dSPACE Implementation for Real-Time Stability Analysis of Three-Phase Grid-Connected Systems Applying MLBS Injection

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Abstract

Renewable resources such as solar and wind are most commonly connected to a utility grid through inverters. The stability and system characteristics of such systems can be defined by the ratio of grid impedance to the inverter output impedance. Since the impedances vary over time with numerous operation conditions, real-time measurements are required to verify the stability. The impedance measurement technique based on maximum-length-binary-sequence (MLBS) injection and Fourier techniques has been proven to be an efficient option for online analysis of grid-connected systems. This paper shows how a hardware-in-the-loop simulation based on dSPACE can be implemented for stability analysis of a grid-connected inverter using the MLBS injection. The method makes it possible to modify the inverter control characteristics and grid conditions online, thereby providing means for various stability and control design studies for grid-connected systems. We have presented a measurement example based on a three-phase grid-connected inverter and used this example to demonstrate the implementation.

Keywords: frequency response, power system measurements, spectral analysis, signal design, real-time systems

1 Introduction

The most common way to connect renewable resources such as wind turbines or photovoltaic generators to a power grid is through inverters. As the penetration of the inverter-connected systems increases, it has globally important effect on the grid's performance. Consequently, interaction issues between the grid-parallel inverters and power grids have been topics of extensive research in recent years (Cespedes and Sun, 2014b; Lu et al., 2015; Hu et al., 2015). One of the most important topics has been the harmonic resonance generated due to the mismatch between the inverter's output impedance and grid impedance. This is commonly known as the harmonics-related power-quality problem, which has had a significant effect on overall energy efficiency and even grid stability (Sun, 2011). Recent studies have shown that the instability can be avoided by measuring the impedances of the grid and inverter, and based on the measurements, adaptively changing the inverter parameters (Cespedes and Sun, 2014a).

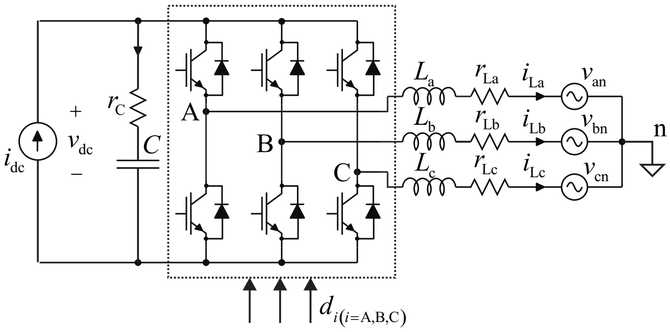

Figure 1. Grid-connected renewable energy inverter.

The impedance measurements of grid-connected systems using a broadband excitation and Fourier techniques have become a popular method in recent years (Barkley and Santi, 2009; Cespedes and Sun, 2014a; Roinila et al., 2013). This method involves injecting an external current on top of the normal output current of the inverter or grid, measuring the resulting voltage responses, and applying Fourier analysis to extract the frequency components in both the voltage and current. The grid or inverter impedance is then determined by the ratio between the voltage and current at different frequencies. The most common excitation types have been impulse (Cespedes and Sun, 2014a) and maximum-length binary sequence (MLBS) (Roinila et al., 2014), from which the MLBS has shown superiority over the impulse. The MLBS is a deterministic and periodic signal. Hence, the effect of external noise can be computationally reduced, and multiple periods can be applied through spectral averaging to further increase the signal-to-noise ratio (SNR). As a result, the amplitude of the excitation can be kept at a much lower level than the amplitude of many other types of excitations. Due to the binary form of the MLBS, the injection is extremely easy to implement, even with a low-cost application, the output of which can only cope with a small number of signal levels.

This paper considers real-time impedance measurements of a grid-connected system using hardware-in-the-loop (HIL) simulation based on dSPACE software

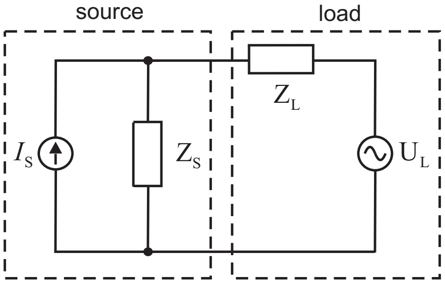

Figure 2. Interconnected source-load subsystem.

and Matlab/Simulink. dSPACE is widely used in real-time analysis and control of various power-electronics applications including three-phase grid-connected systems (Ghani et al., 2009), digitally controlled power converters (Monti et al., 2003), and back-to-back converters (Deshpande et al., 2012). Matlab/Simulink provides a functionality that generates a C-code from the Simulink model. Using dSPACE's real-time interface (RTI), the C-code can be automatically implemented into the I/O board of dSPACE. This method makes it possible to modify the grid characteristics and the inverter's controller parameters online, which in turn enables various stability and control design studies for grid-connected systems in time-varying conditions.

