Modelling Switched Mode DC-DC Converter using System Identification Techniques: A Review

Subhransu Padhee, Umesh Chandra Pati, Kamalakanta Mahapatra
Department of Electronics and Communication Engineering
National Institute of Technology
Rourkela, Odisha, India
subhransupadhee@gmail.com, ucpati@nitrkl.ac.in, kkm@nitrkl.ac.in

***Abstract*— Multi converter based distributed power system (DPS) comprises of several interconnected switched mode power converters. The large scale implementation of DPS in variety of applications has provided new research directions in modeling and control of switched mode power converter. With evolution of DPS, black box, grey box modeling and identification of converter dynamics holds a significant research interest. A large number of papers study the identification aspect as well as real time implementation of identification techniques in switched mode power converter. Therefore, a proper review of available identification methods is the need of the day. In this paper, comprehensive reviews of parametric and non-parametric identification techniques of switched mode power converter have been discussed. This paper is intended to serve as a reference towards identification aspect of switched mode power converter.**

Keywords—distributed power system (DPS); system identification; switched mode power converter

I. INTRODUCTION

With rapid rise of electrical and electronic loads in the power distribution system there is an increased attention towards distributed power system (DPS). DPS consists of multiple interconnected converters which provide reliable and efficient power at different voltage levels to variety of applications such as telecommunication power system, household power system, transportation power system (aircrafts, naval ships and hybrid or electric vehicles), satellite, data centers and utility grid power system [1–5]. The main feature of DPS is its modularity. In order to shorten the time to market, commercial off the shelf (COTS) components are used in DPS. The use of such COTS and other interconnected components increases the system level complexity of DPS to a far greater extent. Complete converter level and system level modeling of DPS gets complicated due to non-availability of detailed technical specifications of COTS. The conventional state space average modeling technique of DC-DC converter provides a small signal model of the converter which ignores the non-linearity of the system and is only valid for a frequency which is half the switching frequency [6-7]. The system level requirement and identification issues of distributed power system are summarized in [8-9].

To find out the dynamic model of the converter, black box and grey box modeling of switched mode power converter is primarily used among the power electronics research community [10–14]. The first work on system identification of power converters can be tracked back to [14–16] where parametric identification technique is used to find out the detailed mathematical model of the converter. There are several promising applications of system identification of switched mode converter such as fault detection [17-18], adaptive control [19] and auto tuning [20] of the controller. Though a significant amount of work has been carried out in the system identification technique of the power converter, a comprehensive review of the above mentioned techniques is missing in the literature.

This paper provides a comprehensive review of state of the art system identification techniques for switched mode power converter. In system identification domain, parametric identification, non-parametric identification, black box and grey box identification has been discussed. Hardware implementation of identification experiment scheme is summarized.

II. SYSTEM IDENTIFICATION

Parsimonious principle states that the model should be no more complex than is required to capture underlying dynamics [21]. A maxim accredited to statistician George Edward Phelam Box states that, “Essentially all models are wrong but some are useful” defines the unique challenge of modeling [22]. In most of the real life situation, there is seldom any reliable information about the system and the environment to develop a mathematical model of the system. Not only lack of knowledge, but various aspects like presence of nonlinear dynamics, large number of features and data uncertainty pose challenge to develop an accurate and reliable mathematical model of a complex system.

System identification is a technique by which the mathematical model of a dynamic system can be obtained using real time experimental data (input, output and disturbance signal) [23]. The system identification procedure is carried out during normal operation of the system without disturbing the usual operation. Given a set of process signal

978-1-4673-7918-2/16/$31.00

values over a period of time, a model structure is assumed for the system. An approximation error criterion and an axiomatic constraint are defined. From the stated criteria a mathematical model is developed which satisfies the model constraints. The estimated mathematical model should be in accordance with the actual model. There can be different types of mathematical model developed for the same system depending upon the desired model accuracy and model complexity. Model complexity is the balance between model accuracy and computational expense. The most common issue considered at the time of model development is model parsimony, ease of development of model and accuracy of the model. The mathematical model obtained from identification exercise, can be used for many purposes like research and development, planning and scheduling, process optimization, safety and monitoring. The model can be used to simulate the system under different operating condition and the model can be used to diagnoses different faults.

