Time-Domain Identification of PWM Converters Aided by the C2000 DSP Family

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Abstract

A discrete time-domain based system identification method for PWM DC-DC converters is presented. The proposed procedure is capable of successfully reconstructing the system's model from an arbitrary excitation at the command input in the presence of noise. The proposed method was evaluated on Buck and Boost converters. The digital data acquisition procedure was implemented on a TMS320F2407 DSP core. The procedure of data transmission to the PC was eased considerably by the memory view feature embedded in Code Composer Studio software. Excellent agreement was found between theoretically derived models and the experimental results.

1. Introduction

One significant source of inaccuracies in controller design is insufficient information of the open-loop response of the plant. This is particularly true in PWM converters, where uncertainties of the system parameters (load range, components spread and parasitics) often occur. The problems that stem from a poor knowledge of the plant become even greater when designing a discrete domain controller since additional error sources such as sampling, quantization and computational delays are present. The accuracy of the design can be improved if the knowledge of the plant is derived from experimental data of the system, that is, by system identification. In practical switch-mode applications, the task of reliable and accurate identification becomes even more challenging due to the presence of noise and parasitic ringing which may corrupt the measurements.

The identification process of a system is carried out under open-loop conditions [1], that is, in a non-regulated state of the system (often obtained upon startup or whenever is desired during operation to correct for changes due to different operating conditions). Therefore it is higly desirable that the identification process would be as fast as possible. Considering the fact all types of parametric identification methods include a numerical fitting process, of similar complexity, and for the same measurement accuracy, the major culprit of the modeling duration would be the amount of data to be processed and the required acquisition time. Thus, it would be advantageous to use an identification scheme that requires as short data samples as possible. This will allow shorter identification time, less computing power and smaller memory allocation.

The most popular system identification is the correlation-based method which often requires long data acquisition sequences to assure data accuracy and noise immunity, and additional manipulations of the data records (by cross-correlation and Fourier transform) [2, 3]. The latter is potentially a cause for inaccurate model extraction due to truncation and quantization errors, and the approximated nature of the s to z transformations. It stands to reason that a short identification procedure that is based on short data acquisition sequences and implemented directly in the discrete domain, would remedy some of these deficiencies. These identification attributes are found in the discrete time-domain based parametric identification method that was proposed by Steiglitz and McBride [4] and has been applied previously on linear (non-switching) systems and on simulation models of grid power systems [5].

In this study we propose an identification procedure for modeling the open-loop response of switching converters. The proposed procedure uses the system's input and output data records in the sampling (time) domain which does not involve additional transformations that may affect the model accuracy and that it utilizes a relatively small number of samples for model reconstruction. Therefore, it is an attractive candidate for integration of fully automated on-line digital control application.

2. System Identification Algorithm

The identification procedure for PWM converters that was developed in this study is based on the parameters extraction concept implemented in the MATLAB 'stmcb' command which is based on Steiglitz and McBride [4]. The most significant advantage of this method is that it uses the time domain data of the input and output records to extract the systems parameters. Below we present the essentials of the method.

It assumes that for every linear single-input single-output (SISO) sampled-data system, the relationship between the input and output records can be represented by a rational division of polynomials of z^{-1}

$$\frac{N(z)}{D(z)} \tag{1}$$

where $N(z)=a_0+a_1z^{-1}+\ldots+a_{n-1}z^{-(n-1)}$ is the system's numerator and $D(z)=1+b_1z^{-1}+\ldots+b_nz^{-n}$ is the denominator, which often referred as the systems characteristic equation.

The essence of the method is described in Fig. 1. It applies an iterative least square minimization procedure to extract the coefficients $\{a_0, a_1, \ldots ,a_{n-1}, b_1, b_2,\ldots,b_n\}$ such that the response of N(z)/D(z) ($\hat{y}$, Fig. 1) to the input records (u ,Fig. 1) will match the actual (measured) output samples (y, Fig. 1).

