Designing Maximum Length Sequence Signal for Frequency Response Measurement of Switched Mode Converters

Matti Vilkko, Tomi Roinila

***Abstract*—Switched mode power converters are extensively used in powering consumer products. Requirements of short time-to-market and low bill of materials set new challenges to designers. The designers should efficiently create stable and robust designs using low-cost components with high parameter variations. Methods to test statistically the dynamical properties of final design would enable the designers to evaluate control design before production ramp-up. However, currently available testing methods require intervention into internal circuitry or are time consuming and too laborious. This paper describes how Maximum Length Binary Sequences can be used to obtain a high through-put frequency response measurement method to analyze the dynamics of switched mode converters. Some well known computational methods for the frequency response calculation are listed and the design of an appropriate maximum length excitation signal is presented. The proposed signal design procedure takes time-aliasing effect, noise reduction, and the disturbing harmonics generated by pulse width modulation of the converter controller into consideration. The results are verified by experimental measurements from a high-frequency switched mode converter.**

***Index Terms*—Identification, Impedance measurement, Sequences, Switched mode power supplies.**

I. Introduction

SWITCHED mode power converters are increasingly integrated into or delivered with mass produced consumer products. This trend sets new requirements for converter design. The design time is minimized to reduce time-to-market and the low-cost components are used to reduce bill of materials. Occasionally, low-cost components do not satisfy tight parameter tolerances. Since the stability of the feedback controlled power converters depends strongly on the parameter values of components the stability may be compromised. Due to tight schedules, fast methods are needed to measure statistically the stability margins from early production series before production ramp-up. To meet these new requirements a high throughput testing method is needed to determine the dynamical properties of the converters.

Manuscript received May 15, 2008.

Matti Vilkko is with Tampere University of Technology, Tampere, Finland (e-mail: Matti.Vilkko@tut.fi).

Tomi Roinila, is with Tampere University of Technology, Tampere, Finland (e-mail:Tomi.Roinila@tut.fi).

Traditional method to analyze the dynamics is to measure the loop-gain as frequency response [1] or use time-domain steady-state load tests by applying load change at the output of the converter. The loop-gain measurement requires intervention into the internal circuitry of the product and therefore, cannot be considered as a high throughput method. The weakness of the transient methods is that they give only a limited estimate of the margins of controlled systems.

The dynamics of a switched-mode converter can be characterized by means of a certain set of transfer functions. The recent studies such as [2] indicate that closed-loop output impedance provides useful information on the internal dynamics of the converter. In addition, the closed-loop output impedance can be directly used to verify the stability of the converter loaded with an arbitrary load [3] and it can be performed without intervention into the internal circuitry.

Usually the appropriate transfer functions are estimated by frequency response (FR) measurements. Typical method to make the FR measurements is to use sine sweep method [4], where sequence of sine signals with different frequencies in a frequency range of interest is injected into a converter and the corresponding responses are measured. In order to get sufficiently accurate frequency responses the transient after each frequency change has to be omitted. This means that FR measurement lasts several minutes per unit under test and does not, therefore, suffice for high throughput measurements.

Instead of injecting sine signals frequency by frequency it is possible to generate arbitrary excitation waveforms with a broadband spectrum to gather all the spectral information in one measurement. There exists a multitude of such signals; Schoukens *et al.* [5] list ten different signals in their survey. One special class of these signals is periodic maximum-length binary sequence (MLBS) signals [6]. The MLBS based measurement techniques have been used as a general method to measure a transfer function of any linear system and have been applied, for example, in the fields of acoustics [7], impedance spectroscopy of single living cells [8] sensors for gas, odour or aroma analysis [9], sonar systems for zooplankton survey [10], and recently, also for the analysis of power converters [11], [12].

To measure a frequency response of a system an appropriate excitation signal and computational method are

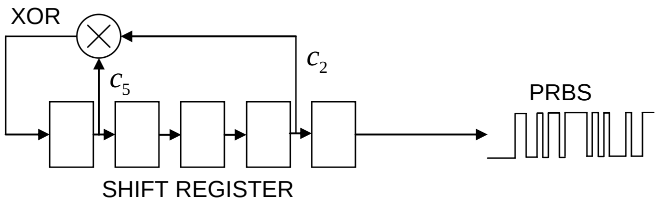

Fig. 1. 5-bit shift register with XOR feedback for PRBS generation.

required. For a proper computational method there are several alternatives. The transfer function of a linear system is the Fourier transform of system's impulse response. The impulse response of a linear system can be determined by applying MLBS excitation to a linear system, sampling the resulting response, and then cross-correlating the response with the MLBS input [13] or using the Fast *M*-sequence Transform [14]. An alternative method to define the transfer function estimate is to calculate the ratio of discrete Fourier transforms of MLBS excitation and system output response. Another method is to calculate the ratio of the cross and power spectra of MLBS excitation and system output [15].

