Broadband Impedance-Measurement Methods in Dynamic Analysis of Dual Active Bridge Converters

Roosa-Maria Sallinen and Tomi Roinila
Faculty of Information Technology and Communication Sciences
Tampere University
Tampere, Finland
email: roosa.sallinen@tuni.fi; tomi.roinila@tuni.fi

***Abstract*—The output impedance of a switched-mode converter is an important parameter in the converter small-signal stability analysis and stability-enhancing control. One of the popular methods for obtaining the converter output impedance is to introduce a broadband signal such as the pseudo-random binary sequence (PRBS) to the converter duty cycle; the resulting output voltage and current are measured, and the output impedance is obtained with Fourier methods. However, such techniques have not been fully considered for dual active bridge (DAB) converters. This paper discusses the challenges of broadband impedance measurements on DAB converters, compares different implementation methods, and outlines guidelines for achieving accurate results. Unlike conventional dc-dc converters, the power of a DAB converter can be controlled by both the duty ratio and phase shift, thus allowing several methods to perform the impedance measurement. Yet, nonlinearity between the power transfer and phase shift and duty ratio introduces potential challenges to the measurement implementations. Experimental measurements based on a DAB converter are shown to demonstrate these challenges as well as the effectiveness of the proposed measurement guidelines.**

***Index Terms*—dual active bridge converter, impedance measurement, broadband methods, system identification, nonlinear power characteristics**

I. Introduction

A dual active bridge (DAB) converter is an isolated bidirectional dc-dc converter. Its advantages include flexible power flow control, zero voltage-switching, high efficiency, and modular structure, which make it useful for a wide variety of modern power-distribution systems. In particular, DAB converters play an important role in many multi-converter systems, such as dc micro grids [1], automotive power systems [2], electric ships [3], and electric aircrafts [4].

In a typical multi-converter system, several switching converters are connected to a common dc bus. Each of these interconnected converters usually has a high-bandwidth feedback control. Converters that are standalone stable may exhibit a different dynamic behavior when interconnected, which can cause undesired interactions among the interconnected converters and compromise the small-signal stability [5], [6]. As the power flow of DAB converters is bidirectional, traditional methods based on Nyquist criterion cannot be utilized directly for stability assessment [7].

In recent years, studies have presented methods such as the passivity-based stability criterion to analyze the small-signal stability of a multi-converter system [7]. This method requires measuring the system bus impedance which can be computed as a combined impedance of all the interconnected converters. Since the criterion only requires the identification of the bus impedance, the method is not dependent on the system grouping nor power flow directions. These characteristics make the technique especially suitable for stability assessment of multi-converter systems that utilize DAB converters.

Recent studies have shown broadband methods suitable for accurate and fast converter impedance measurement [8]–[10]. In these methods, a specifically designed broadband perturbation, such as the pseudo-random binary sequence (PRBS), is added on top of either the converter controller reference or duty cycle. The resulting voltage and current responses are measured at the output of the converter and Fourier analysis is applied to obtain the impedance. By applying the approach to each converter in the system, the bus impedance can be obtained as a combination of single measurements [8]–[10]. Such wideband measurement techniques can be performed online, making the method practical and suitable for various applications. In [10]–[12] the method was used to facilitate stability-enhancing adaptive controllers. In these studies, the effectiveness of the stability-enhancing control relied solely on sufficient impedance measurements.

Including a DAB converter to a multi-converter system increases the complexity of the analysis and impedance measurement. The presented broadband impedance-measurement methods rely on linearity between the perturbed parameter and converter output power. However, in a DAB converter, the relationship between the power transfer and duty ratio and phase shift is more complex and may have a nonlinear nature, depending on the chosen set-point and modulation and control strategy [13]–[17]. Furthermore, since the DAB converters can be controlled by both phase shift and duty ratio, more options for the perturbation implementation are feasible in comparison to performing the measurements on more traditional dc-dc converters in which only duty ratio can be controlled.

