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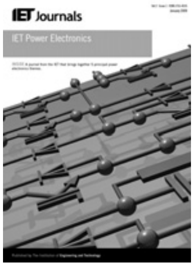

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Time-domain identification of pulse-width modulated converters

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Abstract: A discrete time domain-based system identification method for PWM DC-DC converters is proposed. Accurate information on the system's open-loop response is essential in the design of the system controller in order to obtain the desired closed-loop response. This is especially true in switch-mode converters where component uncertainty exists. It is conjectured in this study that an identification method that is based on time-domain signals will be relatively simple to realise with a digital processor. The method that is proposed is capable of successfully reconstructing the system model by an arbitrary excitation at the command input. In this study, a step perturbation was employed, which is simple to apply and leads to an intuitive interpretation of the output response. The effects of switching and quantisation noise have been overcome by choosing the sampling interval after the switching oscillations have decayed and by averaging the responses of synchronously perturbed sequences. The proposed method has been evaluated on Buck and Boost converters. The method was verified in two phases: Off-line – data acquisition procedure was implemented on a TMS320F2407-DSP and the identification calculations were carried out on a PC. On-line – The identification procedure (data acquisition plus fitting algorithm) was programmed on a TMS320F2808-DSP.

1 Introduction

One significant source of inaccuracies in controller design is insufficient information on the open-loop response of the converter. This is particularly true for pulse-width modulated (PWM) converters, where uncertainties in system parameters (load range, component spread and parasitics) often occur. The problems that stem from a poor knowledge of the converter open-loop transfer function become even greater when designing a discrete domain controller, since additional sources of error such as sampling, quantisation and computational delays are present. After designing a digital controller (either in voltage or current mode control) and even evaluating one by simulation, it is not uncommon to end up with poor closed-loop performance of the physical system due to inaccurate modelling of the system's plant. So, it appears that it would be highly advantageous if the design of a digital controller for PWM converters was based on a system identification procedure in order to obtain a realistic sampled-data model of the system response in open loop.

Two general digital compensator design approaches have been described for PWM converters. The most popular approach is based on the frequency domain [1–3]. In this case, an analogue controller is first derived and then transformed to the discrete form by one of the continuous-to-discrete domain transformations, such as ZOH, p–z matched, and so on [2]. The second approach for a discrete control design uses a direct digital design procedure [4, 5]. This method bypasses some approximations and possible errors stemming from the s-to-z transformation and is thus considered more accurate. The accuracy of the design by this approach could be further improved if a sampled-data model of the converter was extracted from the experimental data of the system, that is, by system identification [1].

Generally, system identification can be divided into parametric and non-parametric methods [2]. Traditionally, non-parametric methods have been used to compute the system's frequency response from the results of either a correlation analysis [1, 2, 6] or spectrum analysis [2]. On the other hand, parametric methods [4, 7] pre-assume the system model (i.e. template), and the identification procedure is then used to extract the parameter values.

It is assumed in this study that an identification method based on time-domain signals and requiring short data acquisition sequences will be relatively simple to realise by the digital processor and can potentially ease the computational workload of the CPU. It is further assumed that an identification procedure that is directly implemented in the discrete domain will bypass errors related to s-to-z transforms and may lead to an accurate system model. These attributes are found in the discrete time-domain-based parametric identification method proposed by Steiglitz and McBride (SM) [7]. This method has been applied to identify linear (non-switching) systems [7] and to extract models of grid power systems based on data that were obtained from a transient simulation [8].

In this work we present an identification procedure for modelling the open-loop response of switching converters. The motivation for this effort is the fact that the extraction procedure uses only the system's input and output data records in the sampling (time) domain and does not involve additional transformations that may affect the accuracy of the model and, furthermore, that the procedure utilises a relatively small number of samples for model reconstruction. The concept of the proposed identification is not limited to specific type of plant; it could be equally applied to identify the output impedance of the converter. Since the control to output transfer function is often used to design the compensator, we chose this transfer function to demonstrate the identification method.