In parametric system identification, a model structure is assumed and the experimental data is fitted with the model. Closed loop identification of the system is preferred because in this identification experiment, the closed loop is never broken and there is minimal change in output due to the identification experiment. In closed loop identification experiment, the time taken to complete the experiment and computational complexity of the identification algorithm plays a vital role. It is desirable that the identification experiment takes minimal time and the computational complexity involved in the algorithm should be moderate.

A. Parametric System Identification

For identification process, certain perturbation signal is used. The most popular form of perturbation signals is pseudo random binary sequence (PRBS) shown in Fig. 1 which can be generated using simple digital circuit [24–26].

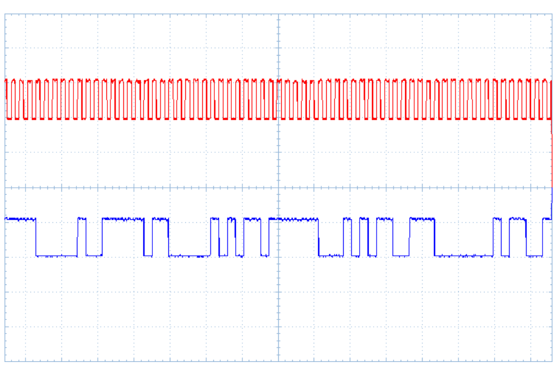

Fig. 1. PRBS signal

The steps of parametric system identification is shown in Fig. 2 which consists of different steps such as design of identification experiment, pre-processing of signals of identification experiment, model structure selection, parameter estimation and model validation. There are different linear as well as non-linear model structures available. The hybrid model structure comprising of both linear and non-linear model are called block oriented model. ARX, ARMAX, ARMA, OE and BJ model are some linear models whereas wiener, hammerstein model, wiener-hammerstein model and hammerstein-wiener model are some of the popular block oriented model available in the literature.

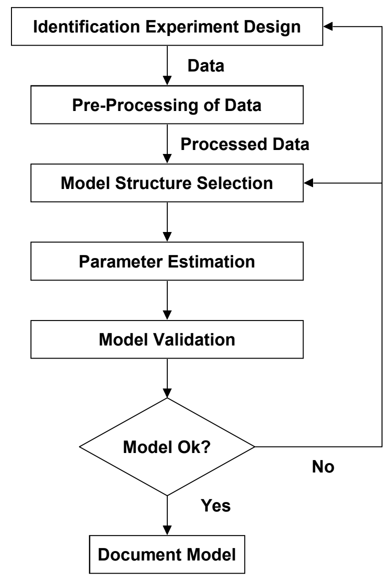

Fig. 2. Steps of parametric system identification

III. PARAMETRIC IDENTIFICATION OF DC-DC CONVERTER

In parametric identification, perturbation input is injected to the system which generates corresponding variations in output. The input-output data samples are collected and are fitted with a pre-defined model structure. The parameters of the model are estimated using different parameter estimation techniques. The estimated model is validated using different model validation tool. In [27], authors identified the transfer function (duty cycle to output voltage) of DC-DC converter in off-line mode using a step perturbation signal. Iterative least square algorithm is used for parameter estimation. In [28], the authors proposed a novel online identification technique for switched mode converter. The proposed technique uses IIR adaptive filter as the plant model and uses Dichotomous Coordinate Descent (DCD) algorithm for parameter estimation. The DCD algorithm reduces the computational complexity involved in parameter estimation step and is more efficient and accurate than conventional RLS algorithm. The proposed block diagram in [28] is shown in Fig. 3.