This paper presents methods for performing broadband

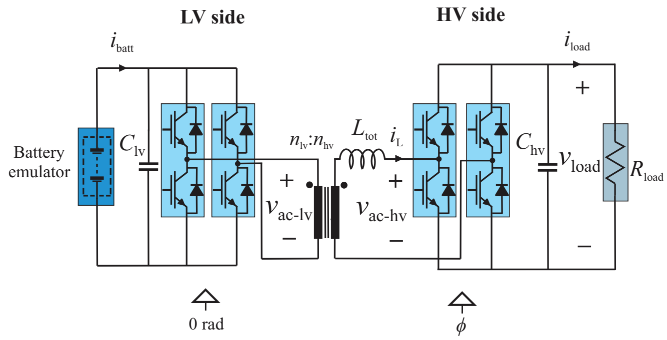


Fig. 1. Dual active bridge converter with battery emulator and resistive load.

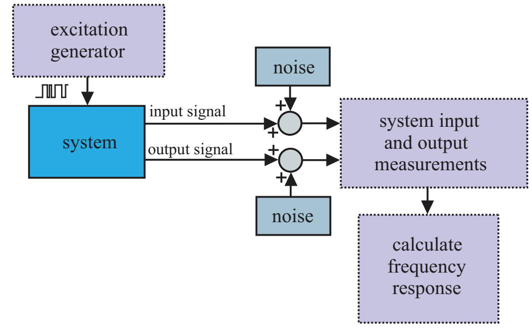


Fig. 2. Typical setup for frequency response measurement.

impedance-measurements on DAB converters. Different strategies for perturbation and measurement implementation are considered and guidelines for obtaining reliable results are outlined. Experimental measurements based on a DAB converter are shown to demonstrate the effectiveness of the proposed methods as well as to demonstrate the possible challenges caused by the nonlinear relationship between the power transfer and phase shift and duty ratio.

The remainder of the paper is organized as follows. Section II describes the relationship between the DAB converter power flow, duty ratio, and phase shift, and provides background on performing impedance measurements in general. Furthermore, guidelines for reliable impedance measurements on DAB converters are outlined. Section III presents experimental results based on a DAB converter with a resistive load. Finally, Section IV draws conclusions.

II. Theory and Methods

A. Power characteristics of dual active bridge converters

DAB converters are typically controlled by manipulating the duty ratio(s) and/or phase shift between the modulating signals of the two bridges. This differentiates DAB converters from more traditional dc-dc converters that can be controlled only by the duty ratio. Various different modulation techniques exist for DAB converters. One of the most popular methods is the phase-shift modulation, which is simple and allows for high powers but reduces the degrees of freedom to phase shift only as the duty ratios are kept constant (usually 0.5).

Fig. 1 shows a schematic diagram of a phase shift modulated and single-phase controlled DAB converter with a battery emulator and resistive load. The modulating signals of the high-voltage-side bridge are delayed by a phase shift ϕ, while the low voltage-side bridge is kept constant (0 rad). The converter power flow is controlled by adjusting the phase shift. When using phase-shift modulation and single-phase-shift control, the power transfer achieved at a certain phase shift can be given as

$$P = \frac{nV_{\mathrm{lv}}V_{\mathrm{hv}}}{2\pi f_{\mathrm{sw}}L_{\mathrm{tot}}}\phi\left(1-\frac{|\phi|}{\pi}\right) \quad (1)$$

where n is the transformer turns ratio, V_{lv} and V_{hv} are the voltages of the low- and high-voltage side, respectively (battery voltage and output/load voltage), f_{sw} is the switching frequency, and L_{tot} is the total inductance. The duty ratio has a fixed value of 0.5. Maximum power transfer is achieved when the phase shift is $\pm\pi/2$. However, due to deadtime, maximum power transfer may be achieved already at a lower phase shift.

If a different modulation and/or control strategy is used, the duty ratios (of one or both of the bridges) may be set to other values than 0.5 and/or both of the phase shifts may be varied. This adds complexity in the relationship between the power transfer and phase shift and duty ratio [13]–[16]. For example, when setting the low voltage-side duty ratio to a constant value of 0.5 and adjusting the power with the high-voltage-side duty ratio and phase shift, depending on the range of phase shift, there are two possible operation states known as inner and outer state. The power for the inner and outer states can be given by (2) and (3), respectively, as

$$P = \frac{nV_{\mathrm{lv}}V_{\mathrm{hv}}}{2\pi f_{\mathrm{sw}}L_{\mathrm{tot}}}\phi D_{\mathrm{hv}} \quad (2)$$

