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Francisco Javier Rocha-Henríquez
Instituto Tecnológico de Canarias, S.A., Las Palmas de Gran Canaria, Span

Ricardo Aguasca
Universidad de Las Palmas de Gran Canaria

Máximo Méndez
Universidad de Las Palmas de Gran Canaria

Patricia Rivera Rodríguez

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Analysis of a lead-acid battery storage system connected to the DC bus of a four quadrants converter to a microgrid

A. F. J. Rocha-Henríquez[1], B. J.M. Cabrera-Peña[2], C. R. Aguasca-Colomo[3], D. M. Méndez-Babey[3] and E. P. Rivera-Rodríguez[2]

[1] Department of Renewable Energy
Instituto Tecnológico de Canarias, (ITC S.A.)
Playa de Pozo Izquierdo, s/n, 35119 Santa Lucía, Las Palmas (Spain)
Phone/Fax number:+0034 928 727500, e-mail A.: **jrocha@itccanarias.org**,

[2] Instituto Universitario de Microelectrónica Aplicada (IUMA), Universidad de Las Palmas de Gran Canaria (ULPGC)
Phone/Fax number:+0034 928 457322, e-mail B.: **jose.cabrera@ulpgc.es,** e-mail E.: **patriciariverarodriguez@gmail.com**,

[3] Instituto Universitario de Sistemas Inteligentes y Aplicaciones Numéricas en Ingeniería (IUSIANI), Universidad de Las Palmas de Gran Canaria (ULPGC)
Phone/Fax number:+0034 928 451264, e-mail C.: **ricardo.aguasca@ulpgc.es**, e-mail D.: **maximo.mendez@ulpgc.es**

Abstract.

The main problem found in the implementation of small microgrids where consumption is based on a certain number of loads (8,326,369 KWh total in the Canary Islands in 2017) [1] is the great variability of obtaining energy (361,1 MWh total in 2017) from renewable sources, the most important in the Canary Islands being wind and photovoltaic [2]. For these microgrids to be feasible and their power flows to be as constant as possible they must contain storage means, so that this energy can be used to stabilize the microgrid by compensating the irregularities of renewable energy sources [3], using them to perform regulation of voltage and frequency. In this sense, the batteries degrade very quickly when having to perform this type of highly dynamic efforts.

The purpose of this paper is to make a model of lead-acid battery and investigate the possibilities of application that the use of these batteries could have in the field of renewable energy. Specifically in the simulation of power electronics and control of back-to-back converters that allows to analyze, in different ranges of applications in a microgrid system of Pozo Izquierdo, where the following measurements have been made.

Key words

Back-to-Back converter, microgrid and modelling lead-acid batteries.

1. Introduction

The designed system, consisting of the following elements of a power electronics system, (Fig. 1), are two bidirectional four-quadrant AC/DC and DC/AC converters. The use of double-quadrant converters known as Back-to-Back converters stands out in the field of small and medium power synchronous generators that operate in a very variable speed regime, such as wind generators. In this type of applications it is common to use an AC/DC conversion stage to transform the energy generated from alternating current into direct current, as a preliminary step to DC/AC transformation, in the same way for its coupling to an electrical system with a fixed frequency and voltage [4].

The DC bus is the energy "store" of the inverter, normally accessible at the terminals. The scheme is simplified and only a battery and capacitor appears to minimize the ripple of the current from the Complete Three-Phase Switch Bridge, since in reality there are more elements to stabilize the energy, therefore, the converter, in its DC Bus has to work between a maximum and a minimum voltage [5].

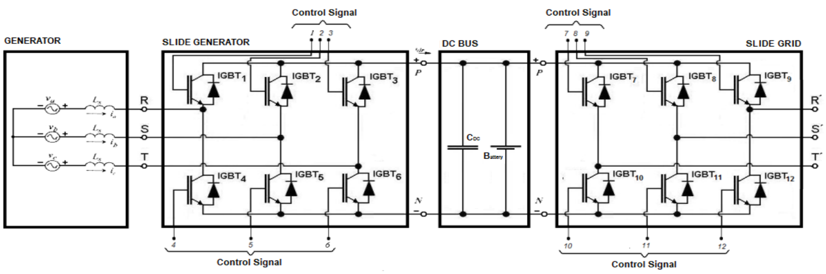

Fig. 1. Schematic system with bidirectional converter AC/DC and DC/AC.

