Black Box Modelling of a Bidirectional Battery Charger for Electric Vehicles

Antreas Naziris, Rafael Asensi, Javier Uceda

Centro de Electrónica Industrial

Universidad Politécnica de Madrid

Madrid, Spain

andreasnaziris1@gmail.com, {rafael.asensi, javier.uceda}@upm.es

***Abstract*— This paper proposes a black box modelling strategy for a bidirectional battery charger (BBC) for Electric Vehicles (EV)[1], either the BBC is operating in the vehicle to grid (V2G) mode or not. Due to the increasing penetration of EV, the number of battery chargers connected to the grid is also increasing, being a challenge to assess the impact of such growing number of battery chargers into the grid performance. At the same time, there is no detailed information (static and dynamic) of the commercial chargers used in EV and connected to the grid. In this approach, a behavioural black box model is proposed. The generation of the model requests for performing a number of simple tests to the BBC in order to identify the model parameters. In the paper, a detailed switching model in PSIM is used as the actual BBC. The model thoroughly tested by simulation, and compared with the results of the generated black box model and the detailed switching model used as a reference.**

Keywords— black box; electric vehicles; bidirectional battery charger.

I. INTRODUCTION

Since climate change has become obvious, some measures are required to stop the disaster of the ecosystem or at least delay it. Dates like 2020, 2030 and 2050 [1] linked with energy packages and frameworks worldwide and in each country independently are some of the measures. Every country has to contribute by reducing its carbon budget and introduce a more eco-friendly, green path. Following the same path, smart grid technologies with renewables will play a key role at electric grids in short-term future.

Electric Vehicles already exist in the market in the form of Plug in EVs (PIEV), Hybrid EVs (HEV) and Fuel Cell EVs (FCEV). In addition, the structure of the particular charger comes in different schemes. In the vast amount of approaches, the system works unidirectional (only charge EV). However, more examples that are recent are bidirectional [2, 3, 4]. Here we have the return of the energy back to the grid, which means a direct profit to the user in the electric energy bill and a possibility to use this energy flow to stabilize the grid by the Technical System Operator.

[1] This work was supported by the Spanish Ministry of Economy and Competitiveness under the project IDENMRED with reference DPI2016-78644-P

In the first part of the paper, the description of a detailed switching model (Fig.1) of a bidirectional battery EV charger takes place using Power simulation (PSIM) program [5]. The charger includes a Dual Active Bridge (DAB) DC-DC converter with a battery circuit and an AC-DC boost converter. The second part of the paper deals with the development of the black box model implemented in MATLAB. A dynamic system in a black box provides flexibility to illustrate practically any dynamic without having insight knowledge of the actual system.

II. BIDIRECTIONAL BATTERY CHARGER

The first part involves a detailed switching modelling of a Dual Active Bridge (DAB) DC-DC converter and a battery circuit. The converter is working in both operating modes such as constant current and constant voltage [6, 7]. In addition, charging/discharging power from grid and to the grid depends on the sign of the reference current induced, which indicates whether we are providers or consumers. The working principle of the converter is the following:

- Control operates based on (soft-switched) phase shift strategy. The phase shift φ determines the direction and amount of power transfers between dc buses. (Fig.2)

- Diagonal switching pairs turned on with 50% duty and with 180 degrees phase shift [8] between two legs.

A charging strategy (Fig.3) [9, 10, 11, 12] of the battery model relies on the constant current and voltage modes strategy. In the present circuit, for the first stage, a current amount is set as the reference current. Battery is charging with that reference current until it reaches a reference voltage, previously set. This first stage is the constant current mode. The second stage, which is the constant voltage mode, starts