2 System identification algorithm

The identification procedure for PWM converters is based on the parameter extraction concept presented earlier in [7] by Steiglitz and McBride and is implemented in the MATLAB 'stmcb' command which applies the method [9]. The most significant advantage of this method is the usage of time-domain data of the input and output records when extracting system parameters. Below, we present the essentials of the method.

The method applies to linear single-input single-output (SISO) sampled-data systems, which can be represented by a rational discrete-time transfer function of z^{-1}

$$\frac{N(z)}{D(z)} = \frac{a_0 + a_1 z^{-1} + \cdots + a_{n-1} z^{-(n-1)}}{1 + b_1 z^{-1} + \cdots + b_n z^{-n}} \quad (1)$$

where $N(z)$ is the system numerator and $D(z)$ is the system denominator, that is, the system's characteristic equation.

Also required by the procedure is the system's template. This can be derived from prior knowledge of the system dynamic characteristics.

The essence of the method is shown in Fig. 1. It applies a least-square minimisation procedure to extract the coefficients $\{a_0, a_1, \ldots, a_{n-1}, b_1, b_2, \ldots, b_n\}$, so that the response of $N(z)/D(z)$ ($\hat{y}$, Fig. 1) to input records (u, Fig. 1) matches the actual (measured) output samples (y, Fig. 1). This minimisation procedure was defined in [7, 10] as

$$\sum e_j^2 = \oint \left| u(z)\frac{N(z)}{D(z)} - y(z) \right|^2 \frac{\mathrm{d}z}{z} = \min \quad (2)$$

where the contour of integration is the unit circle.

It was shown in [7] that there is no direct solution to the problem of (2). Therefore an iterative procedure is suggested to solve (2). It is based on the solvable least-squares problem of

$$\sum e_j^2 = \oint \left| u(z)\frac{N_i(z)}{D_{i-1}(z)} - y(z)\frac{D_i(z)}{D_{i-1}(z)} \right|^2 \frac{\mathrm{d}z}{z} = \min \quad (3)$$

where i is the iteration index.

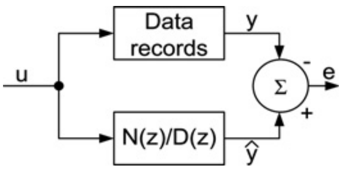

Fig. 1 *Identification objective*

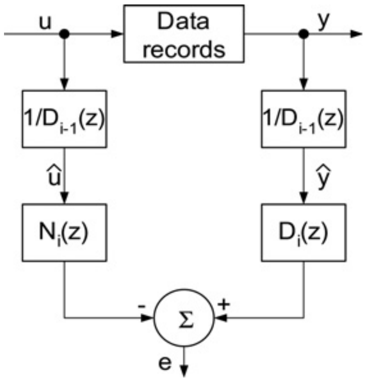

Fig. 2 *Iteration of the SM identification procedure*

The idea behind the iterative is that as the coefficients converge (after one or more iterations), (3) can be reduced to (2).

The solution of problem (3) is shown in [7] to be relatively simple to implement with the following relationship

$$\begin{bmatrix} \boldsymbol{a} \\ \boldsymbol{b} \end{bmatrix} = [\boldsymbol{Q}]^{-1}\begin{bmatrix} \boldsymbol{x} & \boldsymbol{y} \end{bmatrix} \quad (4)$$

where $\begin{bmatrix} \boldsymbol{a} \\ \boldsymbol{b} \end{bmatrix}$ is the coefficients vector, $[\boldsymbol{Q}]$ is the input–output correlation matrix and $[\boldsymbol{x} \quad \boldsymbol{y}]$ is the vector of data records.

The operation of the iterative identification procedure (Fig. 2) is as follows. Based on the system's template provided by the user, a 'first-estimate' of the coefficients is calculated [10], yielding $D_1(z)$ and $N_1(z)$. The method finds the coefficients of $D_1(z)/N_1(z)$ by solving the linear regression of the input and output records. Finally, once a 'first-estimate' is set, then for each step, the previously extracted characteristic equation ($D_{i-1}(z)$) is used to create a new set of input and output records to be used in the minimisation process. This is done by subjecting $1/D_{i-1}(z)$ to the input excitation 'u' and to the output response 'y', then deriving the new data records $\hat{u}$ and $\hat{y}$, Fig. 2, respectively.