2. DC Bus modelling and simulation

Although accumulators are a widely used element in a large number of high and low power applications, they are still difficult to control, due to the fact that the electrochemical reactions that govern their behaviour are very complex. This is why it is necessary to model the accumulators, to control to some degree the performance of the battery and foresee its evolution both in the short and long term, under different working conditions

The great versatility of application of the batteries means that they can be subjected to a wide range of operating conditions. For this reason, to carry out the modeling of this electrochemical system, first of all, it is necessary to know its main characteristics and how they are affected by the working conditions in which it is carried out.

A lead-acid battery has several features that provide information about it, which can be divided into three groups:

1) *Physical magnitudes* directly measurable on the battery,
2) *Characteristics* to be determined on the basis of laboratory tests,
3) *Indicators that can only be estimated on the basis of other magnitudes of the accumulator belonging to the two previous groups.*

Within the physical magnitudes that can be measured in the accumulator are the voltage, current, temperature and density of the electrolyte. The characteristics to be determined by laboratory tests are: capacity, internal resistance, and frequency response; and finally, the indicators to be estimated correspond to the electrolyte density:

1) *State of Charge (SoC)*
2) *State of Health (SoH).*

The accumulator characteristics directly measurable magnitudes have the particularity of being measured directly from the battery, by means of specialized sensors for this purpose. They correspond to: voltage, current, temperature, and density of the electrolyte ([6]-[9]).

While the magnitudes of the accumulators obtained through experimental tests, the characteristics of the energy accumulators to be determined were analyzed: Capacity, internal impedance and frequency spectrum. The frequency spectrum of an accumulator provides information on the status of the accumulator [10]. This information is related to battery characteristics, such as SoC, SoH, temperature, life cycles, among other parameters [11]. The frequency response of the accumulator is determined by the technique called Electrochemical Impedance Spectroscopy (EIS) [12]. This technique involves applying a sinusoidal voltage of variable frequency to the system under study and recording its current response. Once this has been done, the impedance at the given frequency is determined as the quotient between the applied voltage and the current measured at the output, where the time lag is not taken into account as this value is despicable.

A. DC Bus Modelling Development

The adaptation to the PSIM simulation program will be done by means of the integral method of the current. This method consists of recording by means of sensors, the incoming or outgoing current of the accumulator bed and integrating it to estimate the capacity that has been extracted. Once this is done, the SoC is determined [13] by the equation (1):

$$SoC = SoC_0 - \frac{1}{C_N}\int_{t_0}^{t} I d\tau \tag{1}$$

Where, C_N corresponds to the nominal capacity of the accumulator and I corresponds to the input/output current. Commonly to the expression (1), a coulombic efficiency factor is added (n_i), for which it is transformed into the expression given by (2):

$$SoC = SoC_0 - \frac{1}{C_N}\int_{t_0}^{t} n_i \cdot I d\tau \tag{2}$$

Where n_i=1 for charging and ni<1 for discharging. The algorithm corresponds to a closed control loop, in which the accumulator affects the plant of the system, which has two inputs, the first of them conforms to the real SoC, and the second to the input/output accumulator current. It should be noted that the actual SoC is the result of the sum of the SoC determined by the integral of the current and the output of the feedback. Finally, it should be noted that the system reference corresponds to the voltage at the battery terminals. In summary, this algorithm tries to correct the errors due to the integral of the current, using a control system, which contributes to improve the accuracy of the SoC based on keeping the output of the plant equal to the reference. The algorithm thus formulated, is compared with the conventional method of integral current, resulting in more immune to noise and errors in initialization [14].

The advantages of this approach are that its implementation requires few computational resources in comparison with other methods ([15]-[16]), in addition to being able to be used in real time, and finally, its development has been done with real data generated by a programmable load. The disadvantage of this study is that it does not take into account the effects of temperature on the system, and it does not use an efficiency factor in the integral of the current (n_i).