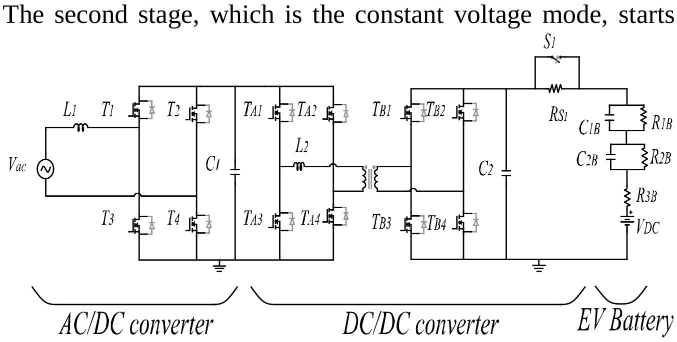

Fig. 1: Scheme of bidirectional battery charger

immediately after battery reaches the maximum reference voltage. At this part, the voltage of the battery keeps steady while current is dropping gradually to a minimum reference current and then drops to 0. The battery model at the end of the DC-DC converter represents the battery pack of the Electric Vehicle cells (EV). A battery pack contains a number of cells in rows and columns. The structure of one cell includes a resistor, which represents the internal resistance of the battery, a resistor and capacitor in parallel, which represent the effects in the surface of electrodes, and one more resistor and capacitor in parallel, which represent the diffusion processes in the electrolyte [13, 14].

The second and last part of the circuit is an AC-DC boost converter. The particular boost rectifier is implemented as single phase. Therefore, a D-Q rotating frame (Fig.4) takes place with the Park transformation. In order to achieve an orthogonal signal with 90 degrees of difference between the two phases an All-Pass Filter [15] (APF) is applied. All-pass filter is preferred over other techniques, like phase delay and differentiator. All-Pass Filter is faster than phase delay and does not degrade performance of the controller. Also, it is less noisy than the differentiator technique. Another reason, which ended up with APF technique, is the easy implementation.

The boost rectifier is controlling the Active and Reactive power in both directions with the help of a V-Q controller. At the AC part of the rectifier, a voltage and a current sensor exist to provide the Phase-Locked Loops (PLL) of voltage and current. In addition, there is a voltage sensor in the DC part of the rectifier to interact with a constant voltage value. After transformation of the D-Q rotation from alpha and beta and the DC values of voltage and reactive power the signals flow through the pulse width modulation to the MOSFETs. V-Q controller (Fig.5) can operate in all regions of P-Q plane. In the Fig. 6 and 7, it can be seen the results by changing only reactive power and keeping real power steady on positive values.

