J Inf Process Syst, Vol.13, No.6, pp.1487~1495, December 2017
https://doi.org/10.3745/JIPS.01.0020

ISSN 1976-913X (Print)
ISSN 2092-805X (Electronic)

JOURNAL OF INFORMATION PROCESSING SYSTEMS JIPS

Designing Test Methods for IT-Enabled Energy Storage System to Evaluate Energy Dynamics

Young Gon Kim*, Dong Hoon Kim*, and Eun-Kyu Lee*

Abstract

With increasing interests in renewables, more consumers are installing an energy storage system (ESS) in their backyards, and thus, the ESS will play a critical role in the emerging smart grid. Due to mechanical properties, however its operational dynamics must be well understood before connecting the ESS to the smart grid (and eventually to an IT system). To this end, we investigate charging and discharging processes in detail. This paper, then, proposes methods for four type tests (state of charge test, conversion efficiency test, response time test, and ramp rate test) that can assess the dynamics of the ESS. The proposed methods can capture accurate delay values of mechanical processes in the ESS, and it is expected for those values to help design real-time communication systems in the smart grid involving the ESS.

Keywords

Converged IT Service, Cyber-Physical System, Energy Dynamics, Energy Storage System, Microgrid, Test Method, Smart Grid

1. Introduction

Energy (or power), just as other resources like water [1], has been one of critical resources that enables human activities in a modern society and in Information Technology (IT) area, in particular. In this sense, many research has tried to tackle issues of how to manage power in a variety of computer systems and networks [2,3]. A smart grid is emerging as a future model of smart infrastructure that integrates mechanical and electrical devices with IT technologies and communication capabilities. That is, the smart grid becomes a representative example of a cyber-physical system (CPS). With growing penetration of renewables such as solar panels in the smart grid, the importance of an Energy Storage System (ESS) also increases. Due to sensitive mechanical characteristics in ESS, its operational dynamics must be well tested and monitored when connecting it to the smart grid. For instance, an energy management system must be capable of monitoring whether charging and discharging processes run as expected and of evaluating the probability of its mechanical failures. However, few research examined test methods considering operational properties in detail. This paper proposes methods of four type tests (state of charge test, conversion efficiency test, response time test, and ramp rate test) that can assess the dynamics of the ESS system. The proposed methods can be used to understand the system's

Manuscript received March 28, 2017, first revision June 16, 2017; accepted July 1, 2017.
Corresponding Author: Eun-Kyu Lee (eklee@inu.ac.kr)
* School of Information Technology, Incheon National University, Incheon, Korea ({hyper1003, dhkim85, eklee}@inu.ac.kr)

operational processes and thus to help design real-time communication models.

The rest of this paper is organized as follows. Section 2 provides an overview of the ESS system, and Section 3 discusses issues in ESS testing and performance. Section 4 designs four test methods that can evaluate energy dynamics of the ESS system. We conclude this paper in Section 5.

2. Energy Storage System in Smart Grid

An ESS is a set of devices where the physical process of energy storing takes place. In most real-world applications, this process relies on the principles of electrical (capacitors), electrochemical (batteries) or mechanical (flywheels). A power converter, in deployment, is needed in most cases of grid-connected energy storage between a power grid and an energy storage. The converter may be a single converter or a distributed conversion system. Also, there is a transformer between the grid and the ESS system. A storage management system continues to monitor and control the state of the physical energy storage; it is often called Battery Management System (BMS) in case of battery and redox flow battery. An Energy Management System (EMS) performs high-level controls that determine the system's functionality—when and at what rate the system is charged, discharged, or stayed on idle. Based on local measurement (e.g., voltage, current, power, and frequency) and external data, this happens locally with minimal response times (milliseconds and below). Fig. 1 shows a general block diagram of the ESS system. The figure also includes some peripheral components; for instance, a cooling system, liquid pump, or vacuum pumps. Consequently, the ESS system include all components needed to make the system perform as required.