$$P = \frac{nV_{\mathrm{lv}}V_{\mathrm{hv}}}{2\pi f_{\mathrm{sw}}L_{\mathrm{tot}}}\left[\phi\left(1-\frac{|\phi|}{\pi}\right)-\frac{\pi}{4}\left(1-D_{\mathrm{hv}}\right)^2\right] \quad (3)$$

where D_{hv} is the high-voltage-side duty ratio [13]. Decreasing the high-voltage-side duty ratio increases the power capability. Thus, a higher maximum power can be achieved compared to the power available with both duty ratios set to 0.5. If a dual-phase-shift control strategy is used, that is, both the high and low voltage-side duty ratios are varied, the power characteristics are more complicated.

Regardless of the chosen modulation and control strategy of a DAB converter, the presence of deadtime complicates the power characteristics further due to voltage distortion phenomena, such as voltage polarity reversal, voltage sag, phase drift, and duty-cycle abnormity [17]. Especially when operating at high switching frequencies, the effect of deadtime on voltage distortion and efficiency degradation is significant and cannot be ignored. The deadtime effect on average power transfer occurs due to a voltage polarity reversal phenomenon [17]. Various methods to avoid or mitigate deadtime effects have been suggested [18]–[21] but the applicability of these methods depends strongly on the chosen application, such as the modulation and control method.

B. Broadband measurements

A switched-mode converter can be considered as a linear time-invariant (LTI) system up to half of its switching frequency. The dynamics of such a system can typically be characterized by system frequency-response functions. Fig. 2 shows a general measurement setup for obtaining the system frequency-response function. An excitation signal is introduced to the plant by, for example, applying the plant actuator/controller. The input and output signals are measured, and Fourier methods are applied to obtain the system frequency response.

The selection of an excitation signal plays an important role in measuring the system frequency response. A conventional technique is to apply sine sweeps. This technique provides the highest possible signal-to-noise ratio and hence the most reliable and accurate estimate of the frequency-response. However, sine sweeps are not well suited for online measurements due to long measurement time and difficulties in implementing the injection.

Recent studies have presented methods based on broadband perturbations to measure the frequency response(s) of various power-electronics systems [22]–[24]. One of the most popular excitation signals is the maximum-length binary sequence (MLBS). The MLBS broadband signal has a very high total energy in relation to the signal time-domain amplitude, thus minimizing the signal interference on the measured system [25]. Unlike a sine-based signal, the MLBS signal has energy at multiple frequencies. Therefore, the frequency response measurement is acquired at multiple frequencies simultaneously. Furthermore, since the MLBS consists only of two signal levels, the signal generation is straightforward: it can be easily implemented on the converter controller platform using a shift register with exclusive-or feedback [26]. The sequence length is always $N = 2^n - 1$, where n is an integer that denotes the number of bits in the shift register.

Designing the MLBS typically requires defining the following specification variables [25]:

- frequency resolution
- measurable bandwidth
- measurement time
- variance and/or SNR

Then, the sequence is generated using the following design parameters:

- sequence length
- sequence generation frequency
- perturbation amplitude
- number of averaged periods

C. Impedance measurement on DAB converters

Performing impedance measurements on a DAB converter is more complex compared to traditional dc-dc converters. First, depending on the operating point, the relationship between the transferred power and duty ratio and phase shift may be nonlinear. Yet, the MLBS-based measurement methods rely on linearity between the perturbed parameter and converter output power. Second, since the DAB converters can be controlled by both phase shift and duty ratio, an alternative option for the perturbation injection design is obtained compared to conventional dc-dc converters where only the duty ratio can be controlled.

Due to nonlinearity between the perturbed parameter and converter output power, the MLBS energy at a specific frequency may not translate to the same frequency in the converter output power, thus degrading the measurement accuracy. Some strategies can be considered to avoid or mitigate the nonlinearity [18]–[21] but the applicability of these approaches depends strongly on the chosen application.