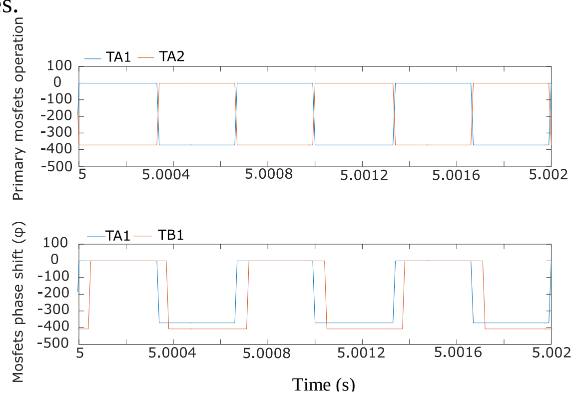

Fig. 2: Mosfets operation

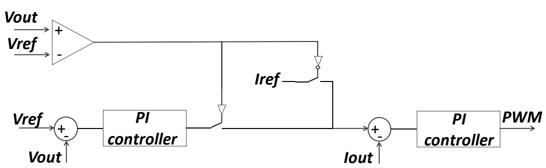

Fig. 3: Constant Current/Constant Voltage controller

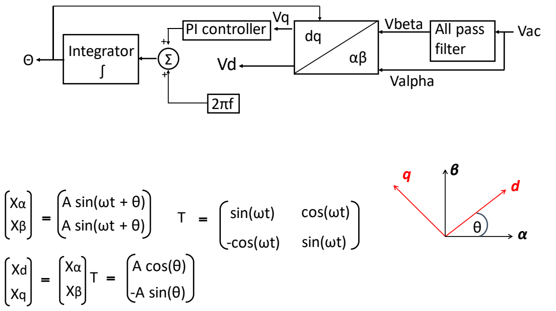

Fig. 4: αβ/dq transformation

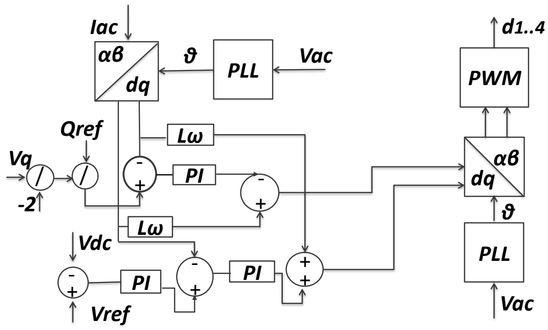

Fig. 5: V-Q controller

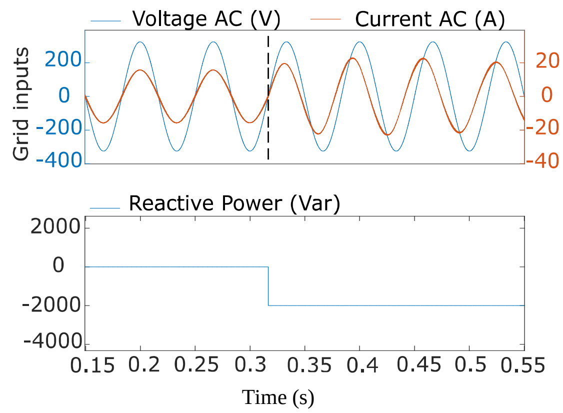

Fig. 6: Charging with capacitive operation

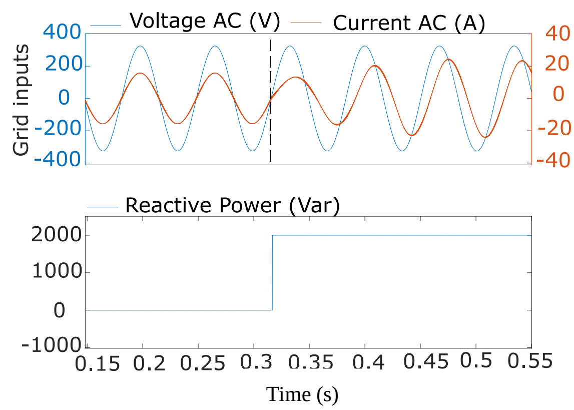

Fig. 7: Charging with inductive operation

The complete system, implemented in Power Simulation program (PSIM) in closed loop, can regulate the current between the two ends of the rectifier and converter part as a single stage.

III. BLACK BOX MODEL OF THE SYSTEM

The black box model is obtained through a number of simple tests applied to the actual equipment. Using the input-output data generated during a test phase, a black box model will be identified by MATLAB. In our approach the detailed switching model, which refers in the previous section in PSIM is used as the actual equipment under test. The black box model has been widely tested and compared with the simulation results generated by the detailed PSIM switching model, showing a very good accuracy.

By constructing in a dynamical system, a linear black box gives the opportunity to portray practically any linear dynamic [16]. The system identification goal passes through a structural model to end up with an accurate model (Fig.8). What is essential in approximation is to estimate the system, regardless of having any internal information about the structure of the dynamical model by taking advantage of the already known physical information and knowledge of the system. There are 3 levels of such models with prior knowledge: Firstly, the white-box model in which all the data are known, secondly, there is the grey-box model in which some information is given and finally, the black box model, where insight knowledge is unknown. The model has satisfactory flexibility and is close to previous working example.

The procedure for modelling [17] the dynamic of a system, is system identification, obtained from input/output measurement of the system. Data collection comes from different experiments (with a unique operation point each time) designed and constructed. Next step is the model structure selection. After that estimation of the model structure, experimental data take place and it follows the validation. At the end, an appropriate model is obtained and a model analysis can be executed for forthcoming model applications.