For the purpose of demonstrating the proof-of-concept of the identification algorithm, the procedure was implemented by SM function ('stmcb') of the signal processing toolbox [9] of MATLAB. The algorithm was also realised experimentally on a digital core. This was accomplished by rewriting the algorithm based on the solution of the minimisation problem of (4). The details of the online realisation of the identification procedure are given later in Section 4.

3 Realisation of the identification method for PWM converters

3.1 Generalised model template for PWM converters operating in continuous conduction mode (CCM)

The control-to-output transfer function of boost and buck–boost converters, neglecting losses, and a buck converter including losses in CCM can be modelled by the small-signal continuous form template

$$A(s) = G_{\mathrm{DC}} \frac{1 + (s/\omega_z)}{1 + (s/Q\omega_0) + (s/\omega_0)^2} \quad (5)$$

where G_{DC} is the steady-state gain, ω_z is the frequency location of the system zero, ω_0 is the natural frequency and Q is the quality factor of the converter.

It should be noted that the method can be equally applied under different load settings within the CCM operation of the converter using the same template.

Analogously, applying the $p-z$ matching transformation, the unified discrete domain template is [4]

$$A(z) = \frac{az + b}{z^2 + cz + d} \tag{6}$$

where $\{a, b, c, d\}$ are the parameters to be estimated.

In CCM operation, the boost and buck–boost topologies include two left half-plane (LHP) poles and a right half-plane (RHP) zero and are therefore stable, albeit non-minimum phase, systems. The buck converter, also has two LHP poles and one zero. However, in the case of buck converter, the zero is in the LHP and the system is therefore a minimum phase system. This implies that all three topologies share the same model template but with different coefficients. This attribute simplifies the implementation of the identification algorithm by making it general and topology-independent.

The model of (5) can be generalised to account for the effect of losses on the transfer function of the boost and buck–boost converters by considering a numerator that includes two zeros (ω_{z1} and ω_{z2}) [11].

$$A(s) = G_{DC}\frac{(1 + (s/\omega_{z1}))(1 + (s/\omega_{z2}))}{1 + (s/Q\omega_0) + (s/\omega_0)^2} \tag{7}$$

The z-domain template will now be [12]

$$A(z) = \frac{az^2 + bz + c}{z^2 + dz + e} \tag{8}$$

In this model representation, the boost and buck–boost converters include two zeros in the RHP and an additional LHP zero due to the output capacitor's ESR.

The model is valid, as is, for boost and buck–boost topologies and is applicable to the buck case, if the location of one of the zeros is at high-enough frequency to cause it to converge, de facto, to the model of (5).

One possibility for identifying the control-to-output transfer function of a system is by the impulse response of (8). However, in real applications, such a disturbance is not practical to apply due to the infinite magnitude of the delta signal. Fortunately, the SM algorithm is capable of reconstructing the discrete-time filter response of any type of disturbance, as long as the relations between the input and output records satisfy (1). This enables the application of more convenient and intuitive approach such as a step perturbation in the duty cycle command.

3.2 Simulation-based identification

To verify the algorithm of the identification concept outlined above, it was carried out on data collected by average model simulation [13] applying OrCad PSPICE Version 10.0. In this type of simulation, the switching frequency is transparent to the model, that is, on/off operation in this model is not performed, but the average value of the signals is used instead. The use of average model allows verification of the algorithm of the proposed identification method without presence of noise, as a preliminary step before it is applied to an experimental system. The following steps were applied:

1. An average modelled buck stage (Fig. 3) was subjected to a unit step. The parameters of the buck were: $L = 75\ \mu$H, ($R_L = 150\ \text{m}\Omega$), $C = 100\ \mu$F (ESR $= 300\ \text{m}\Omega$), $V_{\text{in}} = 15$ V. Voltage-controlled voltage source (EVALUE, $E1$, Fig. 3) is used to emulate the average (DC) value of the signal that is fed to the output filter ($L1$, $C1$, Fig. 3).
2. Data records of V(Don) (Fig. 3) and V(out) (Fig. 3) were collected at fixed sampling intervals (20 μs) to emulate A/D operation once every switching cycle. This was accomplished by the print-to-file option of PSpice (PRN element, Fig. 3).
3. Then the samples array was used in a MATLAB identification procedure {stmcb(n, d, it)} [9], 'n' and 'd' are the order of the numerator and denominator, respectively and 'it' is the number of iterations to be performed.