Excitation signal design is an important step in the design of a system frequency response measurement experiment. The selection attributes are bandwidth, maximum amplitude, generation frequency, frequency resolution and the signal to noise ratio of the measurement. The decision variables in the problem of MLBS excitation signal design are the length of the period, the amplitude [16], the generation and sampling frequencies [17], and the number of the MLBS periods.

FR measurement of a switched mode converter with MLBS excitation set a unique requirement for the signal design. Verghese and Thottuvelil show in [18] how the pulse width modulation (PWM) generates harmonics to output response depending on the perturbation in duty cycle. Since the feedback control of a converter is implemented with PWM the excitation signal should be bandwidth limited.

This paper describes how general design issues of MLBS signal should be taken into account and how special issues of switched mode converters have to be considered when designing MLBS excitation signal for frequency response measurement. Since the switched mode converters contain PWM the conventional methods to design an appropriate MLBS excitation have to be modified.

The rest of the paper is organized as follows. Section 2 gives a review of basic theory of MLBS based frequency response measurement. Section 3 describes how the restrictions induced by PWM have to be considered in the excitation signal design. The signal design method is verified experimentally in Section 4 by measuring the output impedance of a high-frequency switched mode buck converter as a frequency response. Finally, the methods and results are summarized and conclusions are drawn in Section 5.

II. Review of MLBS Theory

A. Maximum Length Sequence Signal Generation

MLBS $\{a_k\}$ is a pseudorandom binary sequence if and only if it satisfies a linear recurrence

$$a_k = \sum_{i=1}^{n} c_i a_{k-i} \pmod 2 \tag{1}$$

and has a period $P = 2^n - 1$ [19]. The period length of pseudorandom binary sequence obtained by (1) depends on the values of c_i and with appropriate choice the sequence has a maximum length. MLBS can be generated efficiently by an n bit shift register with exclusive or (XOR) feedback, illustrated in Fig. 1.

In practice the values 0 and 1 generated by the shift register are mapped to +1 and –1, respectively, to produce a symmetrical maximum length sequence (MLS) signal $\{x_k\}$ with mean close to zero.

B. Time aliasing

An autocorrelation function of a zero mean signal $x(k)$ is

$$\phi_{xx}(k) = \lim_{N\to\infty} \frac{1}{N} \sum_{n=-N}^{N} x(k)x(n+k) \tag{2}$$

Since all the periods of a periodic signal are similar, for a periodic signal $\tilde{x}(k)$ the autocorrelation (2) can be rewritten as a circular autocorrelation

$$\tilde{\phi}_{xx}(k) = \frac{1}{P} \sum_{p=1}^{P} \tilde{x}(k)\tilde{x}(p+k) \tag{3}$$

where all the index calculations are performed modulo P. The tilde is used to separate periodic and aperiodic signals and functions.

For a dynamic system defined by its impulse response function $h(k)$ and excited by an input signal $x(k)$ the response signal $y(k)$ is

$$y(k) = \sum_{n=-\infty}^{+\infty} x(n)h(k-n) \tag{4}$$

For a periodic excitation $\tilde{x}(k)$ with period P the response $\tilde{y}(k)$ is periodic and it is possible to define periodic impulse response function $\tilde{h}(k)$

$$\tilde{y}(k) = \sum_{p=1}^{P} \tilde{x}(p)\tilde{h}(k-p) \tag{5}$$

where indices are calculated modulo P. The relationship between impulse response and periodic impulse response can be determined by convolution [13]

$$\tilde{h}(k) = \sum_{n=-\infty}^{+\infty} \tilde{\delta}(n)h(k-n) = \sum_{n=-\infty}^{+\infty} h(k+nP) \tag{6}$$

where $\tilde{\delta}(k)$ is periodic unit pulse sequence of period P

$$\tilde{\delta}(k)=\begin{cases}1 & k \bmod P=0\\ 0 & \text{otherwise}\end{cases} \tag{7}$$

The relation between impulse response $h(k)$ and periodic impulse response $\tilde{h}(k)$ implies that they are equal at interval $[0,P]$ only if the impulse response is zero with the phase greater than P. If this is not the case, impulse response values $h(k-nP)$ wrap additively with $h(k)$ to form $\tilde{h}(k)$. This is called the process of time aliasing. Hence, in absence of time aliasing, aperiodic impulse response can be measured with periodic experiments.