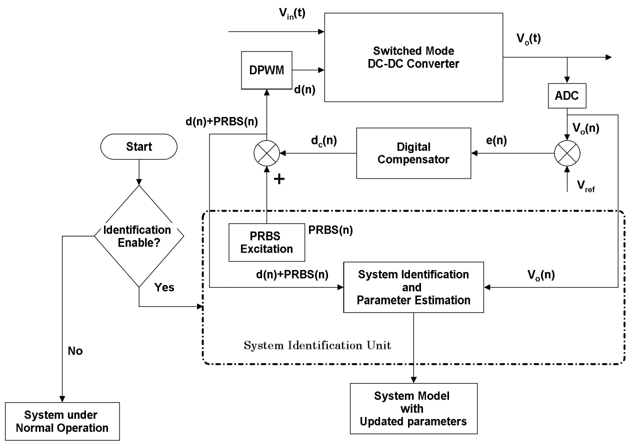

Fig. 3. Parametric system identification of DC-DC converter

As shown in Fig. 3, the identification feature can be switched on at any time according to the requirement. If the error crosses a threshold then this feature is automatically enabled. $PRBS(n)$ is added to the controller output $d(n)$ to create a modified signal $PRBS(n)+d(n)$. When the modified signal is applied to DPWM, a small disturbance in duty cycle is observed. The duty cycle will vary in between $d(n) \pm PRBS(n)$. Because of the variation in duty cycle, there is variation in output voltage. The input PRBS signal and varied output voltage is considered for parametric identification exercise. Unwanted measurement noise of output signal and offset of PRBS signal is removed using low pass filter prior to system identification and parameter estimation. Though there are numerous estimation algorithms, the most widely used online parameter estimation algorithm is Recursive Least Square (RLS) algorithm. RLS has fast convergence but higher complexity of $O(N^2)$ per sample where N is the filter length. For efficient and low complexity parameter estimation technique, Dichotomous Coordinate Descent (DCD) technique is used. Not only RLS and DCD techniques many other techniques such as Kalman filter and fast affine projection algorithms are used for accurate parameter estimation of switched mode DC-DC converter [29-30].

A. Nonlinear Identification

Considering the switched mode power electronics converter as a nonlinear system, researchers used nonlinear auto regressive moving average exogeneous input (NARMAX) to derive the dynamics of the converter from time domain data [15]. Considering the voltage source converter as single input multiple output (SIMO) black box model, researchers proposed NARX model to identify the dynamics of the converter [31].

B. Modelling using Block Oriented Model

Block oriented model is a special kind of nonlinear model, which is a cascaded form of static nonlinear block and dynamic linear block. Some of the well-known block oriented models are namely wiener model and hammerstein model. The combination of these two models provides hybrid block oriented model such as wiener-hammerstein model and hammerstein-wiener model. Use of block oriented model for identification of power electronics converter have been reported in literature. Hammerstein model is used to find the transfer function of boost converter [32]. Wiener-Hammerstein structure is used for modeling of DC-DC converter in [33] where the authors manage to predict the power consumption, efficiency, stability and other parameters of the converter. Grey box modeling of DC-DC boost converter using Hammerstain-Bilinear structure is proposed [34].

C. Black Box Identification

Black box system identification approach provides a discrete time small signal linear equivalent model of general class of converters. Grey-box identification of buck converter is reported in [35]. In grey-box identification, some priori information is available about the system. Black box model of zero voltage power converter and resonant power converter is reported in [14].

D. Neural Network Based Identification

Multi-layer feed forward neural network is considered as universal approximation. Neural network is widely used for system identification in many related fields except power electronics. Some researchers made an attempt to introduce neural network based identification in switched mode power converter [36]. In this paper, neural network emulator is used to identify the dynamics of switched mode power converter during uncertainty and change in parameters.

E. Non-parametric Identification Based Model

Non parametric system identification technique comprises of following techniques: correlation analysis, transient response analysis, frequency response analysis and Fourier or spectrum analysis. The main challenge of non-parametric identification is the time required for identification and computational requirement (memory and computational cost) for identification.

