Compared to the DIBS the design of multisine is much simpler. However, the multisine (and other types of nonbinary sequences) consists of an infinite number of signal levels, resulting in problems if the input transducer can only generate a small number of discrete amplitudes. In addition, the multisine usually presents large peaks on the waveform, and hence the system under test may easily drift out of its linear operational range. It is possible to use different optimization algorithms to reduce the peak values in the signal time-domain waveform but the signal may need to be redesigned for a different system [46].

The synthesis of the DIBS is well documented [58]. The technique is based on the iterative minimization of a cost function. The method eventually produces a binary sequence in which most of the spectral energy lies at the specified harmonic frequencies.

Fig. 11 compares the DIBS and the conventional MLBS in the time and frequency domains. The sequences have the same time-domain amplitude. The DIBS has 1024 and the MLBS 1023 bits. Both sequences have been generated at 10 kHz, thus having approximately the same frequency resolution. For the DIBS, 18 harmonic frequencies were specified (linearly over 5 kHz band) where the energy was to be maximized. For clarity only the specified harmonics of the DIBS have been shown. As the figure shows, the energy at the specified harmonics of the DIBS is 4–6 times higher than the energy at the corresponding harmonics of

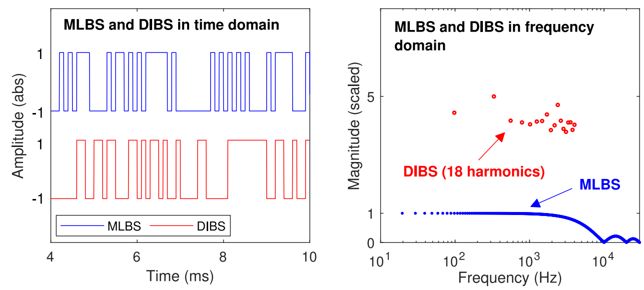


Fig. 11. Sample of MLBS and DIBS in the time and frequency domain.

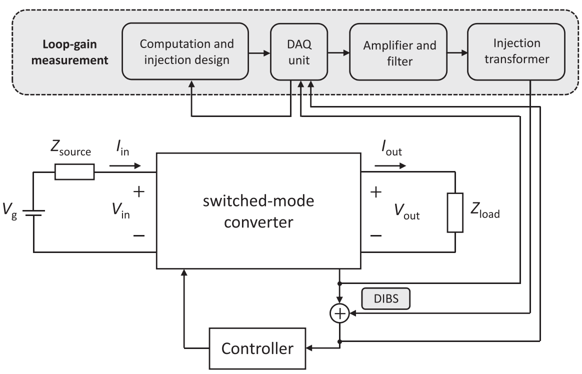


Fig. 12. Conceptual diagram of the measurement system used to measure control loop gain.

the MLBS even though the signals' time-domain amplitudes are the same. The figure also shows that the amplitude spectrum of the DIBS is clearly nonuniform. This is caused by the design procedure. It should also be emphasized that the design of DIBS allows to specify the harmonics arbitrarily. Hence, it is possible to select the harmonics, for example, logarithmically.

The DIBS was applied to dc power-converter systems for the first time in [43]. The work considered the online measurement of a converter loop gain. The loop gain is typically very sensitive to the variation of the external injection. The main problem in the measurement process is that certain frequencies require more injection energy than others in order to obtain accurate frequency-response estimates. As the spectral energy of the conventional MLBS is divided into a large number of harmonics, the signal amplitude needs to be often increased to an unnecessarily high value in order to produce an adequate amount of energy at specific frequencies. Results in [43] showed that the DIBS produced a highly accurate estimate of the converter loop gain whereas the MLBS failed within the given amplitude constraints. The DIBS was later applied also in ac power distribution systems in [59] and [58]. In these papers the injection was used for measuring three-phase grid impedance under stiff grid conditions, which require larger excitation signals.