Further details of the identification procedure are given in Fig. 2. It is based on the assumption that the system's order is known. This can be accomplished either by inspection or an a priori knowledge of the system's dynamic characteristics. Secondly, a 'first-estimate' of the coefficients is calculated using the Prony estimate [6], yielding $D_1(z)$ and $N_1(z)$. This method finds the filter coefficients by solving the linear regression on the input and output records. Finally, once the 'first-estimate' is set, then, for each step, the previous extracted characteristic equation ($D_{i-1}(z)$) is used to prefilter the data records, deriving thereby new sets of input and output records ($\hat{u}$ and $\hat{y}$, Fig. 2) to be used in the minimization process

This identification calculation is implemented in the SM function of the signal processing toolbox [7] of MATLAB. The extraction of the 'first-estimate' is already imbedded in the algorithm.

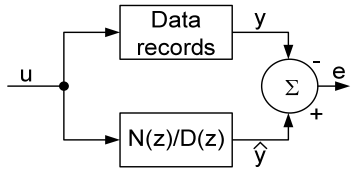


Figure. 1. Identification objective.

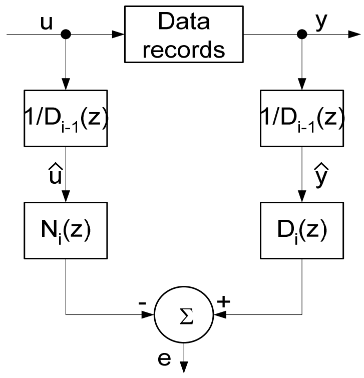


Figure. 2. The SM identification procedure.

3. Proposed Identification Method for PWM Converters

All three basic topologies of DCDC converters (Buck, Boost and Buck-boost) can be modeled by a unified template, small-signal continuous form model [1]

$$A(s) = G_{DC} \frac{1 - \frac{s}{\omega_Z}}{1 + \frac{s}{Q\omega_0} + \left(\frac{s}{\omega_0}\right)^2} \tag{2}$$

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

Analogously, applying p-z matching transformation, the unified discrete domain template will be [8]

$$A(z) = \frac{az + b}{z^2 + cz + d} \tag{3}$$

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

In CCM operation, the Boost and Buck-boost topologies are considered to be stable and non-minimum phase systems. That is, they include two left half plane poles and a right half plane (RHP) zero, while the Buck converter will have two poles and LHP zero and is therefore regarded as a minimum phase system. In other words, all three topologies share the same model template with different coefficients. This attribute simplifies the implementation of the identification algorithm by making it general and topology independent.

The discrete form of the small-signal transfer function given in (3) describes the response of the output signal of a converter (v_{out} in present study) to impulse perturbation of the control command (duty cycle, d). All for a given operating conditions. However, in practical applications, such 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 from any type of disturbance, as long as the relation between the input and output records satisfy (1). This enables us to apply a more convenient and intuitive approach such as a step perturbation of the duty cycle command.

3.1 Practical implementation of the method

In order to implement the identification method experimentally on PWM converters, there is a need to reduce the effects of switching noise and parasitic ringing. This can be accomplished by setting the sampling instant to the end of each switching cycle, after the ringing related to the off transitions decay significantly (Fig. 3a). Another measure that is proposed for the reduction of noise interference and hence increases the accuracy of the measurement is by synchronous averaging of repeated perturbations, allowing the system to stabilize before the next excitation (Fig. 3b). The improvement of the signal to noise ratio obtained by this procedure is due to the fact that the converter can be considered 'time-invariant' and will thus exhibit identical responses to the same disturbances over time, while the noise will averaged out.

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 A/D conversion, a compromise between the measurement resolution and SNR, and the step size must be reached. The size of the step disturbance should be selected such that: (a) will not move significantly the operating point, but (b) excite a sufficient change at the output to allow reliable measurement.

