Measurement: Sensors 18 (2021) 100079

Contents lists available at ScienceDirect

Measurement: Sensors

journal homepage: www.sciencedirect.com/journal/measurement-sensors

Online sweep frequency analysis testing on UPS for resilience

ARTICLE INFO

Keywords
Resilience
SFRA
Lead-acid battery
Monitoring

ABSTRACT

Resilience in the context of power systems involves several aspects of design, control, and monitoring. The uninterruptible power sources (UPS) are mostly adopted for several applications, to prevent data loss, to temporary power providing for mission-critical and safety-critical systems, like medical devices or strategical systems. The most adopted solution is still to use lead-acid batteries. The monitoring of the status of the battery pack in UPS, in which the pack is maintained charged for a long time, is of interest, to prevent catastrophic failures due to the unexpected battery fault. In this paper, the application of the SFRA online is proposed for the evaluation of the UPS performance, as a first step for the proposal of a resilience-oriented monitoring methodology. The testing system and some experimental results are presented and discussed.

1. Introduction

Resilience in the context of power systems involves several aspects of design, control, and monitoring. Generally, resilience can be explained as the ability of a system to return to its original configuration and performance after a stressful event. In electrical engineering, resilience is obtained if a power system can recover quickly after a disaster, or if it is also able to anticipate negative and critical events, even low-probable [1].

By limiting our attention on the service continuity, the uninterruptible power sources (UPS) are mostly adopted for several applications, to prevent data loss due to power quality phenomena affecting office power systems, up to the temporary power providing for mission-critical and safety-critical systems, like medical devices or strategical systems.

In applications in which the mass and dimensions of the batteries are not critical, the most adopted solution is to use lead-acid batteries. In fact, despite the increasing development of new typologies of batteries, the Compound Annual Growth Rate (CAGR) of the global lead-acid battery market is projected to grow at a Compound Annual Growth Rate (CAGR) of 5.2% from USD 65.57 billion in 2019 to USD 99.10 billion in 2027 [2]. Usually, small and medium-size UPS are equipped with packs of lead-acid batteries, whose performance has an impact on the reliability of the power system; the research devoted to increase the performance and reduce the cost of UPS has been deepened in recent years [3].

The monitoring of the status of the battery pack in UPS is of interest for several goals; firstly, in absence of interruptions the pack is maintained charged for a long time, so no information about the health of the pack can be evaluated during the charging and discharging processes as in automotive applications, and it is possible that the UPS could fail because of an unexpected lack of batteries power. Moreover, the battery pack itself can create a fire risk, so a UPS can turn in a catastrophic event source [4,5].

Different methodologies for battery monitoring have been proposed and investigated [6,7]. In this paper, we are mostly concerned with the proposal of a new technique, based on an evolution of the sweep frequency response analysis (SFRA) [8,9] to be applied to online or active devices. In previous research activities, the testing system has been applied to induction motors grid-connected, and to domestic power systems, for fault analysis and noninvasive load monitoring, with satisfactory results [10,11]. The testing system will be adopted to acquire transfer functions (TF) with the SFRA approach, on a commercial small-size UPS, with a sealed 12V lead-acid battery; the proposed technique allows the monitoring of the battery in all the actual conditions, with the UPS linked to the grid, with or without a load, and during a fault in which it is supplying the load. The obtained results will be adopted as a first reference TF set for further monitoring applications.

2. The online sweep frequency analysis and the testing system

The goal of the Frequency Response Analysis is to obtain data about the features of the system under test at different frequency values, to be processed in comparison with reference transfer functions, of the same device in health conditions, or other apparatuses with comparable features [8].

The SFRA testing method allows the user to perform verifications with low-cost devices, by high reliability and good repeatability of the obtained data. It is non-destructive because the applied voltages are in the range of few volts, so the tests can be repeated several times, without appreciable stress on the devices under test.

In standard conditions, the testing device generates signals at variable frequency, usually in the range of 20 Hz - 2 MHz; narrower bands can be adopted to investigate deeply the behavior of the tested devices [12,13]. The obtained TF are compared qualitatively and numerically, with reference TF by means of correlation indexes. Information can be obtained from the phase shift functions, too.