A. *Experiment Example: Applying DIBS*

Fig. 12 shows a conceptual measurement setup used for measuring the loop gain of a flyback-based commercial battery charger (5.0 V_{dc}/500 mA). The setup was similar to the previous experiment examples, but the perturbation was injected on top of the controller input signal. A loop injection was used

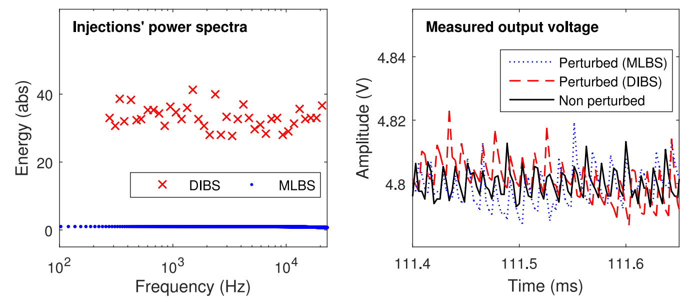


Fig. 13. Power spectra of applied MLBS and DIBS injections (left), and sample of measured feedback signal (right).

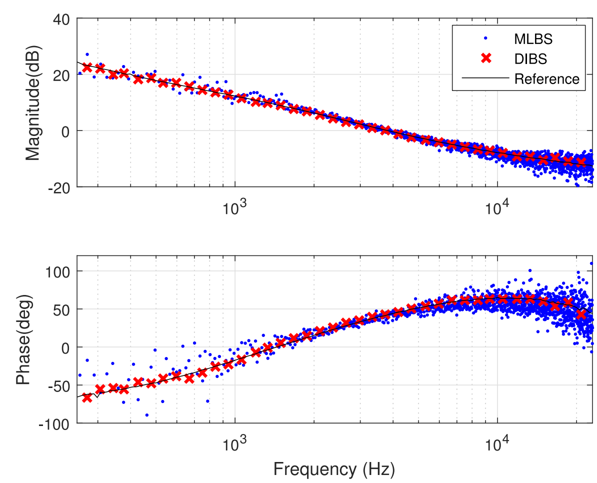


Fig. 14. Measured loop gain by using MLBS and DIBS injections.

and the signals on both sides of injection were measured. The measurement setup is presented in more detail in [43].

The DIBS was designed by specifying 39 harmonic frequencies from a 4096-bit-length-binary sequence. The harmonics were selected quasilogarithmically up to 23 kHz, having as much power as possible with the given injection amplitude. The injection generation frequency was set to 70 kHz. The signal amplitude was set to 25 mV, which was approximately 0.5% of the converter steady-state output voltage. The measurement was also performed by the conventional MLBS. In order to provide a fair comparison between the signals, all the measurement parameters were approximately identical between the measurements.

Both sequences were separately injected into the feedback loop in accordance with the setup shown in Fig. 12. In both cases, the measurements were averaged over five injection periods. The total injection time of each perturbation was approximately 0.29 s. Fig. 13 shows the power spectra of the designed DIBS and MLBS injections. The vertical axis has a linear scale and is scaled such that the MLBS has a maximum power of one. The DIBS has around 35 times more power in the specified harmonics (even though the signals' time-domain amplitudes are identical). The figure also shows samples of the measured output signal.

Fig. 14 shows the frequency response of the loop gain obtained both by the DIBS and MLBS. The loop gain was also measured by the network analyzer under the same operating conditions (reference). As the figure shows, the response obtained by the DIBS highly accurately follows the reference in a wide frequency range. The response obtained by the MLBS suffers from strong inaccuracy caused by too low injection spectral energy, especially at high frequencies, where the low-pass nature of the system causes significant attenuation.

VI. Orthogonal Binary Sequences

Most dc power distribution systems are multiple-input-multiple-output (MIMO) systems. They have more than one input and output, and, most often, the inputs and outputs are cross coupled and cannot be approximated as multiple single-input-single-output systems. Good examples are the multiconverter systems often found in on-board ship applications [2]. In such systems, multiple converters are connected to the same dc bus, thus creating a complex interconnected system. Consequently, a number of issues related to stability and power quality arise due to interactions among the subsystems.

Frequency responses of MIMO systems are conventionally measured by applying the superposition theorem; a broadband excitation is injected to each system input one at a time, the responses are measured at all outputs in turn, and (1) is applied to each input and output signal combination. A highly acceptable alternative to analyze MIMO systems is to apply OBS. In the method, several orthogonal injections are simultaneously injected (e.g., by the existing converters in a multiconverter system). As the injections are orthogonal, i.e., 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 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 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 [46], [47]. 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 [60]. The other approach applies Hadamard modulation to obtain uncorrelated injections so that the effects of different inputs are decoupled [46]. 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. Using this technique, a set of orthogonal excitation sequences are obtained as follows [47]:

1) Generate a conventional MLBS by using a shift-register circuitry with feedback.
2) The second signal is obtained by forming an IRS from the MLBS; i.e., 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.