To successfully use the MLBS for the impedance measurement of a DAB converter it is of paramount importance to appropriately define the perturbation amplitude. Depending on the effects of noise and other distortions as well as the allowable system interference, the amplitude is usually chosen so that the output deviates 1-5% from the nominal value. If the perturbation is injected on top of the controller reference, the amplitude selection is typically not very sensitive because the injection is strongly affected by the controller dynamics. However, if the perturbation is injected to the duty ratio or phase shift, the perturbation amplitude requires more careful design to ensure that the perturbation produces high enough spectral energy to the whole frequency band of interest. In the presence of nonlinearity, increasing the perturbation amplitude may not improve the measurements but yields unreliable estimates. Thus, the injection method that provides the most linear behavior between the perturbed parameter and the converter output power at the chosen set-point should be used.

Three different injection methods can be applied when implementing a broadband impedance measurement for a DAB converter.

Method 1—*Injection to output voltage or current reference*: In this method the amplitude design of the excitation is less sensitive compared to other methods because the injection is affected by the controller dynamics. The amplitude value as well as other parameters of the injection can be designed by general guidelines [25].

Methods 2 and 3—*Injection to duty ratio or phase-shift*: In this method the amplitude design is sensitive and set-point dependent due to nonlinear behavior between the perturbed parameter and output power. Hence, it is recommended to identify the nonlinear operating points and use the injection method which produces the most linear behavior around the chosen set-point. The perturbation amplitude can then be increased so that the desired SNR is reached without violating interference requirements. It is emphasized that under strong nonlinearities the measured impedance accuracy cannot be improved by increasing the injection amplitude. Instead, strategies to mitigate or to avoid nonlinear effects should be considered. The other injection parameters can be designed by general guidelines [25].

III. Experimental results

A power-converter system depicted in Fig. 3 was constructed in the laboratory. The system consists of a DAB with a battery

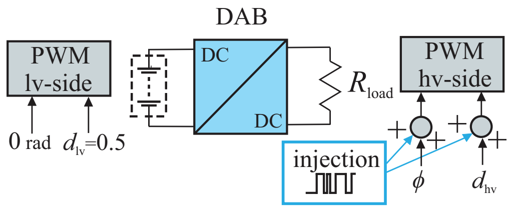


Fig. 3. Simplified schematic of the setup used for experimental results. The perturbation is injected either to the phase shift or duty ratio of the high-voltage-side switches.

TABLE I
PARAMETERS USED IN EXPERIMENTAL RESULTS.

Parameter	Value	Description
f_{sw}	50 kHz	switching frequency
t_d	2 μs	deadtime
V_{lv}	100 V	dc voltage on low-voltage side
R_{load}	150 Ω	resistive load
n	2.6	transformer turns ratio (n_{hv}/n_{lv})
C_{lv}	520 μF	capacitance on low-voltage side
C_{hv}	520 μF	capacitance on high-voltage side
L_{tot}	300 μH	equivalent/total inductance on high-voltage side
ϕ	1 rad (range -$\frac{\pi}{2}$...$\frac{\pi}{2}$)	phase shift between the modulating signals
D_{hv}	0.5 (range 0...1)	duty ratio for high-voltage-side bridge
D_{lv}	0.5	duty ratio for low-voltage-side bridge

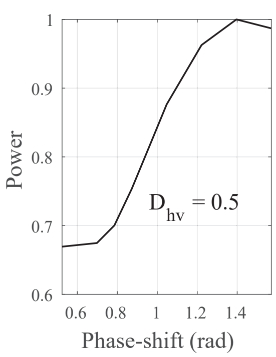


Fig. 4. Measured transferred power (normalized) as a function of the phase shift. $D_{\rm hv} = 0.5$.

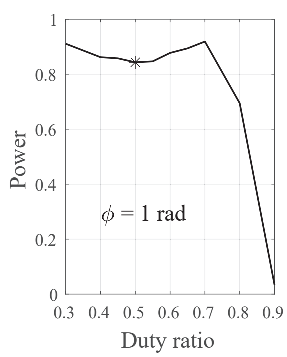
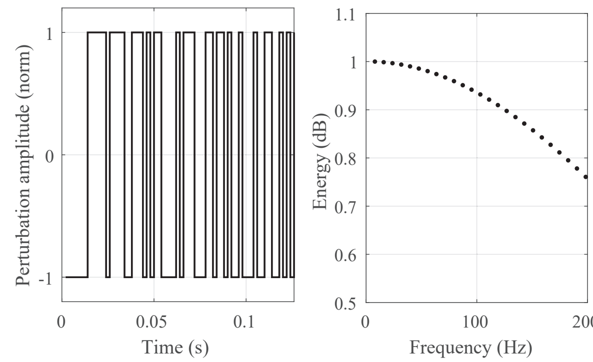