A. *Small Signal Model*

A small signal model with G-parameters for dc-dc electronic power system architectures presented by Boroyevich [18]. The dynamic behavior of different converters connected together in different configurations with loads and source (ac and dc) can be investigated with these behavioral models. This DC application of this approach has been widely investigated with the use of small signal model, with purpose to study interactions between converters [19]. The black box model presented in the current paper models ac and dc input/output values [20] (Fig.9). Modelling of ac input signal requires the Park´s transformation in order to obtain a d-q frame dc signals model. Similarly, by using inverse Park, ac signal output is obtained. The present system considers a dc-dc converter with an EV battery connected to an inverter and then to the grid. In the dc part of the system, it is preferable to have input and output current signals due to the control of the battery explained on the previous section (constant current/constant voltage strategy). On the other hand, for the rectifier is more appropriate to choose voltage and reactive power as inputs, as well as current as output (showing the V2G impact).

The small signal model of this system consists of 12 transfer functions emerged from inputs and outputs as it appears in Fig. 10, where, Vd and Vq are the d-q coordinates of the input ac voltage, Iref, the reference current applied in the electric vehicle battery part and Qref, the reactive power induced at the inverter. Id and Iq are the coordinates before the ac current output and Ibat the current of the EV battery.

Identification of the transfer functions can be obtained by perturbation of input variables –Vd, Vq, Iref, Qref– in frequency or, as in this case, in time domain and the output variables –Id, Iq, Ibat- response operates to implement identification. The perturbations tests on the input variables must be implemented one by one and with the others keeping constant in order to be checked individually. Lastly, as a

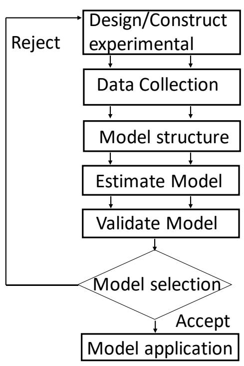

Fig. 8: Identification process

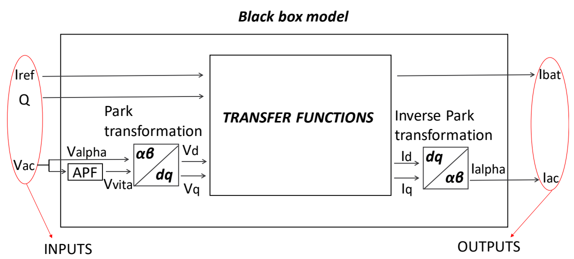

Fig. 9: Block diagram of black box model

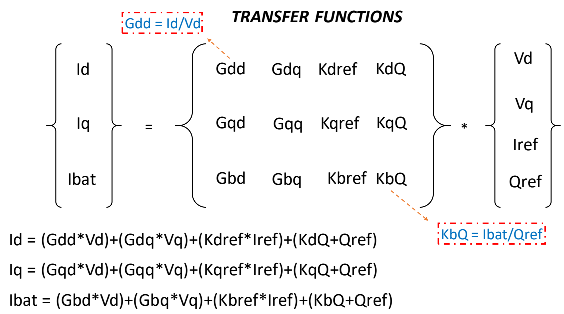

Fig. 10: Transfer functions of small signal

reference for identification, the system identification tools of Matlab are used [21]. The transfer function applied to construct the polynomial models, is output error structure because is the most accurate due to best-fit response and lowest order of linear polynomial parameters. The small signal model is represented in Fig. 11 and the detailed system of black box model appears in Fig. 12.