As a reference, the proposed technique is based on requirements in

https://doi.org/10.1016/j.measen.2021.100079

Available online 17 September 2021

the IEC 60076-18 standard [14] describing the tests, the performance of the instruments to be adopted, the connections, and the data analysis.

A Digilent Analog Discovery 2 NI Edition development board equipped with an Analog Discovery BNC Adapter Board is the core element of the system, with two differential input channels, 14-bit resolution, input range ±25 V, 30 MHz bandwidth, 100 MSamples/s; it is also used to generate the test signal, with an output channel at ± 5 V, 20 MHz bandwidth, 100 MS/s [10].

Unlike in standard SFRA procedures, in which the device under test is turned off and disconnected, in the proposed approach, it is working, so decoupling is needed; the two input channels and the signal generator channel are connected to one third-order Butterworth-type third-order bandpass filter each. The band is in the range 2 kHz - 2 MHz, symmetrical; it is important to stop the harmonics from the mains, at least up to the 40th to avoid faults, and to reduce the noise during the test.

The test system can be programmed to generate signals with a variable frequency. Usually, a first wideband swept is to be performed, and if a narrower band portion is to be investigated, it is possible to define a new testing band accordingly, in terms of frequency range and resolution. The test duration can vary from few seconds to 1 min and a half.

A USB socket is used to connect the testing system to the host PC, that runs the measurement and control application developed in the NI LabVIEW environment. Its main tasks are i) the settings of the frequency ranges, and the number of samples to be generated and acquired in each of them, ii) the simultaneous generation of the test signal and the acquisition of the voltages on the device under test, iii) the processing of the magnitude and phase spectrum for the definition of the transfer functions (TF), iv) the data visualization and saving on the ROM.

For the after processing, some apps have been developed to compare the TF, acquired on the same device in different load conditions, or on a set of devices of the same features, to have a statistical characterization.

3. The UPS under test

The UPS that has been tested, in this early stage of the research, is a standard 1800 VA, 400 W, 220–240 V, 50–60 Hz model, to be adopted for PC and similar devices for home or office applications. It can supply for 8 minutes a load at 50%, or 5 minutes for a load at 75%. The charging time is typically 6–8 hours after a complete discharge. The adopted battery is a sealed lead-acid unit, 7 Ah at 12 V, with standby use voltage 13.5–13.8 V, cycle use voltage 14.4–14.7 V, initial current 2.1 A at 20 °C.

The UPS shell has been modified, by placing ad additional switch that allows the opening of the battery, to perform the SFRA analysis on the battery only if needed.

In Fig. 1, the test system is depicted, with respect to the block diagram of the UPS.

The UPS has been tested with new and healthy batteries, at different charge statuses, and with used batteries with low residual performance.

4. Experimental results

The experimental results, proposed in this paper, have been obtained with the configuration in Fig. 2. As a load, a series of three 47ohm power resistors has been used, for a total of 375 W at 230 V.

The status of the battery has been checked with a Fluke BT521 battery tester, that allows automatic or manual sequence testing of a single battery, and battery stacks, with automatic measurement of voltage, temperature, and resistance; this measurement is performed with an AC current injection, lower than 100 mA at 1kHz, with a typical accuracy of 1% [15].

The first characterization has been performed with the UPS with a used battery, in good conditions, that has been adopted for about 100 hours, without full discharge. Its parameters measured with the BT521 before the test are: 12.98 V, internal resistance 26 mΩ at 21 °C.