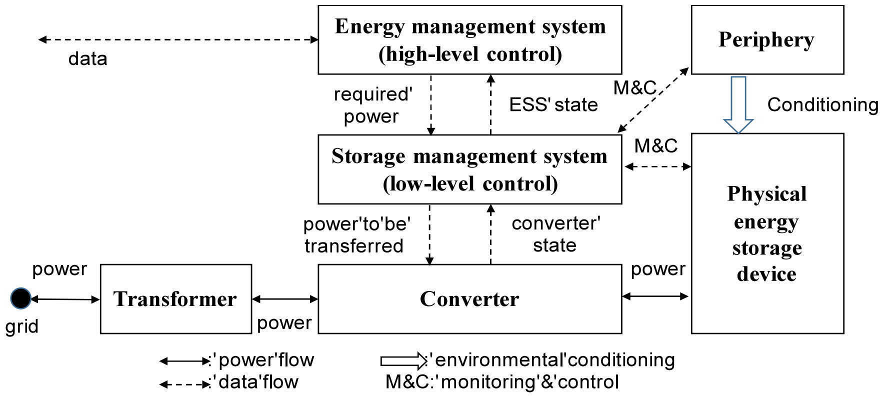

Fig. 1. A block diagram of an EES system shows EES device, converter, auxiliaries and management system. We note that a transformer may not be present, especially for small systems.

The ESS system has been and will be applied to a variety of smart grid applications [4,5]. Below introduces a list of applications groups.

- *Bulk energy service*: An energy storage is used to store energy that may be available at another, more convenient time. In an electrical energy time-shift application, for instance, the ESS is charged with cheap energy and discharged when the price for electricity is high.

- *Ancillary service*: An ancillary service supports the power grid by providing a continuous flow electricity and matching supply and demand. The ESS system also provides start-up power after a total blackout. Load following, regulation, frequency response, and spinning, non-spinning and supplemental reserve are in this category of service.
- *Transmission infrastructure service*: The ESS system plays as a role of energy buffer in a transmission infrastructure service; reducing power congestion and/or defer transmission grid upgrades. Transmission congestion relief and transmission upgrade deferral are two representative applications.
- *Distribution infrastructure service*: The ESS system acts as an energy buffer also in a distribution infrastructure; mainly deferring distribution grid upgrades.
- *Customer energy management service*: A customer energy management service enhances the power quality, improves reliability and/or realizes additional profits for a customer. Demand charge management is also considered as the customer related service.
- *Renewables integration*: The ESS system is often integrated with renewables for some applications described above. In an electrical energy time-shift operation, for instance, the ESS system provides a means to obtain a more stable energy output from renewable sources. This improves the predictability of renewable energy supply to the power grid.

3. ESS Testing and Performance Issues

An ESS is a single unit with full functionalities or a set of elementary units each of which has a specific function. Each unit in ESS should go through tests so as to ensure its proper functionality. From the power grid operation point view, test results can be used to assess whether unique parameters of ESS satisfy requirements for planning and operations. When an ESS is discharged, energy is transferred from the ESS to a power grid. Thus, a grid operator must pay attention to capability of ESS such as synchronization, active power ramping, and abnormal responses. When the ESS is in a state of charge, the operator must continue monitoring such parameters that can influence the grid such as power quality and response to abnormal condition. Test methods for ESS in the smart grid include type test, production test [6], installation test [7], commissioning test, and periodic test. Fig. 2 shows the test overview for the ESS system.