C. Correlation method

An important property of a symmetrical MLS signal in FR measurements is that its periodic autocorrelation function is a periodic unit impulse sequence [13]

$$\tilde{\phi}_{xx}(k)=\begin{cases}\dfrac{P}{P-1} & k \bmod P=0\\ \dfrac{-1}{P-1} & \text{otherwise}\end{cases} \tag{8}$$

The discrete impulse response $\tilde{g}(k)$ of a linear system can be obtained from

$$\tilde{\phi}_{xy}(k)=\tilde{g}(k)*\tilde{\phi}_{xx}(k) \tag{9}$$

where $*$ denotes periodic discrete convolution, $\tilde{\phi}_{xy}(k)$ the periodic cross-correlation function of $\{y_k\}$ and $\{x_k\}$, and $\tilde{\phi}_{xx}(k)$ the periodic autocorrelation function of $\{x_k\}$. The autocorrelation function in Eq. (8) can be approximated with periodic Kronecker delta function $\tilde{\delta}(k)$ with sufficiently large values of P. Since convolution of any function with Kronecker delta function is the function itself the impulse function of the system can be approximated as

$$\tilde{g}(k)\approx\tilde{\phi}_{xy}(k) \tag{10}$$

The frequency response is obtained by applying the Fourier transform to the impulse response function $\tilde{g}(k)$.

D. Spectrum method

The time-convolution theorem [20] allows one to substitute the convolution in the time domain by a simple multiplication in the frequency domain. Thus, Fourier transforming Eq. (9) gives

$$F\{\phi_{xy}(k)\}=G(e^{i\omega})F\{\phi_{xx}(k)\} \tag{11}$$

where $F\{\ \}$ denotes the Fourier transform. The Fourier transforms of the auto- and crosscorrelation are defined by Ljung [21] to be power spectrum $\Phi_{xx}(\omega)$ and cross spectrum $\Phi_{xy}(\omega)$, respectively, and the frequency response measurement can be obtained from

$$G(e^{i\omega})=\frac{\Phi_{xy}(\omega)}{\Phi_{xx}(\omega)} \tag{12}$$

Ljung also introduces empirical transfer function estimate (ETFE) that is the ratio of the Fourier transforms of input and output sequences:

$$G_{ETFE}(e^{j\omega})=\frac{Y(\omega)}{X(\omega)} \tag{13}$$

where $Y(\omega)$ and $X(\omega)$ are the Fourier transforms of the output and input sequences $\{y_k\}$ and $\{x_k\}$, respectively.

E. Averaging multiple periods

It is possible to reduce variance of frequency response measurements by using averaging techniques [15]. The measurement set-up can produce M input-output data blocks $\{y_k\}_m$, $\{x_k\}_m$, $m=1,2,\ldots,M$, either from M separate independent experiments or from M consecutive MLS periods during one experiment. Since the input is periodic with length P such that $x(k)=x(k+Pn)$ with integer n the input sequences $\{x_k\}_m$ are equal. The measurement noise signals $\{n_{y,k}\}_m$ that are part of output signals $\{y_k\}_m$ are assumed to be independent over m. It is possible to average measurements $\{y_k\}_m$ in time domain over the periods and get

$$\hat{y}(k)=\frac{1}{M}\sum_{m=0}^{M-1}y(k+mP) \tag{14}$$

and use the average for frequency response calculations e.g. in Eq. (12) or (13). Due to averaging procedure the noise is reduced by $1/\sqrt{M}$.

F. Spectrum of MLBS

Usually MLS signal is implemented by a zero-order hold circuitry. The Fourier transform of the autocorrelation of a periodic signal is a line spectrum with values only at frequencies

$$f=\frac{k}{P\Delta t} \tag{15}$$

where k is integer and Δt is the clock cycle of the MLS signal generator [22]. The values for a line spectrum of MLS signal are given by

$$\Phi_{xx}(\omega)=\frac{a^2(P+1)}{P^2}\frac{\sin^2(\pi k/P)}{(\pi k/P)^2} \tag{16}$$

where a is the amplitude of the signal. Fig.2 presents a line spectrum of a zero mean MLS signal generated by a 4-bit shift register with $\Delta t=1/15$ second. Consequently, by Eq. (15) the frequency resolution is 1 Hz. The spectrum follows the envelope of squared $\sin(f)/f$ function with a zero power at the MLS generation frequency and its harmonics. The power