The resulting discrete-time buck converter model was found to be

$$A(z) = \frac{0.677z - 0.2683}{z^2 - 1.852z + 0.881} \tag{9}$$

Fig. 4 shows a very good agreement obtained when comparing the results of the step response in average simulation model to the response of the identified system (9).

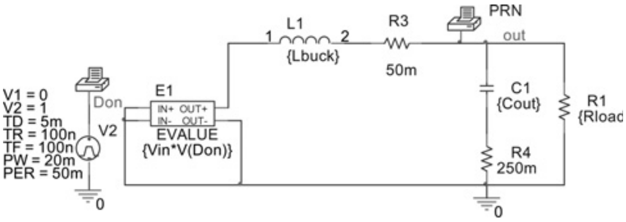

Fig. 3 *Average model of buck-type converter*

Data records are sampled at fixed time intervals

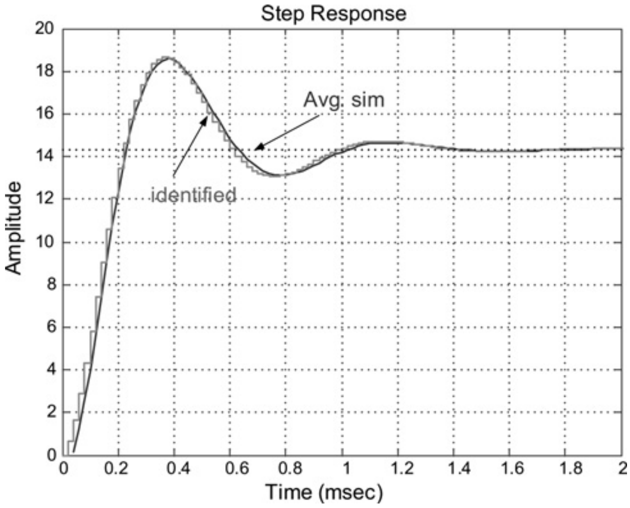

Fig. 4 *Step response of the original records obtained from average simulation model of Fig. 3 and identified buck converter (6)*

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3.3 Practical implementation

In order to implement the identification method experimentally on PWM converters, there is a need to reduce the effects of both switching noise and parasitic ringing. This can be accomplished by setting the sampling instant at the end of each switching cycle, after the ringing related to the off transition has decayed significantly (Fig. 5*a*). Another measure that is proposed for reducing the noise interference and hence for increasing the accuracy of the measurement is a synchronous averaging of repeated perturbations, allowing the system to stabilise before the next excitation (Fig. 5*b*). The improvement of signal-to-noise ratio (SNR), obtained by this procedure, is due to the fact that the converter can be considered 'time-invariant', and exhibits identical responses to the same disturbances over time, while the noise will be averaged out.

An additional issue that needs to be resolved is the magnitude of the injected step. Ideally, the size of the injected perturbation should be kept as small as possible. However, due to practical limitations of analogue to digital (A/D) conversion, a compromise between the measurement resolution and SNR, as well as the step size must be reached. The size of the step disturbance should be selected such that (a) the operating point will not be moved significantly, but (b) a sufficient change at the output is excited to allow a reliable measurement.

The optimal number of iterations needed for successful model reconstruction of the proposed method was explored. This was accomplished by using the generic template of (8) as the source transfer function, subjecting it to a unit step, and applying the data records using the MATLAB command. The model order was kept constant, while for every run the number of iterations to perform was increased until the extracted coefficients were within 2% margin (or less) of the original values. This experiment was run for 40 different model coefficients (20 stable minimum-phase systems and 20 stable non-minimum-phase systems, all having the same template). Convergence was obtained in all runs. It was found that given the second-order template of (8), the optimal number of repetitions needed for maximum error of 2% was four for the minimum-phase systems and seven for the non-minimum-phase systems. A summary of key results is given in Table 1.