In Fig. 3 four TF have been presented; the first is obtained by testing

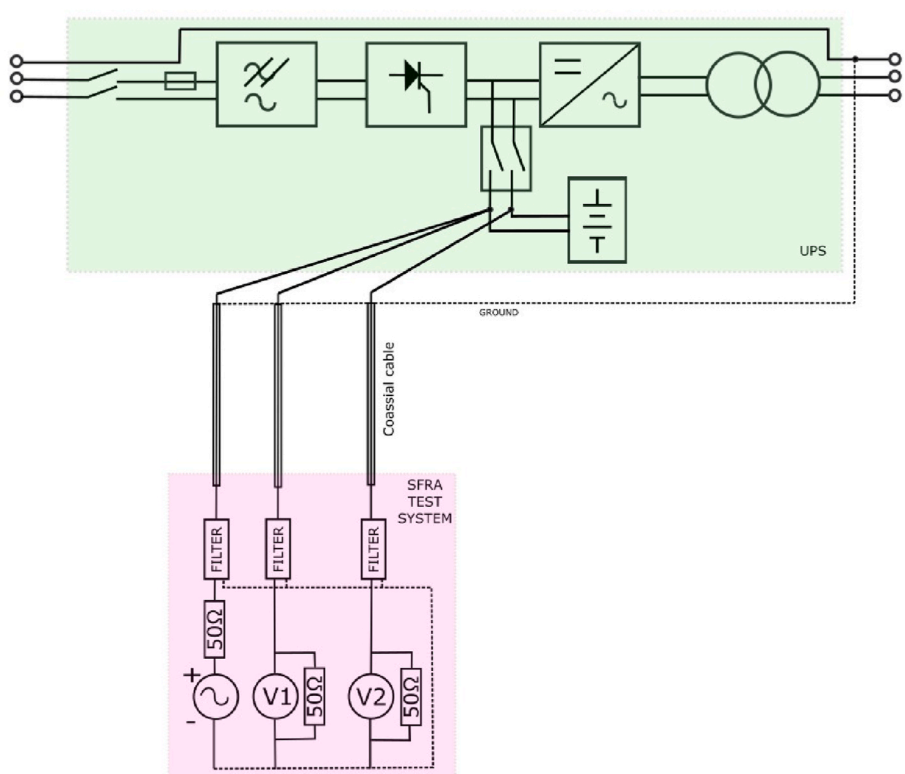

Fig. 1. Block diagram of the test system linked to the UPS.

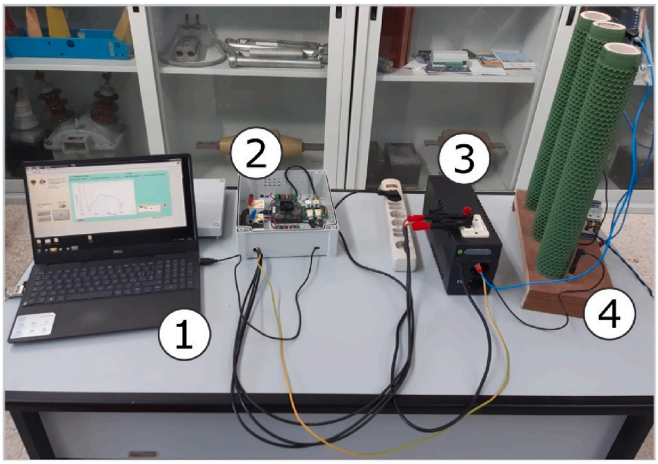

Fig. 2. Experimental test configuration: 1) host Pc running the measurement app; 2) test system; 3) UPS under test; 4) load resistors.

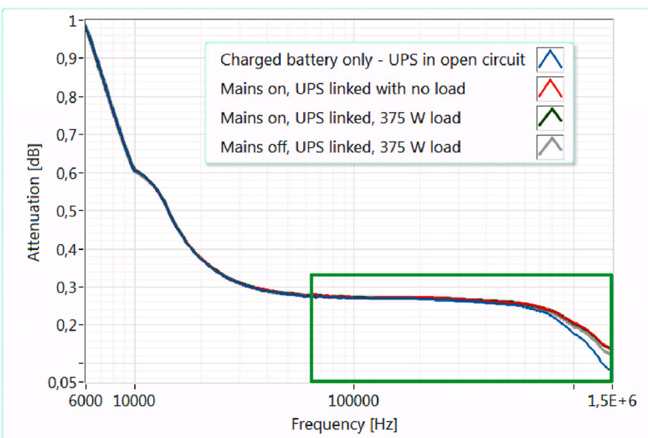

Fig. 3. TF on the UPS in various working conditions, frequency range 6 kHz–1.5 MHz.

the lead-acid battery only. The second is on the UPS with mains on, without load; the third with the mains on, the UPS supplying a 375 W load, and the last is with the mains off, with the UPS supplying the same load. The test has been carried out in a wide band, from 6 kHz to 1.5 MHz.