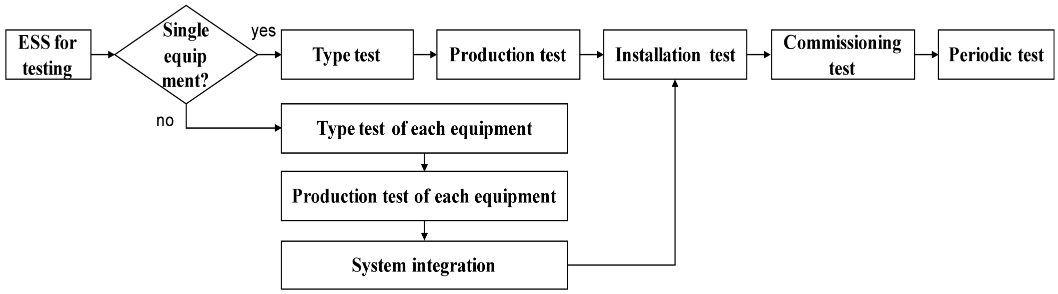

Fig. 2. Each unit in ESS goes through a sequence of tests (from type test to periodic test) to ensure that it operates as expected.

- *Type test* is mainly used to validate ESS design principles. If the ESS consists of several different units, the type tests must be performed on each unit, depending on its function. If the critical nature of the ESS changes, and it can affect the performance of the ESS, the type test must be re-performed. These characteristics includes design, manufacturing process, components, materials, and firmware.
- *Production test* of power grid-applied ESS must be performed before delivery. If the ESS is configured with other units, it should be tested for each unit according to the specific function of each unit.
- *Installation test* includes grounding, isolation, monitoring and fault response of ESS which should be evaluated before commissioning test.
- *Commissioning test* should be performed when operation is ready. If any changes have been made to the software, hardware or firmware, additional type tests must be performed prior to the commissioning test. Commissioning test includes insulation, synchronization, unintentional islanding test, stop charging and discharging function test, etc.
- *Periodic test* ensures that all interconnection-related functions and associated batteries function after a certain period of operation. In the case of modification of the ESS software or firmware or modification, replacement and/or repair of the hardware units, corresponding type test for the relevant unit should be performed. Periodic test includes charge status, response time, ramp rate, harmonic test, etc. Out of them, this paper focuses on the type test.

A performance issue of an ESS system has been considered as a technology- and application-agnostic black box. Performance indicators, however, may be application-specific. Performance indicators, thus, must be carefully defined so that they are widely used for evaluating ESS applications. A list of technical reports and standards categorizes indicators under five categories: power, energy, dynamics, efficiency, and reliability [8].

4. Design of Type Test Methods for ESS Dynamics

When integrating with IT technology the ESS system represents a cyber-physical system. Thus, performance of an ESS system must be well examined and understood in a holistic point of view; a cyber system must be able to process data representing mechanical characteristics in energy dynamics. In this sense, this section designs methods for four integral tests—state of charge test, conversion efficiency test, response time test and ramp rate test.

4.1 State of Charge Test

A state of charge test does not only measure the actual storage capacity of the energy storage battery pack, but also evaluate the accuracy of charging quantity addressed by the BMS.

(1) Connect the measuring device to the common coupling point between the ESS and power grid.
(2) The test ESS should be discharged to the minimum SoC specified by manufacturer.
(3) Record the amount of charge until the maximum SoC specified by manufacturer is reached based on the condition and steps of charge.

(4) Record the amount of discharge until the minimum SoC specified by manufacturer is reached based on the condition and step of discharge.
(5) Calculate the difference between charging quantity and discharging quantity.

Because of the conversion loss, charging quantity and discharging quantity may not be equal and charging quantity should be higher.

(6) Calculate the charging quantity deviation and discharging deviation with follow formulas, respectively.

$$\frac{\overline{C_c}-C_{stated}}{C_{stated}} \times 100\% \quad (1)$$

$$\frac{\overline{C_d}-C_{stated}}{C_{stated}} \times 100\% \quad (2)$$

$\overline{C_c}$ and $\overline{C_d}$ means the average value of charging and discharging quantity respectively and C_{stated} means the capacity stated by the manufacturer.

4.2 Conversion Efficiency Test

The power conversion system (PCS) is one of the major part of ESS. AC and DC conversion between the ESS and the AC grid is realized by PCS. This test is to evaluate the energy conversion efficiency of the PCS. Since the conversion efficiency may vary depending on the rated level, it should be performed separately when the input power is 100%, 80%, 60%, 40%, 20%.