In [37], author regarded the power converter as linear time invariant (LTI) system during steady state for small signal disturbance and implemented cross-correlation and DFT techniques to identify the dynamics of a forward converter. The author used multi-period PRBS as perturbing input signal and eventually determined the frequency response of the system. Fig. 4 shows the flow chart of cross correlation based non-parametric identification technique for switched mode DC-DC converter.

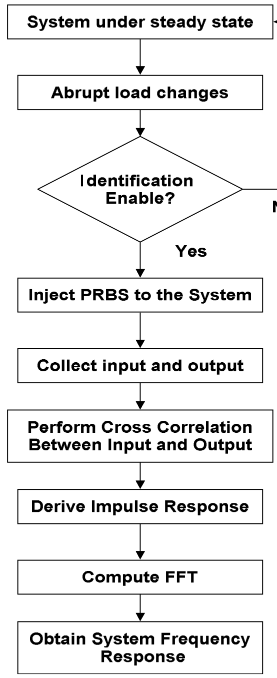

Fig. 4. Cross correlation based non-parametric system identification technique of switched mode DC-DC converter

Adam Bakerly et.al [38], suggested many modifications to improve the accuracy of the cross-correlation based frequency response identification technique. The major contribution of the proposed approach is successful identification of the converter dynamics without breaking the feedback loop. Accuracy of nonparametric system is improved using windowing method, delayed sampling of output voltage and correction of nonideal spectrum of injected PRBS signal. Tomi Roinila et.al [39], implemented circular correlation for identification of transfer function of buck converter. The author implements multi period maximum length PRBS as excitation signal. The major contribution in this paper is the use of fuzzy density approach to compute the measurement uncertainty. Correlation based identification of digitally controlled switched mode power supply (SMPS) is further studied in [40]. A hardware efficient correlation based identification scheme of PWM based DC-DC converter is reported in [41]. This hardware efficient method reduces the quantization effect of analog to digital converter (ADC) to obtain an accurate system frequency response. The impulse response of the system is computed using cross correlation technique. The cross correlation is computed using Walsh-Hadamard transform followed by FFT. The FFT data are smoothed using fractional decade spectral window. The proposed hardware efficient method for nonparametric system identification of digitally controlled switched mode power converter studied by [41] is represented in Fig. 5.

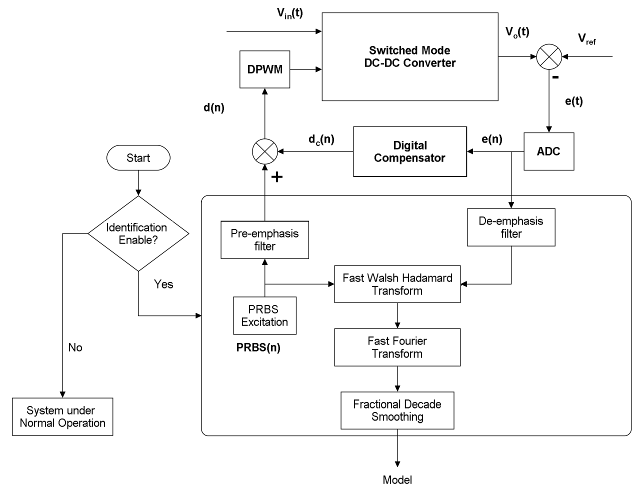

Fig. 5. Non-parametric system identification technique using WHT and FFT

Zhenyu Zhao et al., introduced a new method for efficient system identification and parameter estimation for low power digitally controlled switched mode DC-DC converter [42]. The system identification technique utilizes intentionally generated limit cycle oscillations of DPWM module for system identification and parameter estimation. The schematic block diagram of method presented in [42] is illustrated in Fig. 6.