This paper will show the implementation of a real-time impedance measurement of a grid-connected system using dSPACE. No external signal generator or data-acquisition units are required; the signal generation, injection and computations are all performed in dSPACE. We show the implementation steps, starting from generating the MLBS. As the paper does not consider dSPACE in detail, the reader should have a basic knowledge of the software.

The remainder of this paper is organized as follows. Section 2 briefly reviews the theory behind the stability analysis of grid-connected systems and the synthesis of the MLBS. Section 3 gives an example of a grid-connected system operated by dSPACE, and provides guidelines for generating the MLBS and obtaining the system characterizing responses. Section 4 draws conclusions.

2 Theory

2.1 Stability of Grid-Connected System

Figure 1 depicts a three-phase inverter for direct interfacing of a photovoltaic generator. The inverter is comprised of six power electronic switches, a DC capacitor, and threephase inductors. The inverter controls its switches between conducting and non-conducting mode with sinusoidal control voltages in order to transform DC from the renewable energy source into the three-phase AC required by the power grid.

The stability of a inverter-connected system can be easily assessed in the frequency domain by constructing a small-signal state-space representation for the interfacing inverter and the load subsystem. The stability analysis can be conducted by applying the Nyquist stability criterion to the impedance ratio in an interface (Wang et al., 2014).

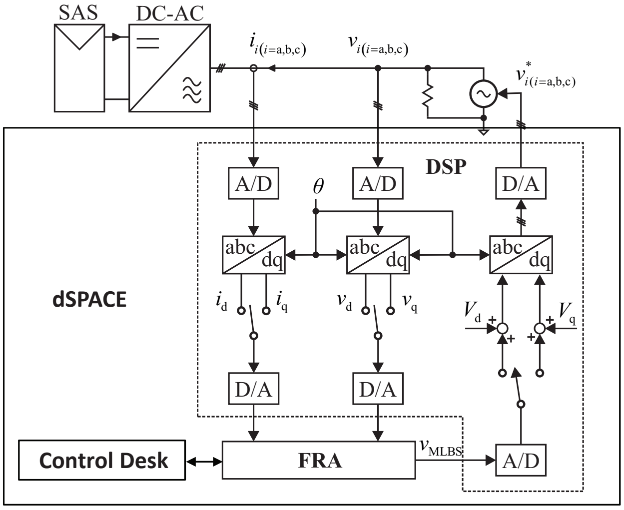

Figure 3. Circuit diagram of three-phase grid-connected inverter connected to real-time spectrum analyzer based on MLBS.

Figure 2 shows a simple example of a single-phase system in which the system consists of one source powering a single load. The source is modeled by a Norton equivalent circuit, as a current source I_S in parallel with the source impedance Z_S. The load voltage is denoted by U_L and the load impedance by Z_L. This combination applies for a grid-parallel inverter in which the grid acts as a voltage-type load and the inverter resembles a controlled current source. Assuming that the source is stable when unloaded and that the load is stable when powered by an ideal source, the stability and other dynamic characteristics of the interconnected system can be determined from the transfer function

$$G(s) = \frac{1}{1 + Z_L(s)/Z_S(s)} \tag{1}$$

The interconnected system is only stable if the impedance ratio $Z_L(s)/Z_S(s)$ satisfies the Nyquist stability criterion. Power systems that are more complex can be represented in the same form and analyzed similarly by putting together multiple sources into a source subsystem and loads into a load subsystem. In general, a grid-connected inverter does not suffer from resonance phenomena caused by impedance-based interactions if the output impedance of the inverter is shaped so that it has a larger magnitude than grid impedance at every frequency.