The results show that, with a healthy battery, there is no appreciable difference among the conditions with mains on and off; only for the frequencies higher than 150 kHz the behavior seems to change. For this reason, the same test has been repeated, with a narrower band and higher resolution, in the range 150 kHz - 2 MHz. The new results are in Fig. 4.

The TF with the lead-battery alone can be easily identified, while the other ones are very close. It suggests the possibility of using these TF as a reference for the UPS in good conditions.

A second test has been performed with a medium-aged battery, of the same type and manufacturer, that have been in service for one year, without total discharge. Its parameters measured with the BT521 before the test are: 13.26 V, internal resistance 56 mΩ at 20 °C.

The test has been performed to compare the TF, in the frequency range 150 kHz–2 MHz, with the mains on, and the UPS supplying the 375 W load, and the UPS with mains off, after 2 minutes and after 4 minutes of supplying. The results are in Fig. 5.

The shape variation is appreciable, and it should be investigated in further tests, with a set of batteries with different age conditions. It is important to underline that the online SFRA performs the analysis of the

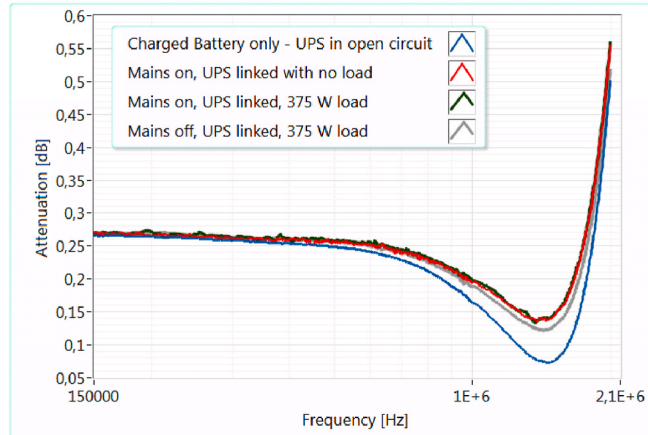

Fig. 4. TF on the UPS in various working conditions, frequency range 150 kHz–2 MHz.

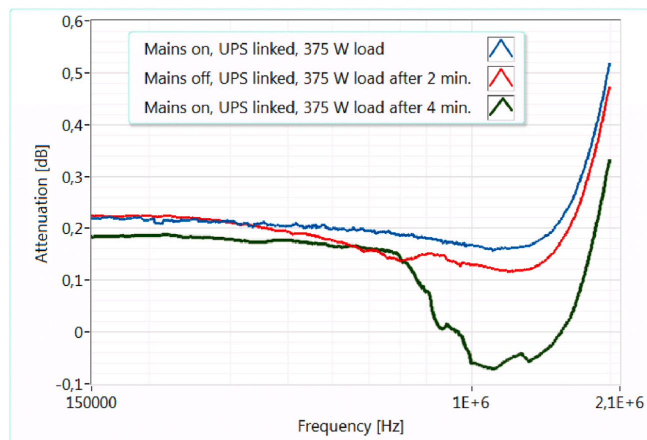

Fig. 5. TF on the UPS with a medium-aged battery, supplying the load with mains off, after 2 and 4 minutes.

while UPS system, so the obtained TF can be related to the features and working point of all the electrical network.

The last experimental data proposed in this paper shows the comparison between the TF of the UPS, with a new battery and with a faulty one, of the same type and manufacturer; the parameters measured on the new battery before the test are: 13.5 V, internal resistance 26 mΩ at 20 °C. The faulty one, before the test, was at 10.7 V, internal resistance 216.2 mΩ at 21 °C.