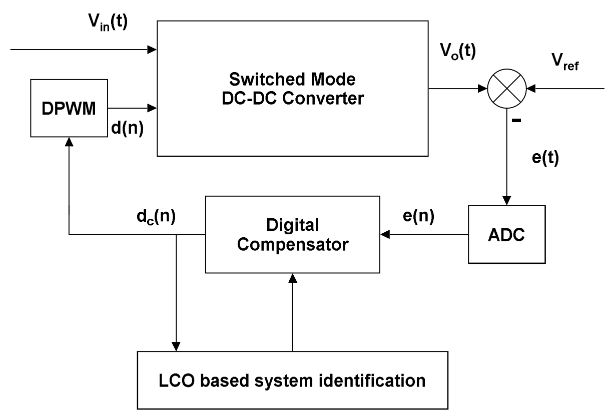

Fig. 6. Limit cycle oscillation based non-parametric identification technique of switched mode converter

Not only cross-correlation and circular correlation but also frequency response measurement is used for non-parametric identification of switched mode power converter because frequency response method provides more useful data for modeling and identification. The transfer function of converter is estimated from frequency response function (FRF). The FRF analysis is carried out using frequency response analyzer (FRA). Frequency response method for identification of PWM DC-DC converter is discussed in [43]. This paper implements inverse repeat binary sequence (IRS) instead of PRBS as an excitation signal.

IV. Hardware Implementation of System Identification Techniques

Real time implementation of system identification and subsequent application of adaptive control scheme in a switched mode power converter is relatively costly affair because of the complexity of the identification and adaptive algorithm. Due to higher complexity of the algorithms, powerful computation devices are used which escalates the cost of the system. Therefore, researchers are trying to reduce the complexity of identification and adaptive algorithm complexity. Fig. 7 illustrates the real time implementation of system identification and adaptive control in switched mode DC-DC converter.

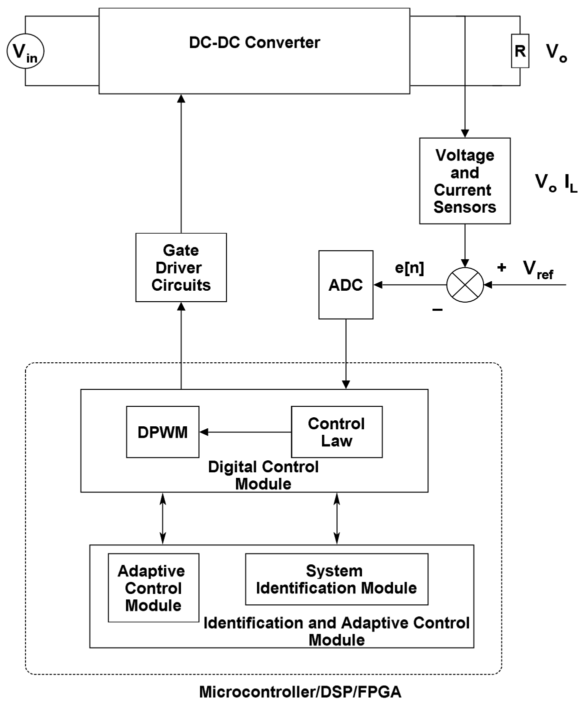

Fig. 7. Real time implementation of system identification and adaptive control of switched mode power converter

Limit cycle oscillation based identification and auto tuning method described in [42], implements the auto tuning algorithm using DSP board and FPGA board. The high frequency programmable resolution DPWM is implemented in FPGA system. Adaptive control for DC-DC converter is implemented using FPGA in [44]–[47]. Parametric system identification and adaptive control of switched mode DC-DC converter is experimentally validated using Digital Signal Processor in [19], [28]. Non parametric identification of switched mode DC-DC converter is implemented in FPGA boards in [20], [37], [41].

V. Conclusions

This paper has presented a detailed description of system identification of switched mode DC-DC converter on the basis of extensive review. Due to the availability of cheaper and faster computing devices, real time implementation of identification aspect has gained a lot of research interest. A number of parametric and non-parametric identification schemes for switched mode power converter which has been published in literature have been discussed in details in this paper. Therefore, this paper can be served as a review paper for identification aspect of switched mode power converter.