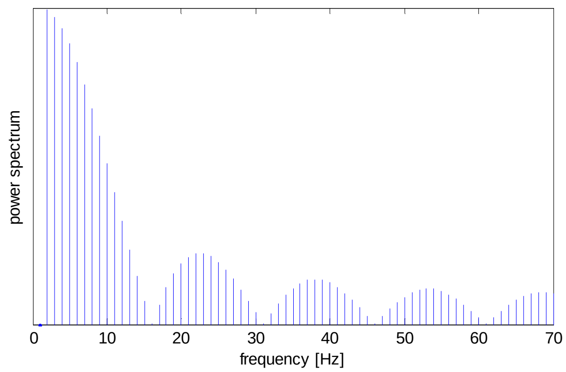

Fig. 2. Power spectrum of MLS signal generated with 4-bit shift register. The length of the period is 15 steps and duration of a step is 1/15 seconds, i.e. the generation frequency is 15 Hz.

at first harmonic is $a^2(P+1)/P^2$ and falls 3 dB by the frequency given by

$$\sin^2(\pi k/P)/(\pi k/P)^2 = 0.707 \tag{17}$$

i.e. approximately $k = P/3$.

III. Excitation Signal Design

The appropriate MLS for system frequency response measurement can be characterized by the following design variables.

- T duration of one MLS period,
- f_{gn} MLS generation frequency,
- P length of one MLS period,
- M number of MLS periods in excitation signal,
- a MLS amplitude and
- f_{BW} bandwidth of interest

As mentioned in Introduction, PWM sets special requirements for excitation signal design of switched-mode converters. When an excitation is injected into a system PWM generates several aliases to the output response. Verghese and Thottuvelil [18] show that perturbing the duty cycle at a particular frequency f_{m} in a PWM converter running at a switching frequency of f_{sw} will cause significant responses at the output voltage at the perturbation frequency, and at sum and difference frequencies formed from the switching and perturbation frequencies and its harmonics, i.e. at frequencies $kf_{\mathrm{sw}} \pm f_{\mathrm{m}}$ for integer k. They conclude that aliasing issues should be considered wherever perturbations are not limited to substantially below half the switching frequency. Thus, due to aliasing effect of PWM the excitation has to be filtered with a cut-off frequency of substantially below the switching frequency. An appropriate choice is to use $f_{\mathrm{BW}} = 0.45 \cdot f_{\mathrm{sw}}$.

As it was shown in Eqs. (16) and (17), the power spectrum of MLS has an envelope and drops three decibels by the frequency of $1/(3\Delta t)$. This can be considered as the limit of the effective frequency band covered by the MLS. Hence, the appropriate generation frequency $f_{\mathrm{gn}} = 1/\Delta t$ is obtained by

$$f_{\mathrm{BW}} = 1/(3\Delta t) \Leftrightarrow f_{\mathrm{gn}} = 1.35 \cdot f_{\mathrm{sw}} \tag{18}$$

The selection of MLS period length P has to fulfill two requirements. To avoid time aliasing, the duration T of one MLS period should be at least as large as the settling time of the system impulse response. Using this information the length of one MLS period can be obtained by

$$P = 2^n - 1 \geq f_{\mathrm{gn}} \cdot T \tag{19}$$

Thus, n has to be selected such that Eq. (19) is satisfied. Another requirement for P is to provide the desired frequency resolution as shown by Eq. (15).

The number of MLS periods M used in the excitation signal depends on the magnitude of external error, such as quantization, switching and measurement noise. Repeated MLS periods in the excitation signal allow applying Eq. (14). From the experimental point of view an appropriate number of periods is around $6-10$. If only a limited amount of data is available, for example due to a small internal buffer in the measurement card or limited experiment time, it is possible to benefit from averaging by allowing some overlapping of segments. The overlapping should not be, however, too great. Carter *et al.* [23] show that in many situations overlapping by up to 60 % improves the results.

The amplitude of the excitation needs to be chosen carefully. It has to be low enough to avoid the effects of nonlinear dynamical phenomena but high enough to provide good signal to noise ratio. The nonlinearities and noise characteristics depend both on the device under test and specified operational conditions. Thus, it is difficult to give general advice for amplitude selection. Therefore, selection of the amplitude should be based on good understanding of the device and its operational requirements.