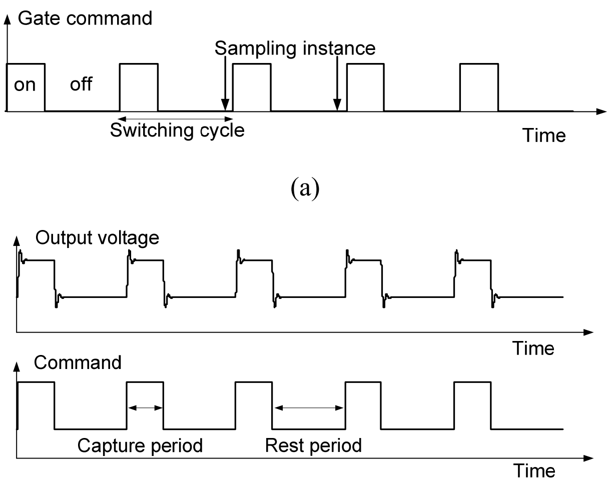


Figure. 3. Data acquisition details. (a) Sampling instance in relation to gate command. (b) Capture and rest periods.

Based on the proposed procedure detailed above, the data acquisition process starts with a generation of a fixed frequency (timer register TxPR) and constant duty-cycle (compare register CMPRx) PWM signal that drives the switch-mode converter's primary switch. The ADC interrupt is programmed by the timer compare register (TxCMPR) to be just before the end of period to ensure 'clean' of ringing measurement. Three additional, user defined, registers are used to determine the length of the capture rest periods by counting the number of ADC interrupts and number of iteration. At the start of the capturing sequence the duty cycle value (CMPRx) is changed and this value is kept thru the measuring sequence. At every ADC interrupt during this period, the ADC value is stored in the local RAM (start 8000h) of the F2407 DSP available for data storage. At the end of the capturing period, the duty cycle value is set to its previous value and an additional memory space is used to flag the end of sequence. The system is allowed to rest with the original duty value, and no data storing until the next capturing period. This process is repeated by the number of iterations that was specified. During this study, for research purposes only, all the samples were stored in the DSP memory. This enabled us to view all the measured data and test noise reduction techniques. Considerable memory space can be saved, of course, by storing the first sequence and then adding to it, on the fly, the subsequent sequences, as required by the proposed averaging technique. This sequenced data acquisition program algorithm is detailed in the flowchart of Fig. 4.

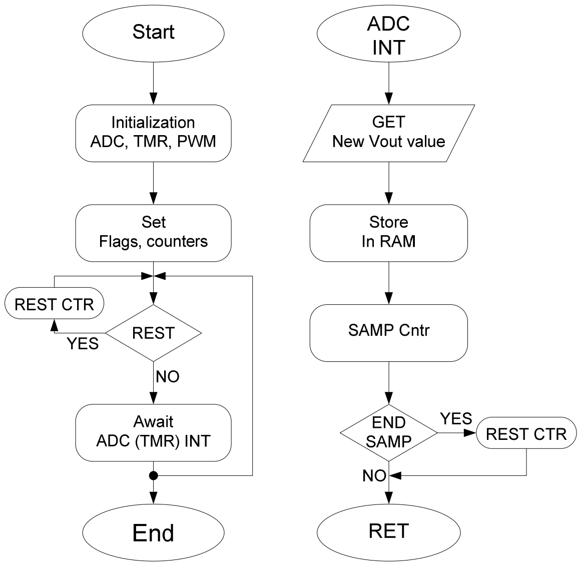


Figure 4. Sequenced data acquisition flowchart.

4. Experimental

Two types of converters (Buck and Boost) were used to evaluate the proposed identification method. The synchronous data acquisition was implemented digitally on a TMS320F2407 DSP evaluation board [9, 10]. The step response were captured by a 10 bits A/D (3mV/bit) to obtain the maximum accuracy available, saved in local RAM and at the end of measuring sequence (repeated step injections) transmitted to a PC for off-line processing in MATLAB on a PC. This enables us to process the actual fixed-point values of the system that were measured, accounting for all the errors related to truncation, quantization noise and sampling delays.