References

[1] G P. Lindman and L. Thorsell, "Applying distributed power modules in telecom systems," *IEEE Trans. Power Electron.*, vol. 11, no. 2, pp. 365–373, 1996.

[2] A. Emadi and M. Ehsani, "Multi-converter power electronic systems: definition and applications," in *Proc. 32nd Annual Power Electronics Specialists Conference*, vol. 2, 2001, pp. 1230–1236.

[3] S. Luo, "A review of distributed power systems part i: Dc distributed power system," *IEEE Aerosp. Electron. Syst. Mag.*, vol. 20, no. 8, pp. 5–16, 2005.

[4] D. Boroyevich, R. Burgos, L. Arnedo, and F. Wang, "Synthesis and integration of future electronic power distribution systems," in *Proc. Power Conversion Conference*, 2007, pp. K–1.

[5] R. Miftakhutdinov, "Power distribution architecture for tele-and data communication system based on new generation intermediate bus converter," in *Proc. 30th Intl. Conf. Telecommunications Energy Conf.*, 2008, pp. 1–8.

[6] R. D. Middlebrook and S. Cuk, "A general unified approach to modelling switching-converter power stages," in *Proc. Power Electronics Specialists Conf.*, vol. 1, 1976, pp. 18–34.

[7] P. T. Krein, J. Bentsman, R. M. Bass, and B. Lesieutre, "On the use of averaging for the analysis of power electronic systems," *IEEE Trans. Power Electron.*, vol. 5, no. 2, pp. 182–190, 1990.

[8] J. Oliver, R. Prieto, L. Laguna, and J. Cobos, "Modeling and simulation requirements for the analysis and design of dc distributed power electronic systems," in *Proc. 11th Power Electronics Congress*, 2008, pp. 204–209.

[9] J. Oliver, R. Prieto, V. Romero, and J. Cobos, "Behavioral modeling of dc-dc converters for large-signal simulation of distributed power systems," in *Proc. Twenty-First Annual Applied Power Electronics Conference and Exposition*, 2006, pp. 6–pp.

[10] L. Amedo, R. Burgos, F. Wang, and D. Boroyevich, "Black-box terminal characterization modeling of dc-to-dc converters," in *Proc. Twenty Second Annual APEC*, 2007, pp. 457–463.

[11] L. Arnedo, D. Boroyevich, R. Burgos, and F. Wang, "Polytopic black-box modeling of dc-dc converters," in *Proc. Power Electronics Specialists Conf.*, 2008, pp. 1015–1021.

[12] V. Valdivia, A. Barrado, A. Roldan, P. Zumel, and C. Raga, "New nonlinear dynamic" grey box" behavioral modeling and identification of voltage mode controlled buck derived dc-dc converters," in *Proc. Twenty-Fourth Annual Applied Power Electronics Conference and Exposition*, 2009, pp. 312–317.

[13] V. Valdivia, A. Barrado, A. Laazaro, P. Zumel, C. Raga, and C. Fernandez, "Simple modeling and identification procedures for ´ black-box behavioral modeling of power converters based on transient response analysis," *IEEE Trans. Power Electron.*, vol. 24, no. 12, pp. 2776–2790, 2009.

[14] J.-Y. Choi, B. H. Cho, H. F. VanLandingham, H.-s. Mok, and J.-H. Song, "System identification of power converters based on a black-box approach," *IEEE Trans. Circuits Syst. I, Fundam. Theory Appl.*, vol. 45, no. 11, pp. 1148–1158, 1998.

[15] K. Chau and C. Chan, "Nonlinear identification of power electronic systems," in *Proc. 1995 Int. Conf. Power Electronics and Drive Systems,* 1995, pp. 329–334.