In addition, an appropriate sampling frequency f_{sp} of input and output signals has to be defined. Ljung [21] suggests the clock frequency of MLS to be about 2.5 times the bandwidth to be covered by the signal. This is close to the value given by Eq. (18). Moreover, Ljung proposes the sampling frequency to be about 10 times faster than the bandwidth of interest. Hence, a proper choice for sampling frequency is to use $f_{\mathrm{sp}} \approx 4 f_{\mathrm{gn}}$.

Another point of view in selecting sampling frequency is based on the fact that the sampled MLS is filtered digitally and implemented with zero-order-hold circuit which creates harmonics at high frequencies. As Fig. 3. shows the power of harmonics decreases and they appear at higher frequencies when the number of samples per a clock cycle increases.

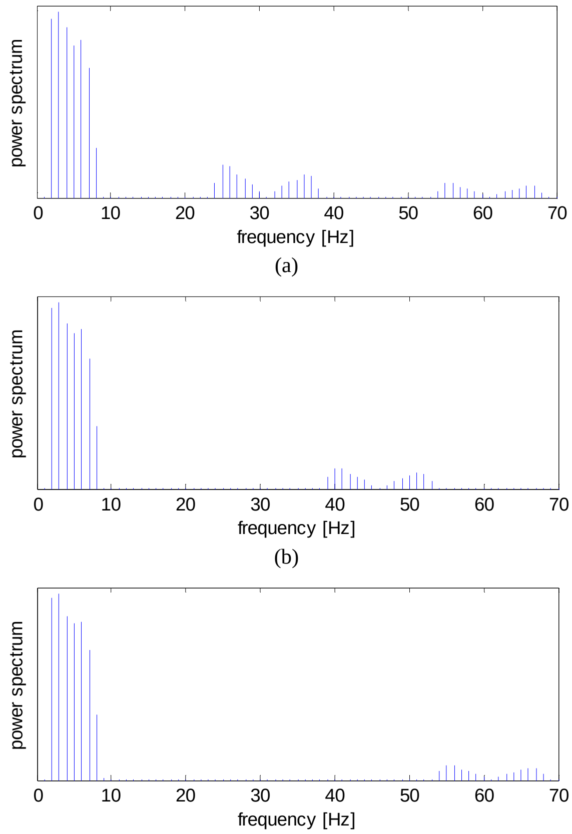

Fig. 3. Power spectrum of sampled MLS signal filtered with 6th order digital Chebyshev filter with a cut-off frequency of $0.45\times$ generation frequency. Sampling frequency is (a) two (b) three (c) four times the generation frequency of MLS and samples are implemented with zero-order-hold circuit. The MLS is generated as in Fig. 2. Increase in sampling frequency shifts zoh harmonics to higher frequencies and reduces their power.

IV. Experimental Verification

The proposed MLS based frequency response measurement method was experimentally tested and verified with a high-frequency switched mode buck converter that operates at closed loop. The implementation was set up by using a PC, measurement card NI PCI-6115 [24], linear amplifier, injection transformer, appropriate low-pass filters, and Matlab Data Acquisition Toolbox software.

The appropriate MLS excitation was designed as shown in Section III. The switching frequency was obtained by observing the output spectrum of the non-perturbed converter. The largest peak of the spectrum occurred at switching frequency. It was measured as 400 kHz. Hence, the excitation was digitally filtered by a cut-off frequency of $0.45\cdot f_{sw}=180$ kHz. Applying Eq. (18) the minimum value for the generation frequency was then obtained as 500 kHz.

The system settling time was evaluated by a simple step response experiment. Output current was increased from 0.5 A to 4 A and output voltage was measured. As shown by Fig. 5. the settling time is about 0.004 second. Hence, by applying Eq. (19) the minimum length of one excitation period was obtained as 2000 and thus, $P\geq 2^{11}-1=2047$. For a better frequency resolution P was set to 4095.

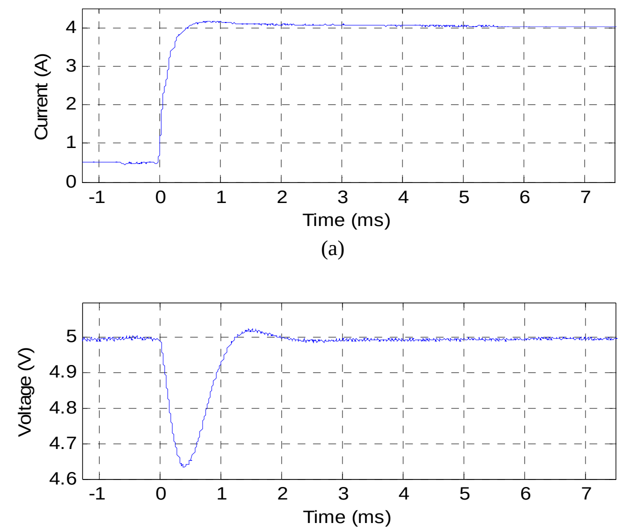

Fig. 4. Step response (b) of the buck-converter when the injected current (a) is changed from 0.5 A to 4 A.