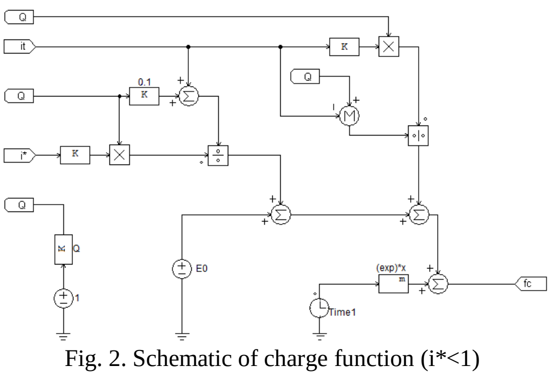

Fig. 2. Schematic of charge function (i*<1)

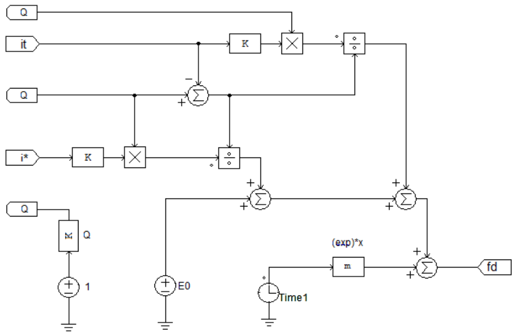

Fig. 3. Schematic of the discharge function (i*>1)

B. *Validation of the battery model for the DC Bus*

We have applied to our theoretical model ([17]-[19]) conditions equivalent to those used in the tests carried out in the ITC's Power Electronics laboratory. Specifically, a constant current source of about 38.9 A for the load and an electronic load equivalent to a constant discharge of 40 A. In the equivalent model applied at the time of charging (Fig. 2), there is a series current source with an equivalent resistance of the wiring used to carry energy to the lead-acid battery bank. Applying the voltage equivalent to that used in the charge and discharge tests to the DC bus gives the curve (Fig. 4).

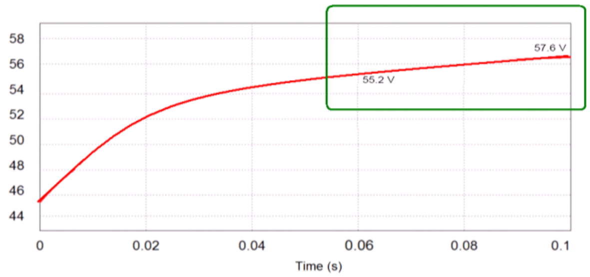

Fig. 4. Simulation of the battery bank charge curve.

The curve was obtained by modifying the system so that the simulation could be carried out in a reasonable time, observing that it is practically identical to the real one during the loading process. As for the discharge (Fig. 3), when performing the simulation under conditions that would allow the time scale to be reduced, the result can be seen in the following curve (Fig. 5), where it is also observed that it is quite close to the real measurements.

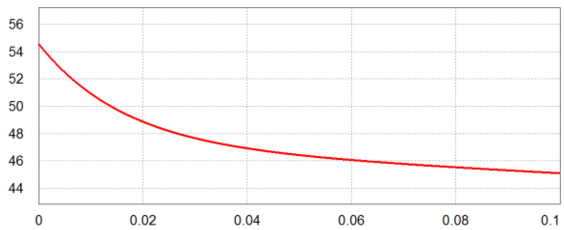

Fig. 5. Simulation of the discharge curve of the battery bank.

C. *Simulation of the Double Quadrant Converter*

It is assumed that the control system of the double quadrant converter will modify the voltage to adapt to the level of load required on the DC Bus. The simplified model is shown in next figure (Fig. 6)

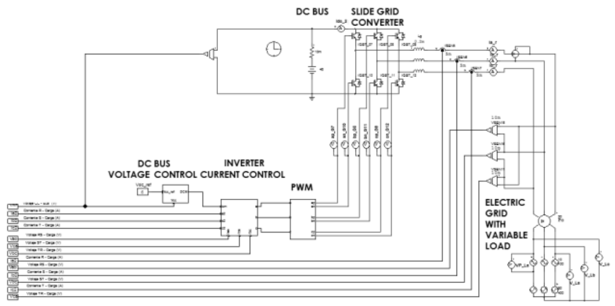

Fig. 6. Controlled three-phase rectifier with automatic correction of Power Factor and total harmonic distortion

With the battery bank completely discharged, the voltage present at the DC bus input, Vdc (Fig. 7).