4.2.1 Inverter mode

Fig. 3. Inverter mode of the PCS for evaluating the DC to AC power conversion efficiency.

(1) As shown in Fig. 3, set the PCS as inverter mode which converts DC input power to AC output power, according to the specification provided by the manufacturer.
(2) With the input and output voltage of PCS set to its nominal value, adjust the input power until the output power of PCS reaches the rated level.
(3) Measure the input voltage (V_{dc}), input current (I_{dc}) and output power (P_o), respectively.
(4) Calculate the input power with follow formula $P_{in} = V_{dc} \times I_{dc}$.
(5) Calculate the efficiency $\eta = \overline{P}_o/\overline{P}_{in}$ where $\overline{P}$ means the averaged value.

4.2.2 Converter mode

Fig. 4. Converter mode of the PCS for evaluating the AC to DC power conversion efficiency.

(1) As shown in Fig. 4, set the PCS as converter mode which converts AC input power to DC output power, according to the specification provided by the manufacturer.
(2) With the input and output voltage of PCS set to its nominal value, adjust the input power until the output power of PCS reaches the rated level.
(3) Measure the input power (P_{in}), output voltage (V_{dc}) and output current (I_{dc}), respectively.
(4) Calculate the input power with follow formula $P_o = V_{dc} \times I_{dc}$.
(5) Calculate the efficiency $\eta = \overline{P}_o / \overline{P}_{in}$ where $\overline{P}$ means the averaged value.

4.3 Response Time Test

A response time test aims to measure how quickly an ESS system reacts upon receiving a control command, and consists of two subparts: discharging and charging. Two annotation symbols for this test are used: $SoC_1 = SoC_{min} + (SoC_{max} - SoC_{min})$ x 80% and $SoC_2 = SoC_{min} + (SoC_{max} - SoC_{min})$ x 20%. A discharging response time measures the time at which the output power of the ESS reaches the rated power. The test results are used to evaluate the discharge response capability.

4.3.1 Procedure for discharging response time test

An ESS systems to be tested (test system) is set to be the SoC_1 that is determined by the manufacturer and stay in a stand-by. A data collection interval in the test system must be adjusted by less than half of the value of the full rated power divided by the discharging slope climbing rate. During the discharging process (when the status of the system changes from active stand-by to full-rated power), at least one test point must be obtained.

A remote control system (it could be a local one) sends out a command signal that is to test communication delay. Record this moment as t_0. Upon receiving the signal, the test system replies with a feedback signal. When the control system receives the signal, it records the moment as t_{rec} (or t_1). Then, compute the communication delay Δt_{CL} using the following formula: $\Delta t_{CL} = (1/2)t_{rec} = t_1$. The control system, then, sends out another command signal that is to trigger the discharging process. Upon receiving the signal, the test system performs the process and records the time (t_3) at which the output power reaches and stabilizes at the rated power with deviation within ±2%. Fig. 5 shows the sequence of recorded moments. The following formula calculates the discharging response time t_R. $t_R = t_3 - t_1$. Reset the test system to SoC_2 determined by the manufacturer, and active stand-by. Then, repeat step 2 to 4.

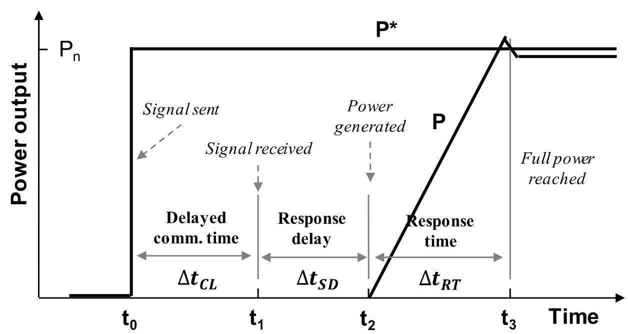

Fig. 5. Schematic figure of discharging response time test.