Three-phase inverters can be modeled in the DQ domain by using direct (d) and quadrature (q) components (Yazdani and Iravani, 2010). The output impedance can be represented in the matrix form shown in (2). The cross-coupling impedances Z_{qd} and Z_{dq} can usually be neglected in stability analysis because they are typically very small in magnitude. Analogous to single-phase systems, the stability of a three-phase system can be determined from the transfer functions in (3) and (4) by applying the Nyquist

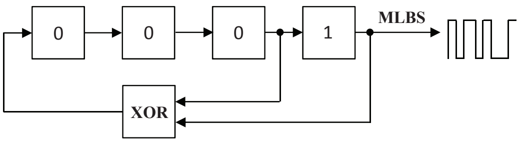

Figure 4. Shift register with XOR and feedback.

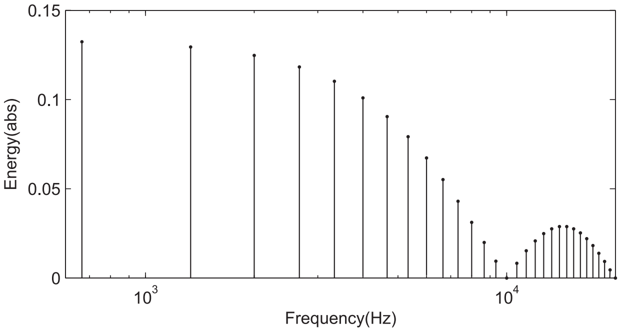

Figure 5. Power spectrum of 15-bit-length MLBS generated at 10 kHz.

stability criterion. Both impedance ratios have to satisfy this criterion for stable operation.

$$\mathbf{Z}_\mathrm{S} = \begin{bmatrix} Z_\mathrm{d} & Z_\mathrm{qd} \\ Z_\mathrm{dq} & Z_\mathrm{q} \end{bmatrix} \tag{2}$$

$$G_\mathrm{d}(s) = \frac{1}{1+Z_\mathrm{L}(s)/Z_\mathrm{d}(s)} \tag{3}$$

$$G_\mathrm{q}(s) = \frac{1}{1+Z_\mathrm{L}(s)/Z_\mathrm{q}(s)} \tag{4}$$

2.2 Maximum-Length Binary Sequence

Pseudo-random binary sequence (PRBS) is a periodic broadband signal based on a sequence of length N. The most commonly used signals are based on maximumlength sequences (MLBS). Such sequences exist for $N = 2^n - 1$, where n is an integer. These are popular because they can be generated using feedback shift-register circuits. (Godfrey, 1993)

Figure 4 shows an example of a shift-register circuit for generating an MLBS of a length $2^4 - 1 = 15$. The feedback is generated from stages 3 and 4. The register can be started with any number other than 0,0,0,0. In practice, the values 0 and 1 are mapped to -1 and +1 to produce a symmetrical MLBS with an average close to zero.

Figure 5 shows the form of the power spectrum of the MLBS generated by the shift register shown in Figure 4. The sequence is generated at 10 kHz and has signal levels ±1 V. The power spectrum has an envelope and drops to zero at the generation frequency and its harmonics. The MLBS x has the lowest possible peak factor $|x|_\mathrm{peak}/x_\mathrm{rms} = 1$ regardless of its length, which means that the sequence is well suited to sensitive systems that require small-amplitude perturbation.
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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.

3 Implementation in dSPACE

This section provides the main steps and guidelines for the frequency-response-measurement procedure using dSPACE. The steps are shown through an example in which the output impedance is measured from a threephase grid-connected inverter.

3.1 System Setup

Figure 3 shows the setup of the system under study. The goal is to measure the d- and q-components of inverter's output impedance. A similar approach can be used to measure the grid impedance or any other system-characterizing frequency response, but the example only considers the output-impedance measurement. The system comprises the power stage and real-time frequency-response analyzer (FRA) based on the MLBS injection. The powerstage components are the photovoltaic generator, the inverter, and the three-phase grid emulator. The details of the power-stage components are omitted because they are not within the scope of this paper.

The MLBS is implemented in dSPACE and runs parallel with the inverter control functions. The "Control Desk"-block in Figure 3 depicts a PC, which is used to modify the MLBS parameters such as the length of the injected signal and its amplitude. The MLBS is injected to the d- or q-component of the grid reference voltage. The perturbed three-phase currents and voltages of the inverter are transformed into their corresponding d- and q-components and collected by the FRA.

The measurements of the d- and q-components of the impedance require two separate measurement cycles; one for injecting and collecting d-components and one for q-components. It should be emphasized that various transfer functions can be measured without disconnecting the system. The possible variables can be defined in dSPACE and can be switched in the "Control Desk" -block. For example, the effect of different control loops on a specific transfer function can easily be analyzed online.