[16] B. Johansson and M. Lenells, “Possibilities of obtaining small-signal models of dc-to-dc power converters by means of system identification,” in *Proc. 22nd Int. Telecommunications Energy Conference*, 2000, pp. 65–75.

[17] G. Buiatti, A. Amaral, and A. Cardoso, “An online technique for estimating the parameters of passive components in non-isolated dc/dc converters,” in *Proc. IEEE Int. Symp. Ind. Electron.*, 2007, pp. 606–610.

[18] T.-J. Kim, J.-W. Baek, J.-H. Jeon, G.-H. Rim, and C.-U. Kim, “A diagnosis method of dc/dc converter aging based on the variation of parasitic,” in *Proc. 30th Annual Conf. Industrial Electronics Society*, vol. 3, 2004, pp. 3037–3041.

[19] M. Algreer, M. Armstrong, and D. Giaouris, “Adaptive pd+ i control of a switch-mode dc–dc power converter using a recursive fir predictor,” *IEEE Trans. Ind. Appl.*, vol. 47, no. 5, pp. 2135–2144, 2011.

[20] M. Shirazi, R. Zane, and D. Maksimovic, “An autotuning digital controller for dc–dc power converters based on online frequency-response measurement,” *IEEE Trans. Power Electron.*, vol. 24, no. 11, pp. 2578–2588, 2009.

[21] S. Billings and S. Chen, *The determination of multivariable nonlinear models for dynamic systems*. Academic Press, 1998.

[22] G. E. Box and N. R. Draper, *Empirical model-building and response surfaces.* John Wiley & Sons, 1987.

[23] L. Ljung, *System identification*. Springer, 1998.

[24] H. Barker, D. Rivera, A. Tan, and K. Godfrey, “Perturbation signal design,” in *Proc. IFAC System Identification*, vol. 14, no. 1, 2006, pp. 1121–1126.

[25] K. Godfrey, H. Barker, and A. Tucker, “Comparison of perturbation signals for linear system identification in the frequency domain,” in *IEE Proceedings-Control Theory and Applications*, vol. 146, no. 6, 1999, pp. 535–548.

[26] K. Godfrey, A. Tan, H. Barker, and B. Chong, “A survey of readily accessible perturbation signals for system identification in the frequency domain,” *Control Engineering Practice*, vol. 13, no. 11, pp. 1391–1402, 2005.

[27] M. Peretz and S. Ben-Yaakov, “Time-domain identification of pulse-width modulated converters,” *IET Power Electron.*, vol. 5, no. 2, pp. 166–172, 2012.

[28] M. Algreer, M. Armstrong, and D. Giaouris, “Active online system identification of switch mode dc–dc power converter based on efficient recursive dcd-iir adaptive filter,” *IEEE Trans. Power Electron.*, vol. 27, no. 11, pp. 4425–4435, 2012.

[29] M. Ahmeid, M. Armstrong, S. Gadoue, and P. Missailidis, “Parameter estimation of a dc-dc converter using a kalman filter approach,” in *Proc. 7th IET Int. Conf. Power Electronics, Machines and Drives*, 2014, pp. 1–6.

[30] C. Wang, M. Armstrong, S. Gadoue, and P. Missailidis, “System identification of a dc-dc converter system using a fast affine projection algorithm,” in *Proc. 7th IET Int. Conf. Power Electronics, Machines and Drives*, 2014, pp. 1–6.

[31] W. ZHENG, X. XIONG, and Z. SHEN, “Dynamic converter modeling using black-box identification method for grid-connected photovoltaic systems,” *Journal of Computational Information Systems*, vol. 9, no. 22, pp. 9083–9093, 2013.

[32] F. Alonge, F. D’Ippolito, F. M. Raimondi, and S. Tumminaro, “Nonlinear modeling of dc/dc converters using the hammerstein’s approach,” *IEEE Trans. Power Electron.*, vol. 22, no. 4, pp. 1210–1221, 2007.