Fig. 5. Measured transferred power (normalized) as a function of the high-voltage side duty ratio. $D_{\rm lv} = 0.5$, $\phi = 1$ rad. The nonlinear point $D_{\rm hv} = 0.5$ has been marked.

emulator and a resistive load. The detailed system parameters are given in Table. I. The converter was operated at open-loop to bypass the effect of the controller. The perturbation was injected to the phase shift or duty ratio of the high-voltage-side bridge, depending on the chosen perturbation method. Two fundamentally different perturbation methods were used: 1) perturbation to phase shift (with a duty ratio of 0.5), and 2) perturbation to duty ratio (with a phase shift of 1 rad). This allowed for straightforward comparison between



(a) MLBS in time-domain. (b) MLBS energy spectrum.

Fig. 6. MLBS signal used for perturbation.

the impedance-measurement-implementation methods as well as a basis for observing the deadtime effects.

Before measuring the impedance, the relationship between the power transfer and phase shift and duty ratio was demonstrated by measuring the output power at different set-points shown in Fig. 4 and Fig. 5. In Fig. 4, the relationship between the phase shift and power around the phase shift of 1 rad is linear. On the other hand, Fig. 5 shows strong nonlinearity between the duty ratio and power around the duty ratio of 0.5: the power increases regardless of how the duty ratio changes (see the marker in Fig. 5). The applied measurement method is based on the assumption of linearity between the perturbed parameter and converter output power. Therefore, implementing the impedance measurement with an injection to the duty ratio at the duty ratio of 0.5 is more complicated and yields unreliable results. To avoid nonlinearity at the measurement point, an additional impedance measurement was done with an *added offset* to the duty ratio. This slightly increased the converter currents and voltages (that is, changed the set-point), but allowed for greatly improved measurement accuracy as the relationship between the power and duty ratio was more linear.

The perturbation design was done with a desired frequency range of 10 Hz to 200 Hz. A 63-bit-long MLBS signal with a generation frequency of 500 Hz was chosen. Three averaging periods were used to mitigate non-systematic noise, which allowed for a measurement time less than 0.4 s. The injection amplitude was selected so that the converter output voltage and current deviated less than 2% of their nominal (average) values. Fig. 6 shows the designed MLBS both in the time and frequency domain.

The designed MLBS was injected into the system by applying three different injection methods. In the first case the phase shift was perturbed. In the second and third cases the duty ratio was perturbed without and with an added offset, respectively. More details of the perturbation parameters are given in Table II. Fig. 7 shows a sample of the perturbed parameters. The corresponding output voltages and currents are shown in Fig. 8 and Fig. 9. The figures show that the resulting waveforms are very different depending

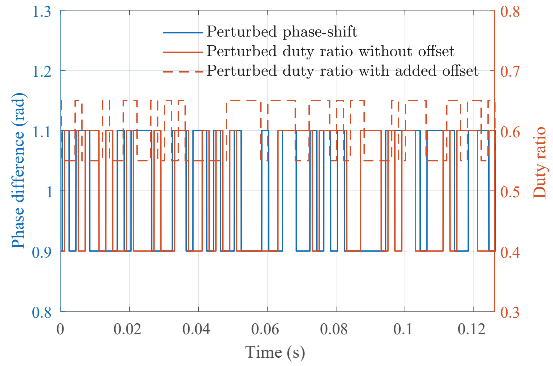


Fig. 7. Samples of perturbed signals.

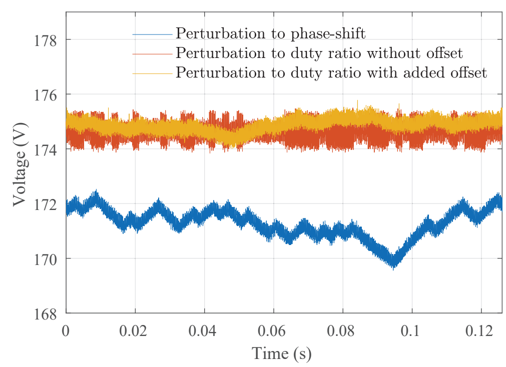


Fig. 8. Voltages for the three cases during one PRBS period.