IV. SIMULATION RESULTS

Various data examples, which were taken from PSIM, were implemented in MATLAB. Those tests have been undertaken to check adaptation of PSIM model to the black box model for battery and grid current. The tests include:

- Operation point test from Grid to Battery
- Step test from Grid to Battery
- Operation point test from Battery to Grid
- Step test from Battery to Grid
- Direction test

On the current paper, the most characteristic results are presented. Figures 13 and 14 illustrate an addition of 6 A to the battery side at 0.3 s while the system operates with 3 A. At 0.47 s, it can be observed that the battery is fully charged and as a result, the current is dropping in order to prevent an overcurrent incidence. Figures 15 and 16 show the change of a consumer being a provider to the system by changing the sign of reference current induced. Moreover, in Fig. 16, it can be observed the voltage and current input from the grid to the system and the same grid current compared with the black box result of grid current. Results for both models are very similar, which implies a good accuracy for the new black box model

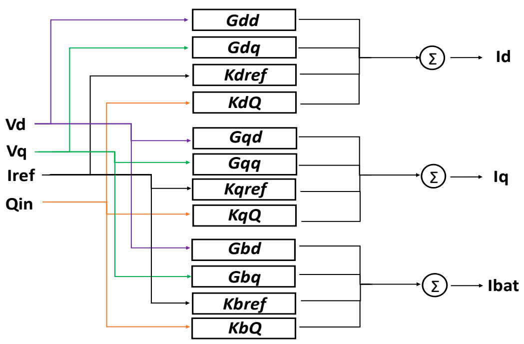

Fig. 11: Block diagram of small signal model

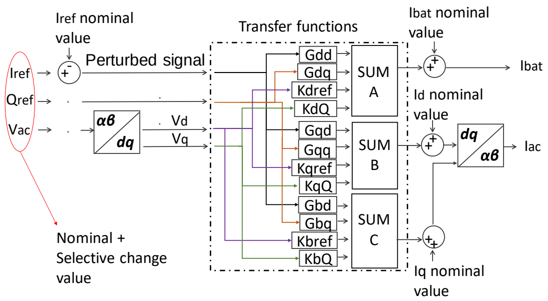

Fig. 12: Black box model of bidirectional battery charger

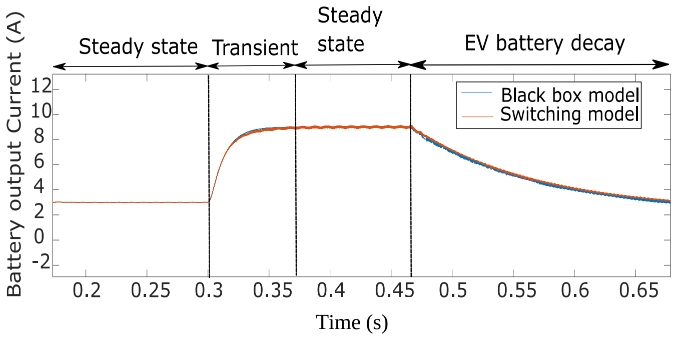

Fig. 13: Step from Grid to Battery (DC part)

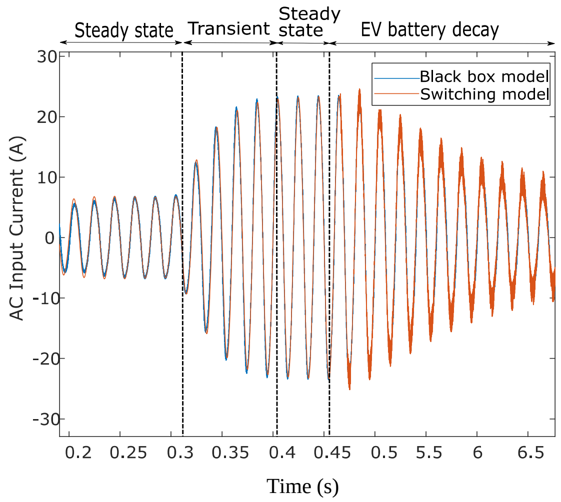

Fig. 14: Step from Grid to battery (AC part)