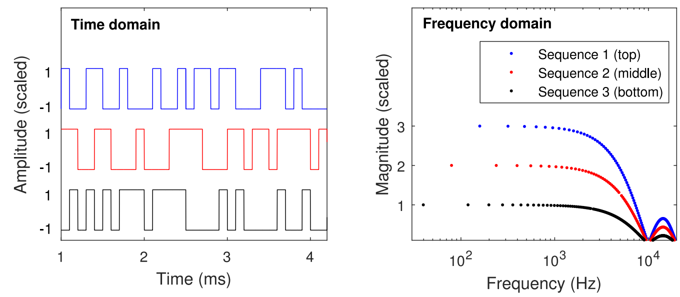


Fig. 15. Samples of three orthogonal sequences in the time and frequency domain.

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.

Fig. 15 shows samples of three OBS 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 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.

Roinila *et al.* [61] applied the OBS to switched-mode power supplies for the first time. A commercial high-frequency current-mode buck converter was considered, and four transfer functions (input and output impedances, forward transfer function, and reverse transfer function) were simultaneously measured. The work presented design steps to obtain appropriate orthogonal sequences, and proposed an implementation setup.

Similar methods were recently applied in [44] and [45]. These works considered multiconverter dc power distribution systems. Such systems have multiple source and load converters connected to a common bus. Each of these interconnected converters typically has a 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. The stability of such multiconverter systems can be analyzed by measuring the bus impedance, which requires measuring the input or output impedances from each converter in the system. These works applied orthogonal sequences, and presented methods to simultaneously measure all the frequency responses from single converters required for defining the complete system stability.

In conclusion, the OBS method can be applied whenever multiple measurements on a system are needed. An example is the procedure for the measurements of unterminated converter models proposed in [62], which requires both input and output side perturbations.

A. Experiment Example: Applying Orthogonal Sequences

The dc power distribution system depicted in Fig. 16 was constructed in the laboratory using custom designed IGBT-based switching converters. The system consists of a source buck

TABLE II
MAIN PROPERTIES OF PSEUDORANDOM BINARY PERTURBATIONS

INJECTION TYPE	SPECIAL PROPERTIES	HOW TO GENERATE	ADVANTAGES	LIMITATIONS	APPLICABILITY
Maximum-length binary sequence (MLBS)	Energy distributed over a large number of harmonic frequencies	Shift register with XOR feedback	Straightforward to generate even with a low-cost application	Sensitive to system nonlinearities	Measuring converter input and output impedances
Inverse-repeat binary sequence (IRS)	Suppresses most dominant nonlinearities	Toggling every other digit of two-period MLBS	Minimizes the effect of nonlinear distortions	Measurement time is doubled compared to the MLBS	Measuring converter input and output impedances under nonlinear effects
Discrete-interval binary sequence (DIBS)	Signal energy concentrated at specific frequencies	Iterative minimization of cost function	Spectral energy can be increased without increasing the time-domain amplitude	Requires high computing power in the signal design phase	Measuring converter loop gain or other parameters that require high SNR
Orthogonal binary sequences	No energy at common frequencies between different signals	Modulation with rows of a Hadamard matrix	Allows simultaneous measurement of several, coupled, small-signal models	Sensitive to system nonlinearities	Measurements and analysis of multi-converter systems

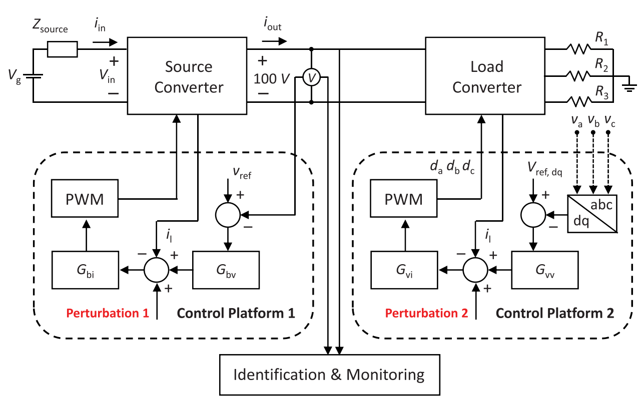


Fig. 16. Conceptual diagram of the measurement system.