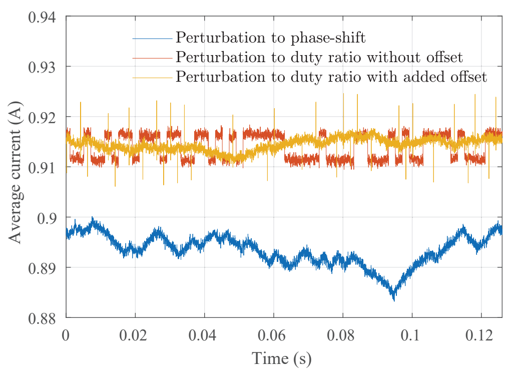


Fig. 9. Currents for the three cases during one PRBS period.

on the chosen perturbation method due to different system dynamics between the perturbed parameter and the voltage and current. The resulting converter output impedances are compared in Fig. 10. When injecting the perturbation to the phase shift the result is more accurate having less than 2.5 dB (5.5%) error in magnitude and 10 degrees in phase. On the other hand, when injecting the perturbation (without the offset) to the duty ratio, the result is not accurate at all (even if the perturbation amplitude is increased). This was expected based on the nonlinear relationship between the power and duty ratio of the DAB converter at the applied set-point. However, by adding a small dc-offset to the perturbation the power is slightly increased but the impedance is more accurately obtained, giving maximum of 3.5 dB (7.8%) error in the

TABLE II
PERTURBATIONS USED IN THE EXPERIMENTAL RESULTS AND THEIR EFFECT ON VOLTAGE AND CURRENT (AS PERCENTAGE OF AVERAGE).

injection method	average	injection amplitude	perturbation amplitude in current	perturbation amplitude in voltage
Phase shift	1.00 rad	0.10 rad	1.9 %	1.7 %
Duty ratio without offset	0.50	0.10	1.1 %	0.9 %
Duty ratio with offset	0.60	0.05	1.1 %	1.0 %

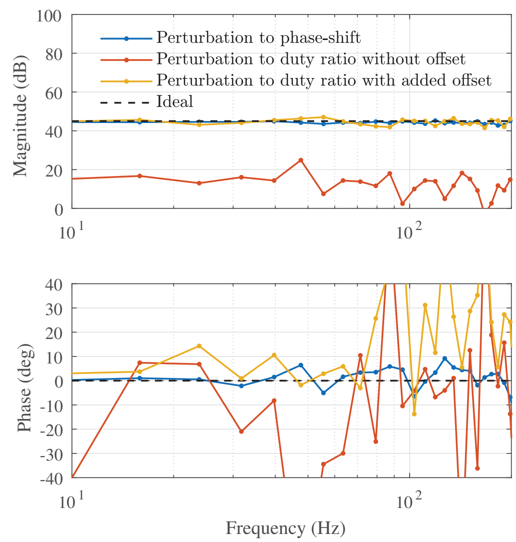


Fig. 10. Measured output impedances for the three cases and an ideal result.

magnitude response. Yet, in the phase response, the maximum error is higher and becomes significant at frequencies above 70 Hz. This phase response accuracy cannot be improved by increasing the amplitude as the relationship between the duty ratio and output power is nonlinear at both set-points $D_{\mathrm{hv}} = 0.5$ and $D_{\mathrm{hv}} = 0.7$. Fig. 11 shows the resulting impedance errors of each method in comparison to an ideal measurement (45 dB in magnitude and zero degrees in phase).

The results clearly show that system nonlinearities strongly affect the impedance measurements of DAB converters. This applies especially when injecting the perturbation to the duty ratio due to the strongly nonlinear characteristics at certain set-points. Therefore, under such nonlinearities, the perturbation should be applied to the phase shift rather than to the duty ratio. However, if the nonlinear set-points are avoided or their effects mitigated, sufficient measurements could be achieved using both perturbation methods.