The data transfer of the measured records was carried out by the ‘memory view’ feature embedded in Code Composer Studio software package that is provided with the evaluation modules. This feature enabled us to inspect the memory (and desired registers) and export it (entirely or in part) to other database format such as simple text file, Excel spreadsheet etc. We have found this feature very efficient for research and design purposes, it enables to have a quick view of specific registers and thus ease the program debugging procedure and saves the effort of writing a code and operating PC-interfacing for this task.

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

The parameters of the Buck stage were: L=75μH (R_L=250mΩ), C=100μF (ESR=300mΩ), load resistance: 5 Ω, switch-on resistance (IRF640): 0.18Ω, diode forward voltage (1N5822): 0.5V. Duty cycle step was: 0.1 to 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=1400μH (R_L=350mΩ), C=100μF (ESR=300mΩ), load resistance: 50 Ω, switch-on resistance (IRF640): 0.18Ω, diode forward voltage (1N5822): 0.5V. Step values: 0.1 to 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 emphasize the RHP zero effect of the boost converter.

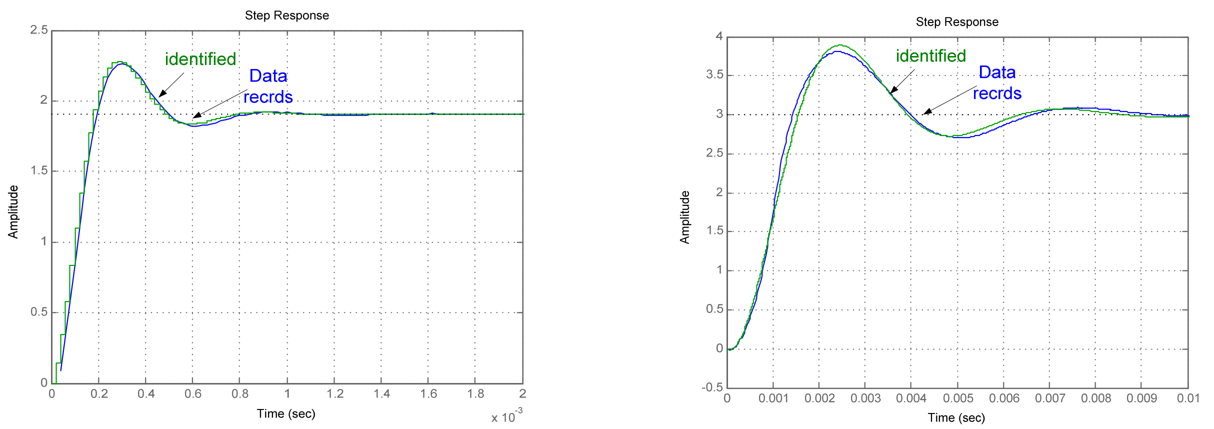
The identified discrete time Buck transfer function was found to be