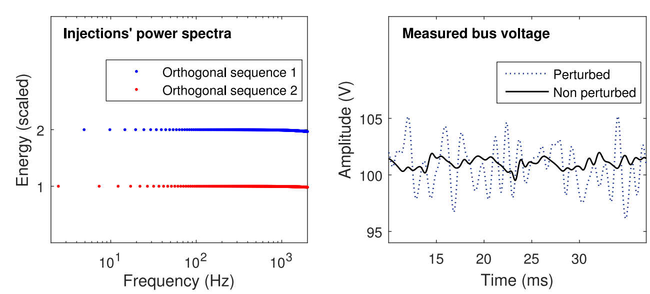


Fig. 17. Power spectra of applied orthogonal injections (left), and sample of measured bus voltage (right).

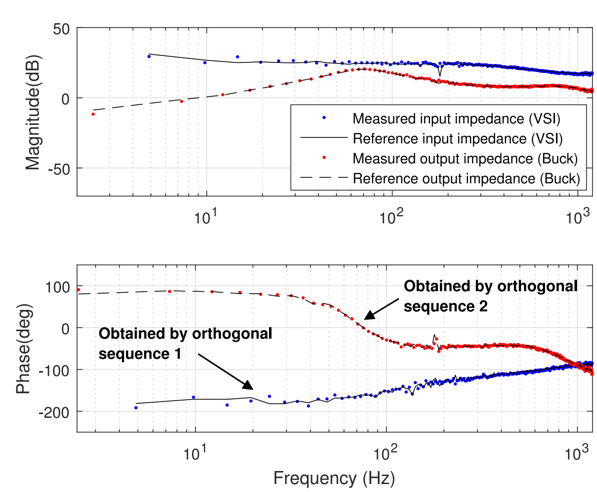


Fig. 18. Measured load and source impedance by using two orthogonal sequences.

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.

Two OBS 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%. 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, (1) was applied. The bus impedance was then computed using the method presented in [45].

Fig. 17 shows a sample of the measured bus voltage with and without the injection. The voltage during the injection deviates from the nominal voltage value only by approximately 5% and, therefore, the system operates well within the defined limits.

Fig. 18 shows the measured input and output 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 were obtained using single MLBS injections, i.e., the converter impedances were separately measured using the conventional MLBS method. The measured bandwidth in this example is only a few kHz. The measured impedance curves are eventually used to obtain the system bus impedance, which, in turn, is used for controller design. The controller desired bandwidth is only few kHz, and therefore, there is no need for measurements at higher frequencies.

VII. Discussion and Conclusion

Broadband methods have become popular in small-signal stability analysis and control of dc power distribution systems. The methods make it possible to rapidly analyze the system in realtime, allowing system monitoring, and fast response to system variations through, for example, adaptive controllers.

This article has reviewed binary-broadband-perturbation methods applied in small-signal analysis of dc power distribution systems. It is emphasized, however, that there exist several broadband methods other that the methods based on pseudorandom sequences. The main reason for considering only the pseudorandom sequences in this article is that such sequences have properties that make them particularly useful for power-electronics applications. First, as the sequences are binary, they are very easy to implement even with a low-cost application system whose output can only generate a small number of signal levels. Therefore, it is possible to utilize existing power converters and sensors in a system to perform the small-signal analysis, rather than adding specialized equipment with associated extra cost and extra size and weight. This is obviously not the case for example with sinusoidal sequences, which have infinite number of signal levels. Second, the binary sequences have the lowest possible peak factor, which means that the signal energy is very high in relation to the signal time-domain amplitude. This is particularly useful when analyzing systems that are sensitive to varying external signals. Third, the sequences considered in this article are all periodic signals so the signal analysis and post processing are much less complicated compared to aperiodic signals. Fourth, the spectral-energy distribution of the pseudorandom sequences is largely controllable, which makes the methods well scalable to different applications.

A number of broadband perturbations other than pseudorandom binary sequences have partially similar advantages but the combination of advantages that the PRBS-type sequences have is exceptional. For example, compared to the PRBS, a step input is easier to generate but the sequence has very weak and uncontrollable spectral-energy content. The same applies for impulse-type perturbation. On the other hand, perturbations based on sinusoidal sequences (such as sum of sinusoids) provide the highest possible spectral controllability and signal-to-noise ratio, but these types of sequences are difficult to implement and they often present large peaks in their time-domain waveforms.