The TF are in Fig. 6; they have been obtained with the UPS supplying the load, and the mains off. The conditions with main off could not be acquired for the UPS with faulty battery because it turned off immediately after the mains switched off.

The effect of the faulty battery is clear; the TF seems to be shifted down with no other effects, on to the extended frequency range. This is a promising result, because it could be adopted for resilience application on UPS installed to be only in power backup service. In these conditions, the UPS battery is always in charge, but no information are available of its internal status because of the lack of periodical discharge. The online SFRA could be investigated to be adopted to monitor the TF of the UPS system; if an appreciable variation in the TF is observed, the maintenance can be programmed. This approach will be the goal of further research activities.

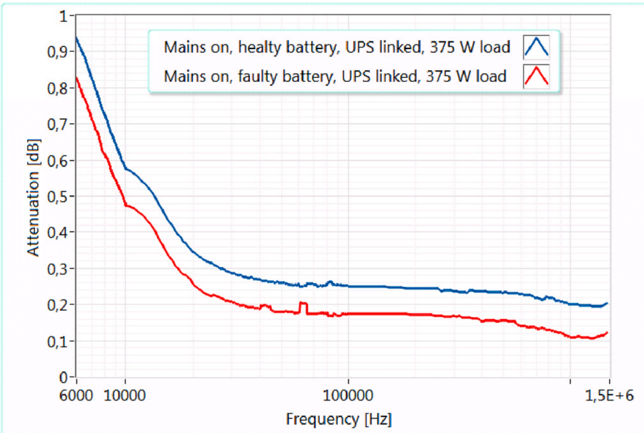

Fig. 6. TF on the UPS supplying a load, with a healthy and faulty batteries.

5. Conclusions

Resilience in the context of power systems involves several aspects of design, control, and monitoring. Generally, resilience can be explained as the ability of a system to return to its original configuration and performance after a stressful event.

The uninterruptible power sources (UPS) are mostly adopted for several applications, to prevent data loss, to temporary power providing for mission-critical and safety-critical systems, like medical devices or strategical systems. If there are no special requirements in terms of mass or sizes, the most adopted solution is still to use lead-acid batteries packs. The monitoring of the status of a battery pack in a UPS, in which it is maintained charged for a long time, is of critical interest, to prevent catastrophic failures due to an unexpected battery fault. In this paper, the application of the SFRA online has been proposed for the evaluation of the UPS performance, as a first step for the proposal of a resilience-oriented monitoring methodology [16].

The first experimental results seem to be promising, so the online SFRA could be adopted for resilience application on UPS installed to be only in power backup service. In these conditions, the UPS battery pack is always in charge, and no information are available of its internal status because of the lack of periodical discharge. The online SFRA could be investigated to be adopted to monitor the TF of the UPS system; if an appreciable variation in the TF is observed, the maintenance can be programmed. This approach will be the goal of further research activities, in which a statistical evaluation on a large set of batteries will be performed.

References

[1] M. Panteli, P. Mancarella, The grid: stronger, bigger, smarter?: presenting a conceptual framework of power system resilience", IEEE Power Energy Mag. 13 (3) (2015) 58–66, https://doi.org/10.1109/MPE.2015.2397334, art. no. 7091066.

[2] Lead acid battery market size, share, Growth & analysis by products (stationary, motive, SLI), by construction methods (VRLA, flooded), by applications (motive industrial, stationary industrial, residential, commercial, others), by regions (North America, Europe, APAC and MEA) and segment forecasts to 2027. https://www.reportsanddata.com/report-detail/lead-acid-battery-market.

[3] J. Xu, X. Dong, D. Dai, C. Shi, W. Li, Y. Xiang, Battery pack construction scheme based on ups system reliability, Advances in Intelligent Systems and Computing 1141 (2021) 725–733, https://doi.org/10.1007/978-981-15-3383-9_65.