Figure 6 is a diagram of the real-time spectrum analyzer including the generation of the MLBS, the sequence injection, and data collection. All the rectangular boxes denote the Simulink blocks that are used for dSPACE. The shift register is implemented by unit-delay blocks. The output of exclusive-or (XOR) replaces the first bit of the sequence through feedback. The generation frequency of the injection is set by the delay value of the unit-delay blocks.

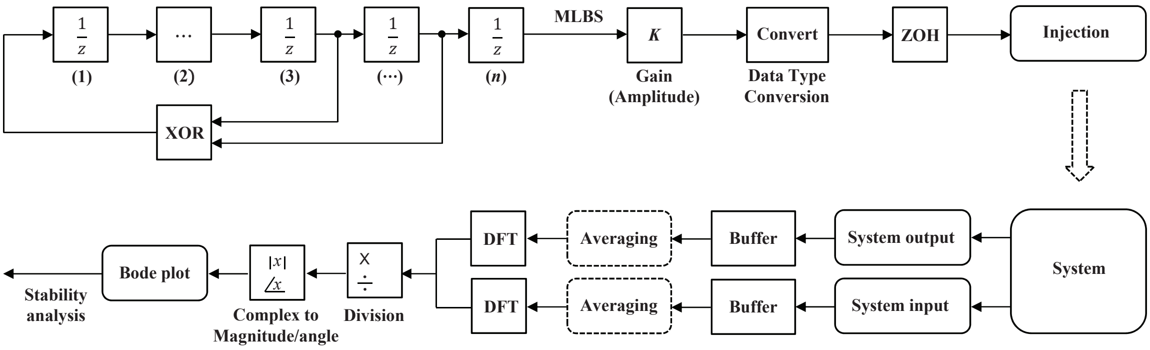

Figure 6. Diagram of the excitation generation, injection and data collection.

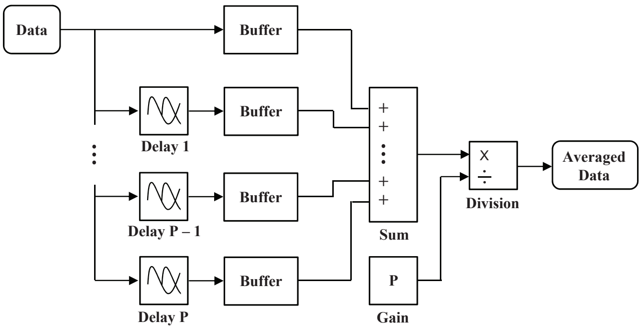

Figure 7. Diagram of the averaging procedure of measured data.

The MLBS is amplified by an adjustable gain (K), after which the sequence is converted from logical numbers to realworld numbers. The zeroorder-hold block is required by dSPACE. The presented concept allows continuous and repeating generation and injection of the MLBS into the system.

The presented implementation also makes it possible to change the injection amplitude in real time. Hence, depending on the noise level and nonlinearities, the amplitude can be experimentally adjusted so that the produced injection energy is high enough. The injection amplitude cannot be too high because the grid-connected systems are typically highly sensitive to external signals and nonlin-earities may easily arise.

The measurements of input and output data are continuously collected and buffered. Once the data is buffered a DFT matrix is applied to perform the Fourier transform (Sundararajan, 2001). The reason for the use of the DFT matrix is that the length of the buffered data is $2^n - 1$ (length of the MLBS). A readily available FFT-block could be used but the block only accepts a data sequence of length 2^n. Therefore, the fast Fourier transform is not applied in the implementation.

The Fourier transformed output data is divided by the input data resulting in the complex transfer function. The Bode plot is obtained by computing the magnitude and phase from the complex data. The refresh rate of the Bode plot is $2^n/f_s$, where n is the length of the shift register and f_s is the sampling frequency.

The effect of external noise can be reduced by applying averaging. Figure 7 shows the diagram for moving average. Input and output data are delayed by $i \cdot f_s 2^n$, where $i = 1, 2, \ldots, P$ where P denotes the number of injection periods.

3.2 Experiment

The applied MLBS injection is generated through a 7-bit-length shift register, resulting in an 127-bit-long sequence. The sampling frequency f_s and injection generation frequency f_g are set to 8 kHz and 4 kHz, respectively. Using the specified values for injection length and generation frequency, the frequency resolution is fixed to $f_g/2^n = 4\text{kHz}/127 \approx 31\text{Hz}$. The measurement system is built in Matlab/Simulink as shown in Figure 6, after which the model is transferred to dSPACE as C-code.