This article considered four different classes of pseudorandom binary signals: MLBS, IRS, DIBS, and OBS. The MLBS is the most popular binary sequence used in dc power conversion systems. The sequence can be easily generated by a shift-register feedback circuit. The MLBS has a partially controllable spectral energy distribution, and provides an approximately smooth energy content up to one third of the signal generation frequency.

An assumption made while using the MLBS is that the process under consideration is linear. However, power converters suffer from various nonlinearities such as switching and quantization effects. Thus, the MLBS may produce inaccurate measurement of the converter linear dynamics. For systems with strong nonlinearities, the IRS provides a better alternative for performing the small-signal measurement. The IRS is generated by considering two periods of the MLBS and toggling every other digit of the two-period sequence. The IRS suppresses the most dominant nonlinearities from the system output, providing more accurate approximation of the system linear part. The IRS has the same attractive properties as the MLBS but the use of the IRS doubles the measurement time and reduces frequency resolution.

The MLBS and IRS have two potential drawbacks. In both sequences the signal energy is distributed over many harmonic frequencies. In small-signal analysis of systems requiring a very high SNR, either the injection amplitude has to be increased, or more periods of injection together with an averaging process have to be used. Both methods may become difficult in practice; increasing the amplitude may drift the system out of its linear region, whereas increasing the number of periods requires more computing power and memory storage. For these measurements, the DIBS provides an efficient method to perform the small-signal measurement. The DIBS is a computer-optimized signal, where the goal of the optimization is to force as much power as possible into specified harmonic frequencies without increasing the signal time-domain amplitude. The energy at the specified harmonic frequencies can be increased to tens of times higher value compared to the corresponding harmonic frequencies of the MLBS.

OBS have been applied to MIMO systems. Often, the complete stability analysis of such systems requires the measurement of several (coupled) small-signal models. As the orthogonal sequences have energy at different frequencies, several frequency responses can be measured at the same time within one measurement cycle. 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. It is emphasized, however, that possible nonlinearities should be carefully considered when applying the orthogonal sequences. As most converter systems are nonlinear, injecting a signal with a given frequency will generate energy at multiple additional frequencies in response to it. 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.

Table II summarizes the main properties of the pseudorandom binary sequences considered in this article.

REFERENCES

[1] V. Kanamarlapudi, B. Wang, P. So, and Z. Wang, "Analysis, design, and implementation of an APWM ZVZCS full-bridge DC-DC converter for battery charging in electric vehicles," *IEEE Trans. Power Electron.*, vol. 32, no. 8, pp. 6145–6160, Aug. 2017.

[2] A. Riccobono *et al.*, "Stability of shipboard DC power distribution: Online impedance-based systems methods," *IEEE Electrific. Mag.*, vol. 5, no. 3, pp. 55–67, Sep. 2017.

[3] A. Deihimi and M. Mahmoodieh, "Analysis and control of battery-integrated dc/dc converters for renewable energy applications," *IET Power Electron.*, vol. 10, no. 14, pp. 1819–1831, Nov. 2017.

[4] A. Frances, R. Asensi, O. Garcia, R. Prieto, and J. Uceda, "Modeling electronic power converters in smart DC microgrids - an overview," *IEEE Trans. Smart Grids*, vol. 9, no. 6, pp. 6274–6287, Nov. 2018.

[5] L. He, Z. Zheng, and D. Guo, "High step-up DC–DC converter with active soft-switching and voltage-clamping for renewable energy systems," *IEEE Trans. Power Electron.*, vol. 33, no. 11, pp. 9496–9505, Nov. 2018.

[6] M. Cupelli, A. Riccobono, M. Mirz, M. Ferdowsi, and A. Monti, *Modern Control DC-Based Power Syst.* New York, NY, USA: Academic, 2018.

[7] M. Kabalan, P. Singh, and D. Niebur, "Large signal lyapunov-based stability studies in micrcogrids: A review," *IEEE Trans. Smart Grid*, vol. 8, no. 5, pp. 2287–2295, Sep. 2017.