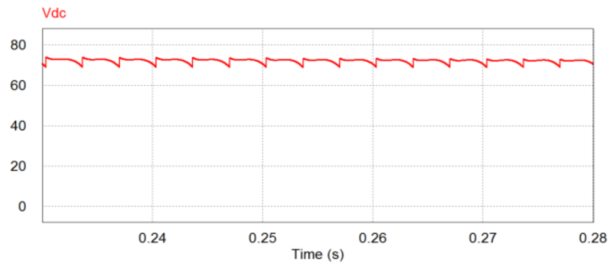

Fig. 7. Voltage present on DC bus with discharged battery bank

At the same time interval, the charge current has the next waveform (Fig. 8). The average current is about 64 A under these conditions. Next, the average current, starting from the totally charged battery bank (Fig. 9-10).

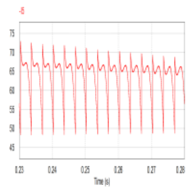

Fig. 8. Charging current on the DC bus.

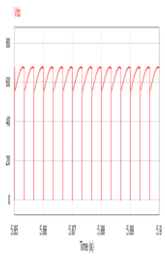

Fig. 9. Voltage present at DC bus input with fully charged battery bank

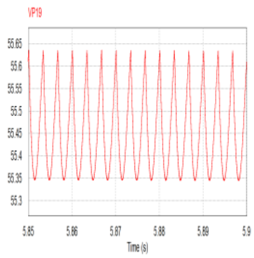

Fig. 10. Detail of the voltage present in the terminals of the battery bank once it is fully charged.

In this time interval the voltage between phases at the output of the converter remains constant, and to compensate for the voltage loss, more and more current is requested from the DC bus (Fig. 11).

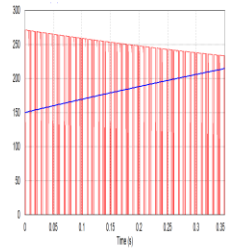

Fig. 11. In red, the instantaneous current demanded from the DC bus is observed, while in blue, the average current.

Note that in simulations, the capacitor is simply for filtering the ripple signal on the DC bus.

3. Conclusion

In the DC bus, below the minimum voltage, the converter cannot supply the necessary power to the grid, and the low voltage alarm appears in the converter control system. Above the maximum voltage, the converter would be supplying too much power to the grid. In most cases, a high voltage on the DC bus indicates that the grid is supplying power to the converter, i.e. the grid does not work as a consumption, but as it is functioning as an electrical generator.

The battery bank operates correctly in the proposed system and maintains the intended voltage once fully charged. Both in the charging process and in the discharge process, it can be observed that the battery bank coupled to the double quadrant converter are capable to store enough energy to maintain for a certain time period by charging the operation of the entire system. This period of time depends on the working frequency of the slide grid which is usually more or less constant. This system would support up to micro power failure<1sec.

References

[1] "Gross production, availability and consumption of electrical energy by Canary Islands and periods", Canary Islands Statistics Institute (ISTAC), URL: http://www.gobiernodecanarias.org/istac/jaxi-istac/tabla.do.

[2] "Energy information on the Canary Islands". Web Local Energy Management Agency of Las Palmas de Gran Canaria. URL: https://energialaspalmasgc.es/informacion-energetica-canarias/

[3] A. F. J. Rocha, B. J. Cabrera, C. R. Aguasca, D. A. Vega, E. M. Méndez and F. J. Torres "Back-to-Back converters. State of the art", ICMEPE-2016, 11 July 2016, pp. 1–4, reference of the paper:149-16-rocha.

[4] A. T. Friedli, B. S. D. Round, C. D. Hassler and D. J. W. Kolar, "Design and Performance of a 200-kHz All-SiC JFET Current DC-Link Back-to-Back Converter", IEEE Transactions on Industry Applications, Vol. 45, Número 5, September 2009, pp.1868- 1878. **DOI:** 10.1109/TIA.2009.2027538

[5] "DC-Link Voltage Balancing Strategy Based on SVM and Reactive Power Exchange for a 5L-MPC Back-to-Back Converter for Medium-Voltage Drives", IEEE Transactions on Industrial Electronics, Vol: 63, Issue: 12, December 2016, pp. 7864– 7875. DOI: 10.1109/TIE.2016.2580128