Figs. 8 and 9 show a sample measurement of the d- and q-components of the inverter's output impedance. The curves are averaged over 12 injection periods. Hence, the time for one measurement cycle took approximately 0.38 s. Because a moving average was applied (Figure 7), a new Bode plot was obtained after each injection period. Therefore, the refresh rate of the Bode plot was approximately 31 Hz. The reference responses are obtained by sine sweeps. Due to long measurement time of the sine-sweep technique (approximately 10 min in the application), the method cannot be applied in practice. The figure shows that the results obtained by the MLBS accurately follow the reference, showing only a few decibels and degrees of error. No external data-acquisition devices were used in the experiment. The signal generation, injection and computations were all performed in dSPACE.

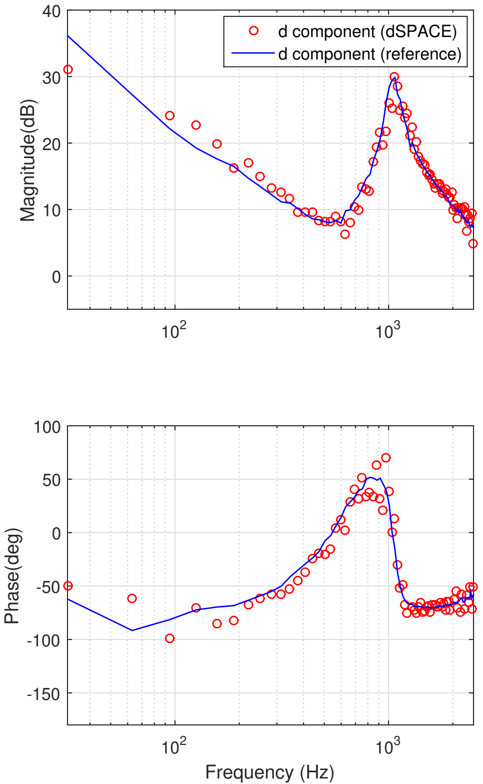

Figure 8. d-components of inverter's output impedance.

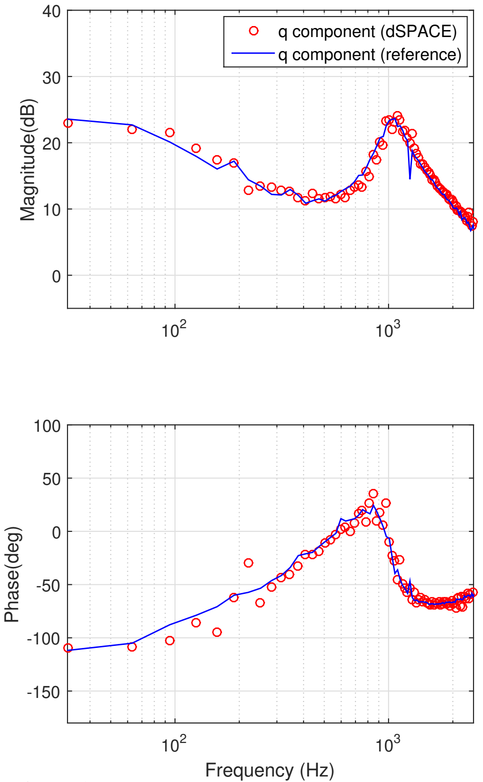

Figure 9. q-components of inverter's output impedance.

4 Conclusions

This paper has presented methods for real-time stability analysis of grid-connected systems using hardware-in-the-loop simulation based on dSPACE and Matlab/Simulink. The MLBS broadband injection was used to measure the output impedance of a three-phase grid-connected inverter. Due to the low peak factor, the amplitude of the injection can be kept relatively small compared to other types of excitations, thereby guaranteeing normal system operation during the identification. Other advantages include straightforward generation of the sequence.

A dSPACE implementation for generating the injection and data acquisition was shown. The proposed methods allow continuous monitoring of system performance and real-time adjustments of the injection properties. The method also makes it possible to modify the inverter control characteristics and grid conditions online, which provides means for analysis under time-varying conditions. Due to fast injection and measurement time, the presentedmethod is useful for various on-line and real-time measurements in, for example, adaptive control of three-phase inverters, and stability analysis of grid-connected systems.

Acknowledgements

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