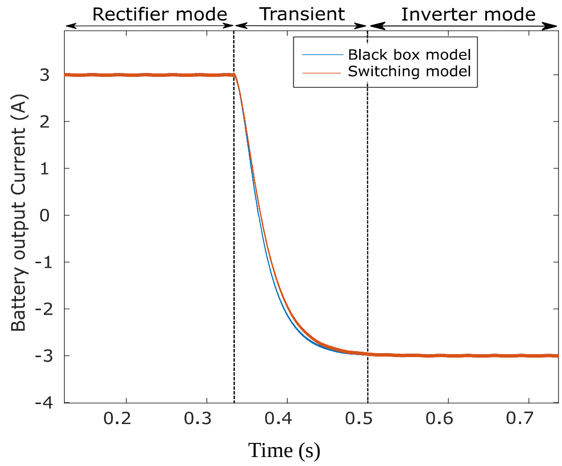

Fig. 15: Direction test (DC part)

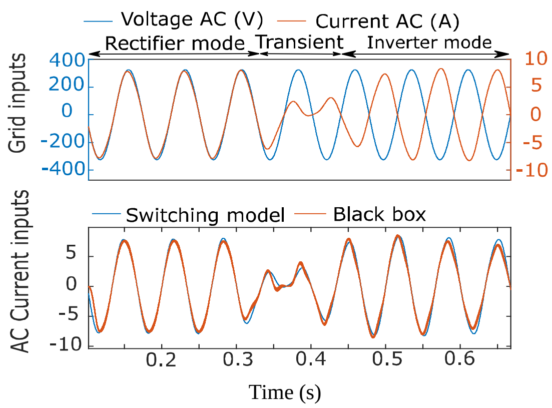

Fig. 16: Direction test (AC part)

proposed in this paper.

V. CONCLUSIONS

Summing up, this research is focusing on the implementation of a black box model of a bidirectional battery charger of EVs and working in system level on micro-grids. Firstly, a detailed switching model is designed using PSIM software. By using this model as the actual converter, a number of tests applied and using the input-output information a black box model is generated. This black box model is implemented in MATLAB. The input and output signals of the circuit were used for identification and then were tested with different examples for verification. The results obtained show that the black box implemented in MATLAB operates as the actual system used as a reference. At the same time, the model may be used to assess the impact of a number of Bidirectional Battery Chargers in micro-grids.

REFERENCES

[1] European Commission. Renewable energy progress report Brussels, 16 June 2015. "Renewable energy progress report." [Online]. Retrieved from http://europa.eu/rapid/press-release_MEMO-15-5181_en.htm

[2] Vishnu Mahadeva Iyer, Srinivas Gulur and Subhashish Bhattacharya, "Small-signal modeling and stability analysis of a bidirectional electric vehicle charger," 2017 IEEE 6th International Conference on Renewable Energy Research and Applications (ICRERA), 5-8 Nov. 2017.

[3] Vishnu Mahadeva Iyer, Srinivas Gulur and Subhashish Bhattacharya, "Variable DC bus control for a bidirectional on-board electric vehicle charger," 2017 IEEE 6th International Conference on Renewable Energy Research and Applications (ICRERA), 5-8 Nov. 2017.

[4] E. Elbakush and A. M. Sharaf, "A FACTS Based Hybrid Filter Compensator (HFC) for H2V Battery Charging Schemes," International Journal of Renewable Energy Research-IJRER, Vol.3, No.2, 2013.

[5] Enes Ugur and Bulent Vural, "Comparison of different small signal modeling methods for bidirectional DC-DC converter," 2014 International Conference on Renewable Energy Research and Application (ICRERA), 19-22 Oct. 2014.

[6] V. Lavanya and N. Senthil Kumar, "A Review: Control Strategies for Power Quality Improvement in Microgrid," International Journal of Renewable Energy Research-IJRER, Vol.8, No.1, March, 2018.

[7] Shinichiro Hattori, Haruhi Eto and Fujio Kurokawa, "High Power Density Battery Charger for Plug-In Micro EV," International Journal of Renewable Energy Research-IJRER, Vol.8, No.2, June, 2018.