IV. CONCLUSIONS

This work has presented broadband impedance-measurement methods for dual-active bridge (DAB) converters. In a DAB converter, the relationship between the power transfer and duty ratio and phase shift may be nonlinear, depending on

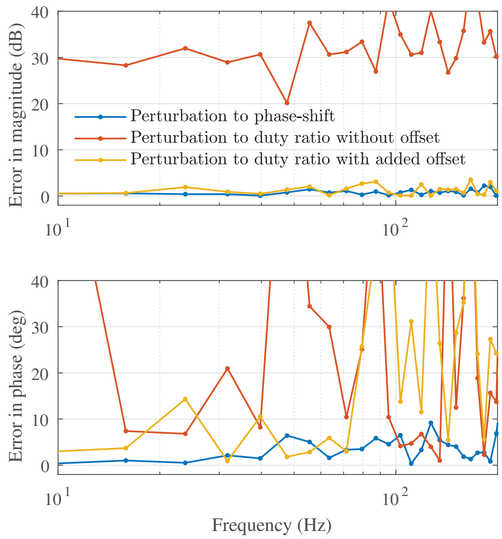


Fig. 11. Errors of the output impedance measurements compared to an ideal measurement.

the chosen set-point and modulation and control strategy. The work showed that it is vital to take into account the system dynamics at the chosen set-point before choosing the perturbation method. When injecting the perturbation on the converter duty ratio, the measurement implementation may be unfeasible at certain set-points due to strong nonlinearity between the duty ratio and output power. On the other hand, when the perturbation is injected into the phase shift, an accurate measurement implementation is more straightforward. Experimental measurements based on a DAB converter were presented to demonstrate the effectiveness of the proposed methods.

References

[1] H. Zhou, T. Duong, S. T. Sing, and A. M. Khambadkone, "Interleaved bi-directional dual active bridge dc-dc converter for interfacing ultracapacitor in micro-grid application," in *Proc. IEEE International Symposium on Industrial Electronics*, 2010, pp. 2229–2234.

[2] L. Xue, D. Boroyevich, and P. Mattavelli, "Switching condition and loss modeling of gan-based dual active bridge converter for phev charger," in *Proc. IEEE Applied Power Electronics Conference and Exposition*, 2016, pp. 1315–1322.

[3] F. Zhang and W. Li, "An equivalent circuit method for modeling and simulation of dual active bridge converter based marine distribution system," in *Proc. IEEE Electric Ship Technologies Symposium*, 2019, pp. 382–387.

[4] R. A. Mastromauro, M. C. Poliseno, S. Pugliese, F. Cupertino, and S. Stasi, "Sic mosfet dual active bridge converter for harsh environment applications in a more-electric-aircraft," in *Proc. International Conference on Electrical Systems for Aircraft, Railway, Ship Propulsion and Road Vehicles*, 2015, pp. 1–6.

[5] Z. Jin, L. Meng, and J. M. Guerrero, "Constant power load instability mitigation in dc shipboard power systems using negative series virtual inductor method," in *Proc. Annual Conference of the IEEE Industrial Electronics Society*, 2017, pp. 6789–6794.

[6] X. Lu, K. Sun, J. M. Guerrero, J. C. Vasquez, L. Huang, and J. Wang, "Stability enhancement based on virtual impedance for dc microgrids with constant power loads," *IEEE Transactions on Smart Grid*, vol. 6, no. 6, pp. 2770–2783, 2015.

[7] A. Riccobono and E. Santi, "Comprehensive review of stability criteria for dc power distribution systems," *IEEE Transactions on Industry Applications*, vol. 50, no. 5, pp. 3525–3535, 2014.

[8] 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 Conversion Congress and Exposition*, 2016, pp. 1–8.

[9] T. Roinila, H. Abdollahi, S. Arrua, and E. Santi, "Real-time stability analysis and control of multiconverter systems by using mimo-identification techniques," *IEEE Transactions on Power Electronics*, vol. 34, no. 4, pp. 3948–3957, 2019.

[10] H. Abdollahi, S. Arrua, T. Roinila, and E. Santi, "A novel dc power distribution system stabilization method based on adaptive resonance-enhanced voltage controller," *IEEE Transactions on Industrial Electronics*, vol. 66, no. 7, pp. 5653–5662, 2019.