[4] Z. Li, Z. Wang, L. Wang, Discussion of the relationship between failure and fire of valve regulated lead acid battery, E3S Web of Conferences 185 (2020), https://doi.org/10.1051/e3sconf/202018501058 art. no. 01058.

[5] G.I. Smelkov, V.A. Pekhotikov, A.I. Ryabikov, A.A. Nazarov, To the issue of accumulator batteries fire safety, Bezop. Tr. Prom.-Sti. 2020 (5) (2020) 56–62, https://doi.org/10.24000/0409-2961-2020-5-56-62.

[6] J. Loukil, F. Masmoudi, N. Derbel, A real-time estimator for model parameters and state of charge of lead acid batteries in photovoltaic applications, Journal of Energy Storage 34 (2021), https://doi.org/10.1016/j.est.2020.102184 art. no. 102184.

[7] W. Li, M. Rentemeister, J. Badeda, D. Jöst, D. Schulte, D.U. Sauer, Digital twin for battery systems: cloud battery management system with online state-of-charge and state-of-health estimation, Journal of Energy Storage 30 (2020), https://doi.org/10.1016/j.est.2020.101557 art. no. 101557.

[8] G. Bucci, F. Ciancetta, A. Fioravanti, E. Fiorucci, A. Prudenzi, Application of SFRA for diagnostics on medical isolation transformers, Int. J. Electr. Power Energy Syst. 117 (2020), https://doi.org/10.1016/j.ijepes.2019.105602 art. no. 105602.

[9] G. Bucci, F. Ciancetta, A. Fioravanti, E. Fiorucci, A. Prudenzi, Improving the power system safety in hospitals by means of periodical sfra tests on medical isolation transformers", Renewable Energy and Power Quality Journal 18 (2020) 282–286, https://doi.org/10.24084/repqj18.300, art. no. 300.

[10] G. Bucci, F. Ciancetta, E. Fiorucci, Apparatus for online continuous diagnosis of induction motors based on the SFRA technique, IEEE Transactions on Instrumentation and Measurement 69 (7) (2020) 4134–4144, https://doi.org/10.1109/TIM.2019.2942172, art. no. 8843945.

[11] A. Fioravanti, A. Prudenzi, G. Bucci, E. Fiorucci, F. Ciancetta, S. Mari, Non Intrusive Electrical Load Identification through an Online SFRA Based Approach, 2020, pp. 694–698, https://doi.org/10.1109/SPEEDAM48782.2020.9161856, 2020 International Symposium on Power Electronics, Electrical Drives, Automation and Motion, SPEEDAM 2020, art. no. 9161856.

[12] D. Gallo, C. Landi, M. Luiso, E. Fiorucci, G. Bucci, F. Ciancetta, A method for linearization of optically insulated voltage transducers, WSEAS Trans. Circuits Syst. 12 (3) (2013) 91–100.

[13] E. Fiorucci, G. Bucci, A low-cost contactless transducer for the measurement of dc currents up to 13 kA for the industry of anodized aluminum, IEEE Transactions on Instrumentation and Measurement 62 (4) (2013) 845–852, https://doi.org/10.1109/TIM.2013.2245186, art. no. 6472290.

[14] IEC 60076-18:2012 Power Transformers - Part 18: Measurement of Frequency Response.

[15] S.-L. Wu, H.-C. Chen, M.-Y. Tsai, AC impedance-based online state-of-charge estimation for li-ion batteries, Sensor. Mater. 30 (3) (2018) 539–550, https://doi.org/10.18494/SAM.2018.1824.

[16] F. Ciancetta, E. Fiorucci, D. Gallo, C. Landi, M. Luiso, A Web Service interface for a distributed measurement system based on decentralized sharing network, Sensors and Transducers 153 (6) (2013) 209–218.

Giovanni Bucci, Fabrizio Ciancetta, Andrea Fioravanti, Edoardo Fiorucci*, Simone Mari, Andrea Silvestri
Dept. of Industrial and Information Engineering and Economics, University of l'Aquila, L'Aquila, Italy

* Corresponding author.
E-mail address: edoardo.fiorucci@univaq.it (E. Fiorucci).