[33] J. Oliver, R. Prieto, J. Cobos, O. Garcia, and P. Alou, “Hybrid wiener-hammerstein structure for grey-box modeling of dc-dc converters,” in *Proc. Twenty-Fourth Annual Conf. Applied Power Electronics Conference and Exposition*, 2009, pp. 280–285.

[34] T. Larkowski, U. Hitzemann, and K. Burnham, “Modelling and identification of a dc-dc boost converter operating in discontinuous conduction mode,” in *Proc. IET Conf. Control and Automation: Uniting Problems and Solutions*, 2013, pp. 1–6.

[35] L. A. Aguirre, P. F. Donoso-Garcia, and R. Santos-Filho, “Use of a priori information in the identification of global nonlinear models-a case study using a buck converter,” *IEEE Trans. Circuits Syst. I, Fundam. Theory Appl,*, vol. 47, no. 7, pp. 1081–1085, 2000.

[36] R. Leyva, L. Martinez-Salamero, B. Jammes, J. C. Marpinard, and F. Guinjoan, “Identification and control of power converters by means of neural networks,” *IEEE Trans. Circuits Syst. I, Fundam. Theory Appl.*, vol. 44, no. 8, pp. 735–742, 1997.

[37] B. Miao, R. Zane, and D. Maksimovic, “System identification of power converters with digital control through cross-correlation methods,” *IEEE Trans. Power Electron.*, vol. 20, no. 5, pp. 1093–1099, 2005.

[38] A. Barkley and E. Santi, “Improved online identification of a dc–dc converter and its control loop gain using cross-correlation methods,” *IEEE Trans. Power Electron.*, vol. 24, no. 8, pp. 2021–2031, 2009.

[39] T. Roinila, T. Helin, M. Vilkko, T. Suntio, and H. Koivisto, “Circular correlation based identification of switching power converter with uncertainty analysis using fuzzy density approach,” *Simulation Modelling Practice and Theory*, vol. 17, no. 6, pp. 1043–1058, 2009.

[40] J.-Y. Liu, C.-H. Yang, and C.-H. Tsai, “Correlation-based system identification of digitally controlled smps,” in *Proc. 2011 IEEE Ninth International Conference on Power Electronics and Drive Systems (PEDS)*, 2011, pp. 1149–1152.

[41] M. Shirazi, J. Morroni, A. Dolgov, R. Zane, and D. Maksimovic, “Integration of frequency response measurement capabilities in digital controllers for dc–dc converters,” *IEEE Trans. Power Electron.*, vol. 23, no. 5, pp. 2524–2535, 2008.

[42] Z. Zhao and A. Prodic, “Limit-cycle oscillations based auto-tuning system for digitally controlled dc–dc power supplies,” *IEEE Trans. Power Electron.*, vol. 22, no. 6, pp. 2211–2222, 2007.

[43] T. Roinila, M. Vilkko, and T. Suntio, “Frequency-response measurement of switched-mode power supplies in the presence of nonlinear distortions,” *IEEE Trans. Power Electron.*, vol. 25, no. 8, pp. 2179–2187, 2010.

[44] K. Hwu, “Forward converter with fpga-based self-tuning pid controller,” *Tamkang Journal of Science and Engineering*, vol. 13, no. 2, pp. 173–180, 2010.

[45] J.-T. Su and C.-W. Liu, “Gain scheduling control scheme for improved transient response of dc/dc converters,” *IET Power Electron.*, vol. 5, no. 6, pp. 678–692, 2012.

[46] J. Morroni, L. Corradini, R. Zane, and D. Maksimovic, “Adaptive tuning of switched-mode power supplies operating in discontinuous and continuous conduction modes,” *IEEE Trans. Power Electron.*, vol. 24, no. 11, pp. 2603–2611, 2009.

[47] V. Arikatla and J. Abu Qahouq, “Adaptive digital proportional-integral-derivative controller for power converters,” *IET Power Electron.*, vol. 5, no. 3, pp. 341–348, 2012.