[8] A. Rodríguez, A. Vázquez, D. G. Lamar, M. M. Hernando and J. Sebastian, "Different Purpose Design Strategies and Techniques to Improve the Performance of a Dual Active Bridge with Phase-Shift Control," IEEE Transactions on Power Electronics, vol. 30, Issue: 2, pp. 790 – 804, Year: 2015.

[9] S. Zeljkovic, R. Vuletic, A. Miller and A. Denais, "Control of SiC-based dual active bridge in high power three phase on-board charger of EVs," in 2015 International Conference on Electrical Systems for Aircraft, Railway, Ship Propulsion and Road Vehicles (ESARS), 2015, pp. 1-6.

[10] W. Shen, T. Tu Vo and A. Kapoor, "Charging algorithms of lithium-ion batteries: An overview," in 2012 7th IEEE Conference on Industrial Electronics and Applications (ICIEA), 2012, pp. 1567-1572.

[11] O. Erdinc, B. Vural and M. Uzunoglu, "A dynamic lithium-ion battery model considering the effects of temperature and capacity fading," in 2009 International Conference on Clean Electrical Power, 2009, pp. 383 - 386.

[12] Asma Mlayah and Adel Khedher, "Sliding Mode Control Strategy for Solar Charging of High Energy Lithium Batteries," International Journal of Renewable Energy Research-IJRER, Vol.8, No.3, September, 2018.

[13] Alfonso Damiano, Claudia Musio and Ignazio Marongiu, "Experimental validation of a dynamic energy model of a battery electric vehicle," 2015 International Conference on Renewable Energy Research and Applications (ICRERA), 22-25 Nov. 2015.

[14] Nazmus Sakib, Jakir Hossain, Eklas Hossain and Ramazan Bayindir, "Modelling and Simulation of Natural Gas Generator and EV Charging Station: A Step to Microgrid Technology," International Journal of Renewable Energy Research-IJRER, Vol.7, No.1, 2017.

[15] N. Akel, M. Pahlevaninezhad and P. Jain, "A D-Q rotating frame reactive power controller for single-phase bi-directional converters," in 2014 IEEE 36th International Telecommunications Energy Conference (INTELEC), 2014, pp. 1-5.

[16] J. Sjöberg, Q. Zhang, L. Ljung, A. Benveniste, B. Delyon, P.-Y. Glorennec, H. Hjalmarsson and A. Juditsky, "Nonlinear black-box modeling in system identification: a unified overview," Science direct, vol. 31, Issue: 12, pp. 1691-1724, Dec. 1995.

[17] N. Patcharaprakiti, K. Kirtikara, D. Chenvidhya, V. Monyakul and B. Muenpinij, "Modeling of Single Phase Inverter of Photovoltaic System Using System Identification," in 2010 Second International Conference on Computer and Network Technology, 2010, pp. 462-466.

[18] D. Boroyevich, R. Burgos, L. Arnedo and F. Wang, "Synthesis and integration of future electronic power distribution systems," in Proc. IEEE Power Conversion Conf., April 2007, pp. K–1–K–8.

[19] S. Vesti, T. Suntio, J. A. Oliver, R. Prieto and J. A. Cobos, "Impedance based stability and transient-performance assessment applying maximum peak criteria," IEEE Trans. Power Electron., vol. 28, no. 5, pp. 2099– 2104, May 2013.

[20] Galo Guarderas, Airán Francés, Rafael Asensi and Javier Uceda, "Large-signal black-box behavioral modeling of grid-supporting power converters in AC microgrids," 2017 IEEE 6th International Conference on Renewable Energy Research and Applications (ICRERA), 5-8 Nov. 2017.

[21] MathWorks, "System Identification Toolbox User's Guide," p. 1164, 2016, accessed 14 Sep. 2017. [Online]. Available:https://es.mathworks.com/help/pdf_doc/ident/ident.pdf.