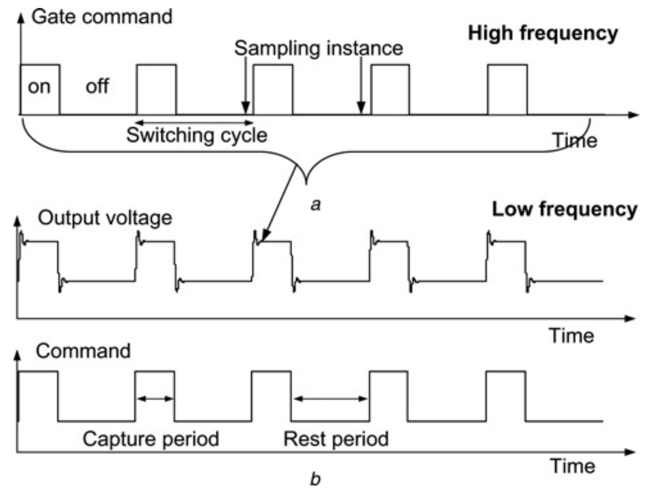

Fig. 5 *Data acquisition details*

a Sampling instance in relation to gate command
b Capture and rest periods

Table 1 Summary of results

Type	Buck – minimum phase	Boost – non-minimum phase
numerator order	avg. model:1	avg. model:2
denominator order	avg. model:2	avg. model:2
number of iterations for maximum error of 2%	4	7

4 Experimental verification

4.1 Offline identification

Two types of converters (buck and boost) were used to evaluate the proposed identification method. Synchronous data acquisition was implemented digitally on a TMS320F2407 digital signal processor (DSP) evaluation board [14, 15]. The step responses were captured by a 10-bit A/D (3 mV/bit), saved in local RAM and at the end of the measuring sequence (repeated step injections) were transmitted to a PC for offline processing in MATLAB on the PC.

For both converters, the input voltage was 10 V. Sensing gain was 1/7 (yielding 21 mV/bit resolution of output sensing). The switching frequency and sampling rate were 50 kHz.

The parameters of the buck stage were: $L = 75\ \mu\text{H}$ ($R_L = 250\ \text{m}\Omega$), $C = 100\ \mu\text{F}$ ($\text{ESR} = 300\ \text{m}\Omega$), load resistance: $5\ \Omega$, switch-on resistance (IRF640): $0.18\ \Omega$, diode forward voltage (1N5822): 0.5 V. Duty cycle step was: 0.1–0.5; sequence length: 200 data points (= switching cycles); number of repeated sequences: 5; rest period between sequences: 500 switching cycles.

The parameters of the boost stage were: $L = 1400\ \mu\text{H}$ ($R_L = 350\ \text{m}\Omega$), $C = 100\ \mu\text{F}$ ($\text{ESR} = 300\ \text{m}\Omega$), load resistance: $50\ \Omega$, switch-on resistance (IRF640): $0.18\ \Omega$, diode forward voltage (1N5822): 0.5 V. Step values: 0.1–0.5; sequence length: 500 data points; number of repeated sequences: 5; rest period between sequences: 1000 switching cycles. The parameters of this experiment were chosen to emphasise the RHP zero effect of the boost converter.

In order to test the possibility of applying the same template to all topologies, the identification of the buck converter response was carried out using both the one-zero template of (6) and the two-zero template of (8). The identified discrete-time buck transfer functions, for the template of (6), was found to be

$$A(z) = \frac{0.8364z - 0.5141}{z^2 - 1.751z + 0.7992} \tag{10}$$

and, for the template of (8)

$$A(z) = \frac{0.0089z^2 + 0.8173z - 0.5037}{z^2 - 1.751z + 0.7992} \tag{11}$$

Although the template (8) produces a second-order term in the numerator of (11), its effect on the transfer function is minuscule due to its small coefficient (0.0089), which is about two orders of magnitude smaller than the coefficients of the other two terms.