[8] R. Erickson and D. Maksimovic, *Fundamentals Power Electronics*, *2nd* ed. Norwell, MA, USA: Kluwer, 2001.

[9] R. Ridley, "Measuring frequency response, tips and methods," *Switching Power Mag.*, pp. 1–12, 2006.

[10] R. Ridley, *Power Supply Design, Volume 1: Control*. Cambridge, U.K.: Ridley Engineering, 2012.

[11] T. Suntio, *Dynamic Profile Switched-Mode Converter*. New York, NY, USA: Wiley, 2009.

[12] R. Pintelon and J. Schoukens, *System Identification - A Frequency Domain Approach*. New York, NY, USA: The Institute of Electrical and Electronics Engineers, Inc., 2001.

[13] L. Ljung, *System Identification-Theory for User*. Englewood Cliffs, NJ, USA: Prentice-Hall, 1999.

[14] K. R. Godfrey, "Introduction to binary signals used in system identification," in *Proc. Int. Conf. Control*, 1991, pp. 161–166.

[15] A. Tan and K. Godfrey, "The generation of binary and near-binary pseudo-random signals: An overview," *IEEE Trans. Instrum. Meas.*, vol. 51, no. 4, pp. 583–588, Aug. 2002. [Online] Available at: http://www.eng.warwick.ac.uk/eed/dsm/prs

[16] K. R. Godfrey, "Introduction to non-binary signals used in system identification," in *Proc. Int. Conf. Control*, 1991, pp. 550–555.

[17] K. Godfrey, "Design and application of multifrequency signals," *Comput. Control Eng. J.*, vol. 2, pp. 187–195, 1991.

[18] B. Miao, R. Zane, and D. Maksimovic, "A modified cross-correlation method for system identification of power converters with digital control," in *Proc. IEEE Power Electron. Specialists Conf.*, 2004, pp. 3728–3733.

[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] B. Miao, R. Zane, and D. Maksimovic, "Practical on-line identification of DC-DC converter dynamic responses," in *Proc. Appl. Power Electron. Conf. Expo.*, 2005, pp. 57–62.

[21] B. Miao, R. Zane, and D. Maksimovic, "FPGA-based digital network analyzer for digitally controlled SMPS," in *Proc. IEEE Workshop Comput. Power Electron.*, 2006, pp. 240–245.

[22] M. Shirazi, J. Morroni, A. Dolgov, and D. Maksimovic, "Integration of frequency response measurement capabilities in digital controllers for DC-DC converters," *IEEE Trans. Power Electron.*, vol. 23, no. 5, pp. 2524–2535, Sep. 2008.

[23] B. Miao, R. Zane, and D. Maksimovic, "Automated digital controller design for switching converters," in *Proc. IEEE Power Electron. Specialists Conf.*, 2005, pp. 2729–2735.

[24] M. Shirazi, R. Zane, D. Maksimovic, L. Corradini, and P. Mattavelli, "Autotuning techniques for digitally-controlled point-of-load converters with wide range of capacitive loads," in *Proc. IEEE Appl. Power Electron. Conf. Expo.*, 2007, pp. 14–20.

[25] M. Shirazi, R. Zane, and D. Maksimovic, "An autotuning digital controller for DC-DC power converters based on online frequency-response measurement," *IEEE Trans. Power Electron.*, vol. 24, no. 11, pp. 2578–2588, Nov. 2009.

[26] A. Barkley and E. Santi, "Improved online identification of switching converters using digital network analyzer techniques," in *Proc. IEEE Power Electron. Specialists Conf.*, 2008, pp. 891–896.

[27] A. Barkley and E. Santi, "Improved online identification of a DC/DC converter and its control loop gain using cross-correlation methods," *IEEE Trans. Power Electron.*, vol. 24, no. 8, pp. 2021–2031, Aug. 2009.

[28] A. Barkley and E. Santi, "Online monitoring of network impedances using digital network analyzer techniques," in *Proc. Appl. Power Electron. Conf. Expo.*, 2009, pp. 440–446.

[29] 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. Model. Pract. Theory*, vol. 17, pp. 1043–1058, 2009.

[30] T. Roinila, T. Helin, M. Vilkko, M. Hankaniemi, and H. Koivisto, "Evaluating the confidence of frequency-response function of a switched-mode converter using distributional models," in *Proc. IEEE Energy Convers. Congr. Expo.*, 2010, pp. 1987–1991.