[11] S. K. Gurumurthy, M. Cupelli, and A. Monti, "A generalized framework for synthesizing virtual output impedance control of grid integrated power electronic converters," in *Proc. IEEE International Conference on Power Electronics, Drives and Energy Systems*, 2018, pp. 1–6.

[12] R.-M. Sallinen, T. Roinila, and H. Abdollahi, "Stability analysis and adaptive resonance damping of multi-converter system applying bidirectional converter," in *Proc. IEEE Workshop on Control and Modeling for Power Electronics*, 2020, pp. 1–7.

[13] M. Jafari, Z. Malekjamshidi, and J. G. Zhu, "Analysis of operation modes and limitations of dual active bridge phase shift converter," in *Proc. IEEE International Conference on Power Electronics and Drive Systems*, 2015, pp. 393–398.

[14] H. Bai and C. Mi, "Eliminate reactive power and increase system efficiency of isolated bidirectional dual-active-bridge dc–dc converters using novel dual-phase-shift control," *IEEE Transactions on Power Electronics*, vol. 23, no. 6, pp. 2905–2914, 2008.

[15] F. Krismer and J. W. Kolar, "Closed form solution for minimum conduction loss modulation of dab converters," *IEEE Transactions on Power Electronics*, vol. 27, no. 1, pp. 174–188, 2012.

[16] H. Shi, K. Sun, H. Wu, and Y. Li, "A unified state-space modeling method for a phase-shift controlled bidirectional dual-active half-bridge converter," *IEEE Transactions on Power Electronics*, vol. 35, no. 3, pp. 3254–3265, 2020.

[17] B. Zhao, Q. Song, W. Liu, and Y. Sun, "Dead-time effect of the high-frequency isolated bidirectional full-bridge dc–dc converter: Comprehensive theoretical analysis and experimental verification," *IEEE Transactions on Power Electronics*, vol. 29, no. 4, pp. 1667–1680, 2014.

[18] K. Takagi and H. Fujita, "Dynamic control and dead-time compensation method of an isolated dual-active-bridge dc-dc converter," in *Proc. European Conference on Power Electronics and Applications*, 2015, pp. 1–10.

[19] C. Song, A. Chen, J. Chen, C. Du, and C. Zhang, "Dead-time effect analysis of dual active bridge dc-dc converter with dual-phase-shift control," in *Proc. Chinese Automation Congress*, 2017, pp. 6545–6550.

[20] J.-i. Itoh, K. Kawauchi, and H. Watanabe, "Non-linear dead-time error compensation method of dual active bridge dc-dc converter for variable dc-bus voltage," in *Proc. International Conference on Smart Grid*, 2018, pp. 208–213.

[21] S. Luo, F. Wu, and G. Wang, "Effect of dead band and transient actions on ctps modulation for dab dc–dc converter and solutions," *IEEE Transactions on Transportation Electrification*, vol. 7, no. 3, pp. 949–957, 2021.

[22] C. Fernandez, L. Ortega, M. Granda, P. Zumel, and A. Barrado, "Online impedance measurement of the batteries and loads connected to a modular multi-active bridge converter," in *Proc. IEEE Workshop on Control and Modeling for Power Electronics*, 2019, pp. 1–6.

[23] T. Roinila, T. Messo, R. Luhtala, R. Scharrenberg, E. C. W. de Jong, A. Fabian, and Y. Sun, "Hardware-in-the-loop methods for real-time frequency-response measurements of on-board power distribution systems," *IEEE Transactions on Industrial Electronics*, vol. 66, no. 7, pp. 5769–5777, 2019.

[24] H. Gong, D. Yang, and X. Wang, "Parametric identification of dq impedance model for three-phase voltage-source converters," in *Proc. IEEE International Power Electronics and Application Conference and Exposition*, 2018, pp. 1–6.

[25] A. H. Tan and K. R. Godfrey, *Industrial Process Identification*. Cham, Switzerland: Springer, 2019.

[26] A. H. Tan and K. Godfrey, "The generation of binary and near-binary pseudorandom signals: an overview," *IEEE Transactions on Instrumentation and Measurement*, vol. 51, no. 4, pp. 583–588, 2002.