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For the boost stage, the identified discrete-time transfer function was found to be

$$A(z) = \frac{-0.1448z^2 + 0.2653z - 0.1147}{z^2 - 1.979z + 0.9797} \qquad (12)$$

Figs. 6 and 7 show the step response of the identified transfer function of the buck and boost converters, respectively, compared to the experimentally obtained step responses. It should be noted that the experimental response is the average of five repeated sequences, as detailed earlier. One reason for the somewhat larger deviation between the identified boost converter response and measured values may be the fact that a boost converter has more complex model (compared to buck) which includes RHP zero. The possibility of higher order template was examined by trial-and-error, however, the second-order template was found to generate the best results.

It should also be noted that the transfer function of (12) was extracted for an experimental boost converter that was designed to emphasise the RHP zero and therefore has a relatively slow response with respect to the sampling rate (switching frequency). As a result, the poles of (12) are very close to the unit circle which requires higher calculation accuracy. This may introduce numerical errors when integrated into a digital core with limited accuracy. Full discussion on coefficients accuracy and system sensitivity as well as suggested remedies to this problem is given [2, 16].

Further confirmation of the accuracy of the identification method has been found by comparing the frequency responses of the identified transfer function to the frequency responses obtained from an analytically derived average model (Figs. 8 and 9).

4.2 Online identification

The proposed identification procedure was realised experimentally on a TMS320F2808 DSP (Texas Instruments, USA). The program included the proposed

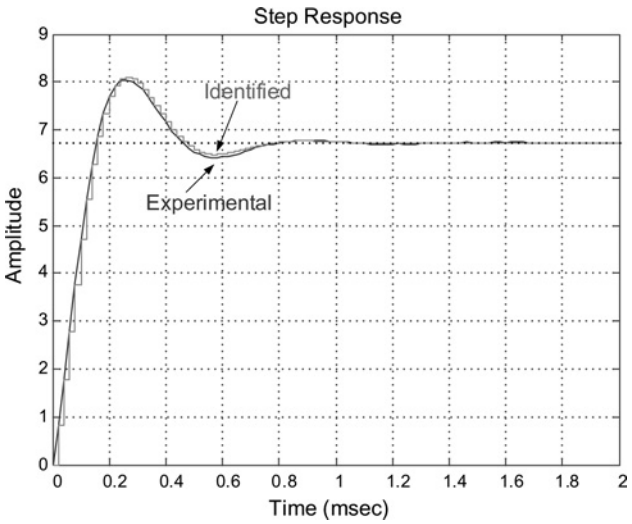

Fig. 6 *Step response obtained from experimental measurements compared to step response derived from identified transfer function of a buck converter*

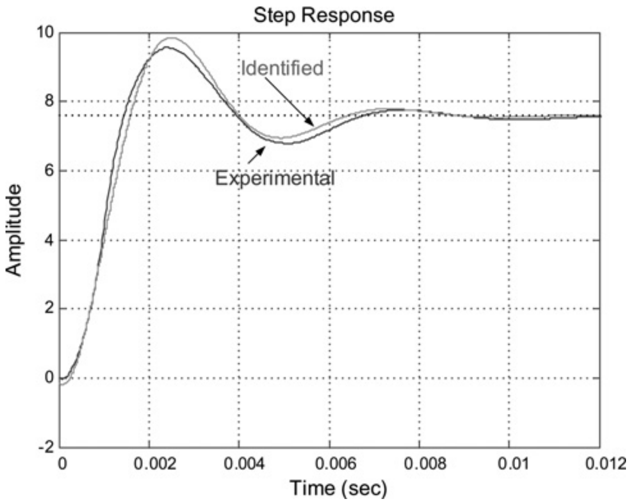

Fig. 7 *Step response obtained from experimental measurements compared to step response derived from identified transfer function of a boost converter*