[31] E. Santi, H. Cho, A. Barkley, D. Martin, and A. Riccobono, "Tools to address system level issues in power electronics: The digital network analyzer method and the positive feedforward control technique," in *Proc. Int. Conf. Power Electron.*, 2011, pp. 2106–2113.

[32] J. Siegers, E. Santi, and A. Barkley, "Wide bandwidth system identification of MVDC distribution system by applying perturbations to an existing converter," in *Proc. IEEE Electric Ship Technol. Symp.*, 2013, pp. 434–441.

[33] A. Riccobono, E. Liegmann, M. Pau, F. Ponci, and A. Monti, "Online parametric identification of power impedances to improve stability and accuracy of power hardware-in-the-loop simulations," *IEEE Trans. Instrum. Meas.*, vol. 66, pp. 2247–2257, Sep. 2017.

[34] A. Riccobono and E. Santi, "Stability analysis of an all-electric ship MVDC power distribution system using a novel passivity-based stability criterion," in *Proc. IEEE Electric Ship Technol. Symp.*, 2013, pp. 411–419.

[35] J. Siegers, S. Arrua, and E. Santi, "Stabilizing controller design for multi-bus MVDC distribution systems using a passivity based stability criterion and positive feed-forward control," in *Proc. IEEE Energy Convers. Congr. Expo.*, 2015, pp. 5180–5187.

[36] 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.

[37] J. Siegers, S. Arrua, and E. Santi, "Stabilizing controller design for multi-bus mvdc distribution systems using a passivity based stability criterion and positive feed-forward control," *IEEE J. Emerg. Sel. Topics Power Electron.*, vol. 5, no. 1, pp. 14–27, Mar. 2017.

[38] J. Siegers, H. Ginn, and E. Santi, "Stability and accuracy considerations in the design and implementation of a kilowatt-scale DC power hardware-in-the-loop platform," in *Proc. IEEE Energy Convers. Congr. Expo.*, 2014, pp. 1126–1133.

[39] J. Siegers and E. Santi, "Improved power hardware-in-the-loop interface algorithm using wideband system identification," in *Proc. IEEE Appl. Power Electron. Conf. Expo.*, 2014, pp. 1198–1204.

[40] J. Siegers and E. Santi, "Stability analysis and control design for an all-electric ship MVDC power distribution system using a passivity based stability criterion and power hardware-in-the-loop simulation," in *Proc. IEEE Electric Ship Technol. Symp.*, 2015, pp. 86–92.

[41] T. Roinila, H. Abdollahi, S. Arrua, and E. Santi, "Adaptive control of interconnected multi-converter systems: Applying pseudo-random sequences and fourier techniques," in *Proc. Int. Power Electron. Conf.*, 2018, pp. 1719–1723.

[42] 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, no. 8, pp. 2179–2187, Aug. 2010.

[43] T. Roinila, M. Vilkko, and T. Suntio, "Fast loop gain measurement of switched-mode converter using binary signal with specified Fourier amplitude spectrum," *IEEE Trans. Power Electron.*, vol. 17, no. 6, pp. 2746–2755, Dec. 2009.

[44] 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.

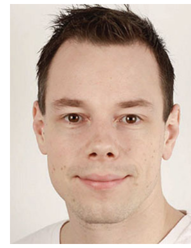
[45] T. Roinila, H. Abdollahi, S. Arrua, and E. Santi, "Real-time stability analysis and control of multi-converter systems by using MIMO-identification techniques," *IEEE Trans. Power Electron.*, vol. 34, no. 4, pp. 3948–3957, Apr. 2019.

[46] A. Tan and K. Godfrey, *Industrial Process Identification - Perturbation Signal Design and Applications*. Cham, Switzerland: Springer, 2019.

[47] K. Godfrey, *Perturbation Signals for System Identification*. Englewood Cliffs, NJ, USA: Prentice-Hall, 1993.

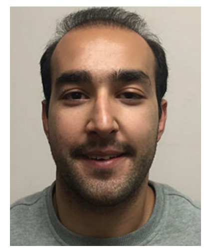
[48] O. Nelles, *Nonlinear System Identification*. Berlin, Germany: Springer, 2001.