[6] A. E. Bianchi, "Elementos de electroquímica: Electrolisis y acumuladores reversibles," Course Notes, University of Chile, Santiago, Chile (2008), pp. 1-67

[7] A. D. G. Murillo, "Modelamiento y análisis de sistemas fotovoltaicos", Doctoral Thesis, Polytechnic University of Catalonia, Barcelona (2003), p.p 1-97

[8] A. B. Severino, "Modelación de un sistema fotovoltaico y un banco de baterías de plomo ácido como elementos de una micro-red", Thesis civil engineer degree electrician, University of Chile, Santiago (2011), pp. 1-45.

[9] A. G. L. Plett, "Extended Kalman filtering for battery management systems of LiPB-based HEV battery packs Part 1. Background", Journal of Power Sources, vol. 134, pp. 252–261, 2004. DOI: 10.1016/j.jpowsour.2004.02.031

[10] A. A. Shafiei, B. A. Momeni and C. S. Williamson, "Battery modeling approaches and management techniques for Plug-in Hybrid Electric Vehicles", Vehicle Power and Propulsion Conference (VPPC), 2011 IEEE, pp. 1- 5, 2011. DOI: 10.1109/VPPC.2011.6043191

[11] A. V. Esfahanian, B. A. Babak Ansari, C. H. Bahramian, D. P. Kheirkhah and E. G. Ahmadi, "Design parameter study on the performance of lead-acid batteries", Springer Journal of Mechanical Science and Technology, June 2014, pp. 2221-2229. DOI: 10.1007/s12206-014-0123-5

[12] A. A. Bogomolova, B. E. Komarova, C. K. Reber, D. T. Gerasimov, E. O. Yavuz, F. S. Bhatt and G. M. Aldissi "Challenges of Electrochemical Impedance Spectroscopy in Protein Biosensing", 2009 American Chemical Society, 13 April 2009, pp. 3944-3949. DOI: 10.1021/ac9002358

[13] A. R. M. S. Santos, B. C. L. G. de S. Alves, C. E. C. T. Macedo, D. J. M. M. Villanueva, E. L. V. Hartmann and F. S.Y.C. Catunda, "Lead Acid Battery SoC Estimation Based on Extended Kalman Filter Method Considering Different Temperature Conditions", in Proc. IEEE International Instrumentation and Measurement Technology Conference, 7 July 2017, pp. 1-6. DOI: 10.1109/I2MTC.2017.7969966

[14] A. Haoting Wang, B. Fan He and C. Lin Ma "Experimental and modeling study of controller-based thermal management of battery modules under dynamic loads", Elsevier Ltd,. International Journal of Heat and Mass Transfer, 11 July 2016, pp. 154–164, DOI: 10.1016/j.ijheatmasstransfer.2016.07.041

[15] A. R. A. Jackey, "A Simple, Effective Lead-Acid Battery Modeling Process for Electrical System Component Selection" The MathWorks, Inc, 2007, pp. 1-9. URL: https://es.mathworks.com/company/newsletters/articles/

[16] A. Xin Zhao and B. Raymond A. de Callafon, "Modeling of battery dynamics and hysteresis for power delivery prediction and SOC estimation", Elsevier Ltd., Applied Energy, 7 August 2016, pp. 823–833. DOI: 10.1016/j.apenergy.2016.08.044

[17] A. Ingemar Kaj and B. Victorien Konané, "Modeling battery cells under discharge using kinetic and stochastic battery models", Elsevier Ltd., Applied Mathematical Modelling, 31 March 2016, pp. 7901–7915. DOI: 10.1016/j.apm.2016.03.049

[18] A. Bing Liu, B. Wangwang Yu, C. Yueqiang Jin, and D. Shuying Wang, "Study on residual discharge time of lead-acid battery based on fitting method", AIP Publishing, May 2017, pp. 020008-1–020008-5, DOI: 10.1063/1.4982373

[19] A. J. M. Lujano-Rojas, B. G. J. Osório, C. T. D. P. Mendes, Covilha and J. P. S. Catalão, "Stochastic modeling of lead-acid battery parameters", IEEE, September 2016, pp. 1-5, INBN: 978-1-5090-4650-8