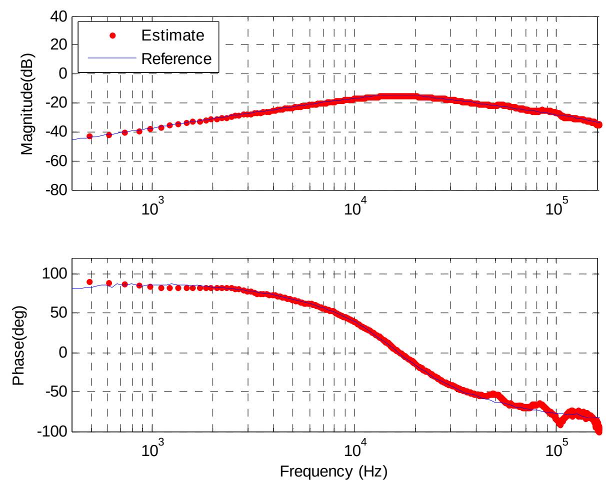

Fig. 5. Frequency response estimate of the buck-converter using spectrum method and network analyzer as a reference measurement.

A 10-period 12-bit MLS was then generated with Matlab using 500 kHz generation frequency. The total length of the excitation signal was then $L=10\cdot\left(2^{12}-1\right)=40950$ steps. Sampling frequency was set to 2 MHz that is four times the MLS generation frequency. The designed MLS was then injected to output current and output voltage was measured. After the data was collected the transient was omitted and Eq.(12) was applied.

The total amount of collected data was 163800 samples. This means that the process of collecting the data took $4L/f_{gn}\approx 0.33$ seconds.

Fig. 5 shows the output impedance of the buck converter as a frequency response when the designed excitation signal and spectrum method Eq. (12) were applied. The measured data was filtered by Whittakker's smoother [25]. The smoother improves the response slightly in high frequencies by reducing the variation of measurements.

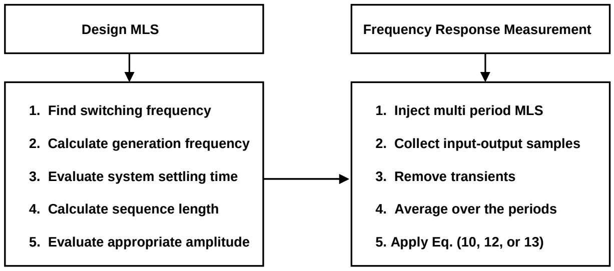

Fig. 6. Implementation procedure of presented methods.

The output impedance was also measured by a Venable 3120 network analyzer [4] under the same operating conditions. This response is considered as a reference response. As Fig. 5 shows the estimated response follows the reference response highly accurately in a wide range of frequencies.

V. CONCLUSIONS

This paper introduced the MLS based frequency response measurement method by means of which an appropriate frequency response of a switched mode converter can be measured fast and accurately. The theoretical background of the method was first introduced and then verified with a practical implementation. The result showed that the frequency response of a buck converter was possible to obtain extremely fast and accurately in a wide range of frequencies. In the presented experiment the measurement time was less than 1/3 seconds.

The method is based on multi frequency excitation signal with a broadband spectrum that gathers all the spectral information in one measurement. The signal contains superposed full period sine signals of different frequencies. Thus only one transient has to be discarded, and hence, the method is fast compared to sine sweep method. Due to time-aliasing, however, the method is valid only if the system response does not contain any slowly decaying or poorly damped transients. This can be considered as an extra motivation to design fast and well damped control.

Authors propose the presented methods to be applied in practical applications as illustrated in Fig. 6. First, an appropriate MLS excitation is designed by the presented steps. Then the excitation is injected into an appropriate input of the system, the appropriate output is measured and a selected computational method is applied.

The methods proposed in this paper can be applied both in development phase and in full scale production of switched mode converters. Possible applications could be, for instance, controller design, system validation, quality control, and fault detection. The methods can be applied both in on-line and off-line analysis and are well suited as a high through put measurement method for statistical quality assessment.

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