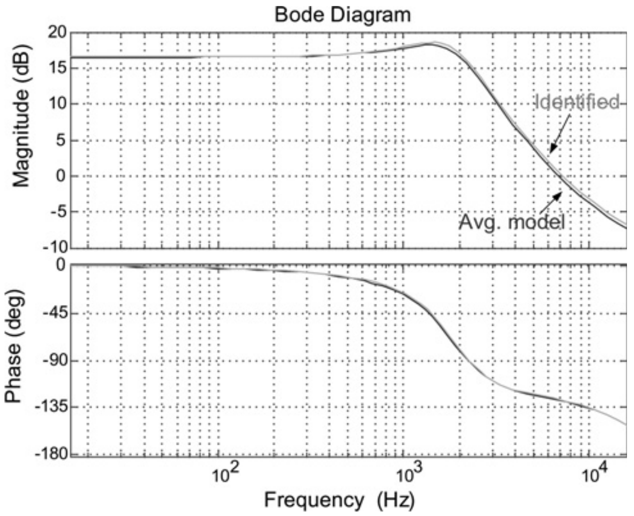

Fig. 8 *Frequency response derived from identified transfer function of a buck converter compared to frequency response calculated by an average model*

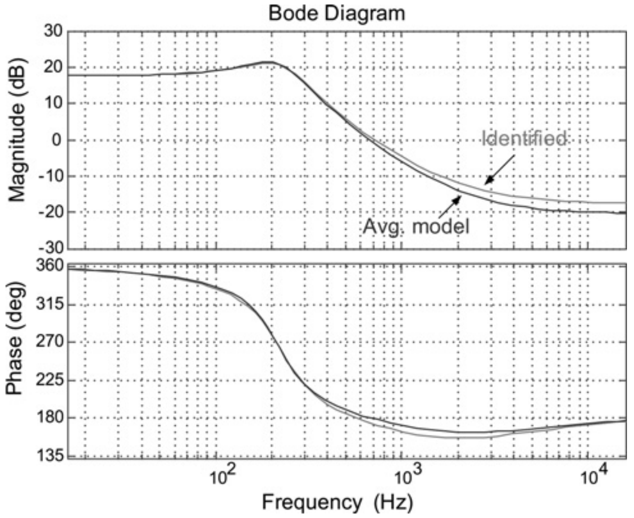

Fig. 9 *Frequency response derived from identified transfer function of a boost converter compared to frequency response calculated by an average model*

synchronous data acquisition sequence which was followed by on-board calculations of the identification process. To implement the proposed fitting process on the digital platform with limited memory and computing power (compared to the MATLAB platform running on a PC), the algorithm was simplified by considering a known order of two in (2) for both the numerator and denominator as suggested by (8). Calculations of the first estimate of the system were not obtained, but instead a generic first estimate of ones was assumed. The number of iterations was limited to five since no improvement was observed when adding a larger number of sequences. A total memory of 200, 16-bit cells was allocated for the input and output records (100 for each) and 500 cells were reserved for calculations. The memory size required for code allocation in the program memory was 2.8 kB.

The programming of the digital processor was assisted by the real-time workshop of MATLAB [17, 18]. This add-on package allows the user to integrate simplified MATLAB code and Simulink schematic designs [19] which can then be converted to specific target processor code such as Texas Instruments, Microchip, etc. The simplified SM-based fitting algorithm was integrated into the Simulink environment as an embedded MATLAB function [18, 19].

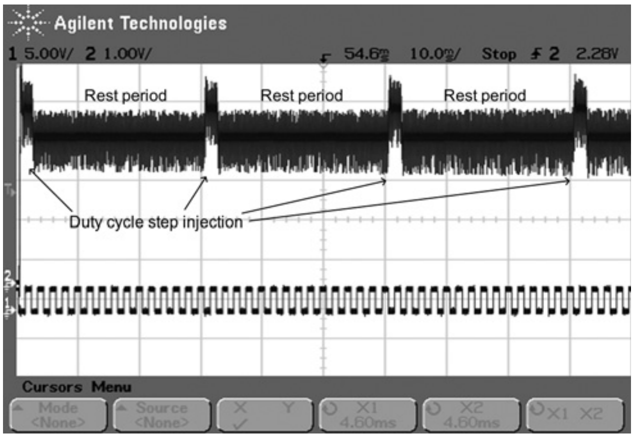

Fig. 10 *Experimental results: data acquisition sequence*

Upper trace: output voltage (1 V/div). Lower trace: synthesised 2 ms timing clock used for scaling purposes (5 V/div). Horizontal scale: 10 ms/div