[49] C. Evans, D. Rees, L. Jones, and M. Weiss, "Periodic signals for measuring nonlinear volterra kernels," *IEEE Trans. Instrum. Meas.*, vol. 45, no. 2, pp. 362–371, Apr. 1996.
[50] W. Davies, *System Identification for Self-Adaptive Control*. New York, NY, USA: Wiley, 1970.
[51] R. Tymerski, "Volterra series modeling of power conversion systems," *IEEE Trans. Power Electron.*, vol. 6, no. 4, pp. 712–718, Oct. 1991.
[52] M. Al-Greer, M. Armstrong, M. Ahmeid, and D. Giaouris, "Advances on system identification techniques for DC-DC switch mode power converter applications," *IEEE Trans. Power Electron.*, vol. 34, no. 7, pp. 6973–6990, Jul. 2019.
[53] L. Aguirre, P. Donoso-Garcia, and R. Santos-Filho, "Use of a priori information in the identification of global nonlinear models-A case study using a buck converter," *IEEE Trans. Circuits Syst.*, vol. 47, no. 7, pp. 1081–1085, Jul. 2000.
[54] F. Alonge, F. D'Ippolito, F. Raimondi, and S. Tumminaro, "Nonlinear modeling of DC-DC converters using the hammerstein's approach," *IEEE Trans. Power Electron.*, vol. 22, no. 4, pp. 1210–1221, Jul. 2007.
[55] V. Valdivia, A. Barrado, A. Lazaro, P. Zumel, C. Raga, and C. Fernandez, "Simple modeling and identification procedures for "black-box" behavioral modeling of power converters based on transient response analysis," *IEEE Trans. Power Electron.*, vol. 24, no. 12, pp. 2776–2790, Dec. 2009.
[56] T. Suntio, "Average and small-signal modeling of self-oscillating flyback converter with applied switching delay," *IEEE Trans. Power Electron.*, vol. 21, no. 2, pp. 479–486, Mar. 2006.
[57] A. V. D. Bos and R. Krol, "Synthesis of discrete-interval binary signals with specified fourier amplitude spectra," *Int. J. Control*, vol. 30, pp. 871–884, 1979.
[58] T. Roinila, M. Vilkko, and J. Sun, "Online grid impedance measurement using discrete-interval binary sequence injection," *IEEE J. Emerg. Sel. Topics Power Electron.*, vol. 2, no. 4, pp. 985–993, Dec. 2014.
[59] T. Roinila, M. Vilkko, and J. Sun, "Online grid impedance measurement using discrete-interval binary sequence injection," in *Proc. IEEE Workshop Control Model. Power Electron.*, 2013, pp. 1–8.
[60] 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.
[61] T. Roinila, J. Huusari, and M. Vilkko, "On frequency-response measurements of power-electronic systems applying MIMO-identification techniques," *IEEE Trans. Ind. Electron.*, vol. 60, no. 11, pp. 5270–5276, Nov. 2013.
[62] I. Cvetkovic, D. Boroyevich, P. Mattavelli, F. Lee, and D. Dong, "Unterminated, low-frequency terminal behavioral model of dc-dc converters," in *Proc. Appl. Power Electron. Conf. Expo.*, 2011, pp. 1873–1880.



Tomi Roinila (Member, IEEE) received the M.Tech. and Ph.D. degrees in automation and control engineering from Tampere University of Technology, Tampere, Finland, in 2006 and 2010, respectively.

He is currently an Assistant Professor with Tampere University, Tampere, Finland. His main research interests include modeling and control of grid-connected power-electronics systems, analysis of energy-storage systems, and modeling of multi-converter systems.



Hessamaldin Abdollahi (Member, IEEE) received the B.Sc. degree in electrical and electronic engineering from Qazvin Azad University, Qazvin, Iran, in 2011, and the M.S. degree (*summa cum laude*) in electrical engineering from Politecnico di Milano, Milan, Italy, in 2015. He is currently working toward the Ph.D. degree in electrical engineering with the Department of Electrical Engineering, University of South Carolina, Columbia, SC, USA.

His research interests include design and control of power converters, stability analysis, and control of multiconverter power distribution systems.

Enrico Santi (Senior Member, IEEE) received the bachelor's degree from the University of Padua, Padua, Italy, in 1988, and the Ph.D. degree from California Institute of Technology, Pasadena, CA, USA, in 1994, all 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 and coauthored more than 200 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.