$$A(z) = \frac{-0{,}00644z + 0.0088}{z^2 - 1.987z + 0.98} \quad (4)$$

and for the Boost stage

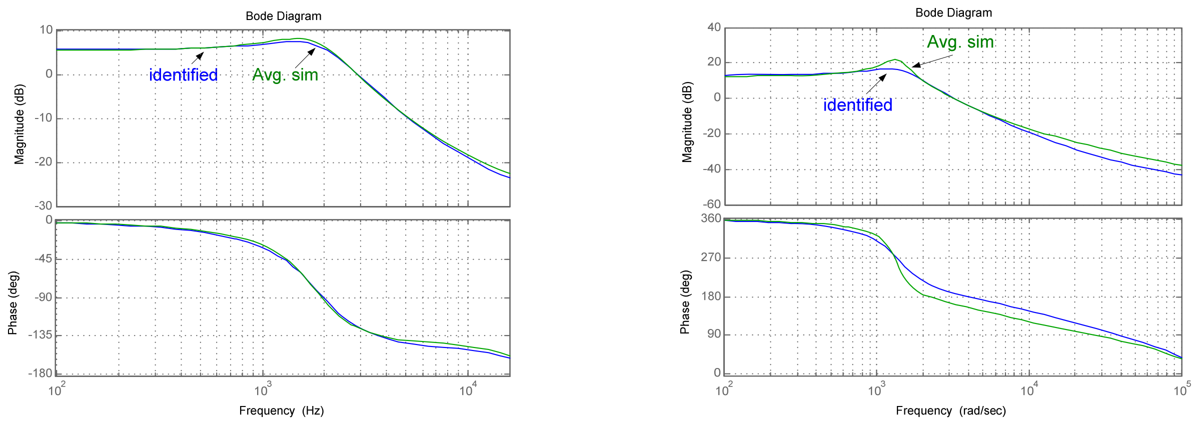
$$A(z) = \frac{0.1414z - 0.047}{z^2 - 1.753z + 0.803} \quad (5)$$

Fig. 5 shows the results of the average of the measured sequences and the step responses obtained from the identified transfer functions of the buck and boost converters. A further confirmation of the accuracy of the identification method can be observed by comparing the frequency responses of the identified converters and the one obtained using average simulation [11] (Fig. 7).



(a) (b)

Figure. 5. Step response of the identified converters and original records obtained from the experimental system: (a) Buck converter (Eq. 4), (b) Boost converter (Eq. 5).



(a) (b)

Figure. 7. Frequency response of the identified experimental converters compared to the frequency response of average simulation: (a) Buck converter (Eq. 4), (b) Boost converter (Eq. 5).

5. Discussion and Conclusions

A time-domain based identification method for PWM converters was developed and verified by simulations and experimentally. The proposed approach overcomes the effects of switching and quantization noise by synchronous sampling and averaging the results of repeated perturbation sequences.

The extracted, template based, models were found to reproduce faithfully the response of a Buck and Boost converters.

A qualitative comparison in terms of memory efficiency and data acquisition time suggests that the proposed identification method is advantageous over frequency-domain based approaches. For instance, in order to properly identify the illustrated Buck type stage, by cross-correlation technique, for the same switching frequency and a modest measurement bandwidth resolution of 50 Hz, in the presence of noise (switching and quantization), a 10-bit random sequence is needed for the excitation and at least three repetitive sequences [3]. This translates into approximately 3000 data cells for the recording of the output signals and equivalent number of cells for the excitation. On the other hand, using the proposed approach, as reported in this study, we utilized only 1000 data cells for the output records, and since we applied a simple step perturbation of the duty command, only five additional synchronization cells to flag the start-of-sequence are needed. That is, the capturing unit would require one-sixth of the memory capacity and the acquisition time is reduced by two-thirds. Obviously, this difference will be substantially larger when a finer bandwidth resolution is attempted.

The advantages of the proposed identification method are: small number of data samples, a straightforward, one stage, procedure, with no need for further data manipulation or transformation, and using a generic template for all PWM topologies. These attributes makes it practical for implementation in on-line identification applications.

A major implementation challenge of on-line identification procedures is the realization of the model extraction optimization code in fixed-point digital cores. This difficulty often prevents on-line identification methods to be performed in real-time since it requires many scaling operations and data manipulations to obtain sufficient accuracy.

The introduction of the 283x series of floating-point control-oriented DSPs provides a straightforward solution to the identification realization problem since it would simplify its implementation and optimize the benefits of the proposed identification algorithm. In general, this DSP series opens the door to a cost effective implementation of on-line methods, and smart (non-linear) control applications.

6. References

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