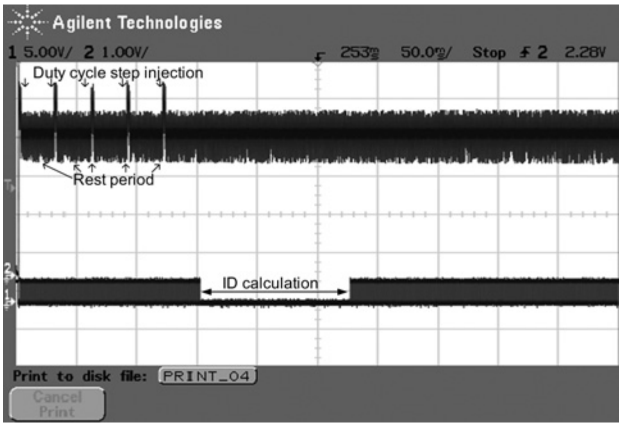

Fig. 11 *Experimental results: data acquisition procedure and time duration of the identification process (ID, 120 ms) for a Buck type converter*

Upper trace: output voltage (1 V/div). Lower trace: synthesised 2 ms timing clock used for scaling purposes (5 V/div). Horizontal scale: 50 ms/div

The program was tested on the two types of converters (buck and boost) described above and reproduced fitted coefficients identical to (11) and (12). In this experiment, the step in duty cycle was set to 5% change (from 0.25 to 0.3) causing a change of 1 V at the output (Fig. 10). Fig. 11 shows the effect of the step perturbations on the experimental buck converter. Fig. 11 also shows a 1 kHz timing signal that was inserted to measure the duration of routines running on the physical target. For the case of an identification process with five iterations running on the F2808 DSP, the duration of the procedure was measured to be 120 ms.

5 Conclusions

A time-domain based identification method for PWM converters has been developed and verified by simulations and experiments. The proposed approach overcomes the effects of switching and quantisation noise by averaging the results of repeated perturbation sequences. It has been found that the optimum number of data sequences is 5, since no improvement of the SNR has been observed when adding a larger number of sequences.

The extracted, template-based models have reproduced faithfully the responses of buck and boost converters. Furthermore, the frequency-domain responses were found to be in good agreement with the responses calculated with average models.

The generic model of the buck converter transfer function includes one LHP zero and two LHP poles. It is thus natural to assume that the template of (6) should be used in the goal model in the buck case. It has been found, however, that even if the two-zero model of (8) is used as the goal template for the buck case, the response of the extracted transfer function is practically identical to the response with a one-zero model (e.g. (7) and (8)). This is because the contribution of the second-order term that appears in the numerator is insignificant due to its small coefficient. This automatic suppression of the surplus zero allows the usage of one unified template for all PWM topologies used in the identification process.

The suggested identification method using the template of (8) takes into account the effect of all losses on the converter's transfer function. This feature is advantageous in practical applications since some system parasitics such as ESR, inductor parasitic resistance and diode losses are difficult to measure or estimate. Moreover, these parasitics are prone to drifts due to changes in operating conditions.

A qualitative assessment of the proposed identification procedure suggests that the method accurately extracts the model coefficients and requires modest memory space and reasonable execution time. For example, an accurate identification of a buck-type stage that was implemented on digital hardware required a memory allocation of 100 data cells for the output records, 500 data cells for algorithm calculations and took 120 ms to perform.

The advantages of the proposed identification method are the following: small number of data samples, straightforward one-stage procedure, in the sense that there is no need for further data manipulation or transformation, and usage of a generic template for all basic PWM topologies.

Integration of the proposed method into practical applications to execute the in situ identification of a system's plant was shown to be possible. It was also shown that the procedure accommodates well small perturbations of the sensed output which makes it suitable for integration not

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only after final assembly or startup, but also during operation periods when small changes in the output are allowed.

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