4.3.2 Procedure for charging response time test

A charging response time measures the time at which the output power of the ESS rises to its rated power. The remote control system sends out a command signal for charging to the test system that now triggers a charging process. With new contexts, repeat the procedure above (for discharging test).

4.4 Ramp Rate Test

A ramp rate test measures the maximum charging and discharging rate that the ESS system can reserve or release. The charging and discharging processes are tested separately because the charging / discharging characteristics of the battery pack are different. *P* represents an actual output power of the test system.

4.4.1 Common (preliminary) procedure for ramp rate test

(1) Place a measuring device at an electrical connection point between the test system and a power grid.

(2) Start the test system, and it stays in active stand-by.

(3) A remote-control system (it could be a local one) sends out a command signal that is to test communication delay. Record this moment as t_0. Upon receiving the signal, the test system replies with a feedback signal. When the control system receives the signal, it records the moment as t_{rec} (or t_1). Then, compute the communication delay Δt_{CL} using the following formula: $\Delta t_{CL} = (1/2)t_{rec} = t_1$. A test procedure for discharging ramp rate is as follow. Send a power control message to the test system. The measuring device records the increasing process of active power when the test system releases energy to the grid.

(4) Adjust the test system at 50% discharging state and run it at least for five minutes so as for it to be on a stable mode. Send out a power control signal to the test system that then discharges itself at full rated power P_n of PCS.

(5) Record the time when the test system starts discharging (t_2) and compute the response delay using the following formula: $\Delta t_{SD} = t_2 - \Delta t_{CL}$.

(6) Record the time (t_3) and the stable state (P_m) when the test system stabilizes at P_m with deviation within ±2%. Then, the following formula calculates the ramp time of actual output power (Δt_{RT}): $\Delta t_{RT} = t_3 - \Delta t_{CL} - \Delta t_{SD}$.

(7) Now, the discharging ramp rate of the test system is calculated as the ratio of stable state to the ramp time as: $R = P_m / \Delta t_{RT}$.

4.4.2 Test procedure for charging ramp rate

For charging ramp test, go through step 1 to 3 described above, first. Then, jump to step 4 below and continue to testing.

(1) Set the test system at 50% charging state. Send out a power control signal to the test system and charge it at full rated power P_n of PCS.

(2) Monitor the actual power P and record the time when the test system starts charging (t'_2) and compute the response delay as the following formula: $\Delta t'_{SD} = t'_2 - \Delta t'_{CL}$.

(3) Keep monitoring P and record the time (t'_3) and the stable state (P'_m) when the test system stabilizes with deviation within ±2%. Then, the following formula calculates the ramp time of actual output power ($\Delta t'_{RT}$): $\Delta t'_{RT} = t'_3 - \Delta t'_{CL} - \Delta t'_{SD}$.

(4) Calculate the charging ramp rate of the test system as follows: $R' = P'_m / \Delta t'_{RT}$.

5. Conclusions

With increasing concerns of cyber-physical systems (connecting physical or mechanical processes to IT systems), it is necessary to understand the dynamics occurring in the physical processes and to accommodate them when designing IT systems. In this paper, we have examined intrinsic properties of mechanical operations (charging and discharging) in the ESS system. Based on the investigation, then, this paper proposed methods of four type tests (state of charge test, conversion efficiency test, response time test and ramp rate test) that could assess the dynamics of the ESS. The methods are able to capture accurate delay values of mechanical processes; it is expected for them to help design real-time communication systems.

We note that this paper addresses type tests, while the ESS units go through a sequence of tests as shown in Fig. 2. This implies that there are still room for improvement for the full set of test methods. One interesting research question to tackle in terms of testing performance is “how to reduce the number of test processes while not scarifying the ESS system’s performance?” Simplifying test processes or performing tests in parallel could be solutions that we can examine further. We leave the question as one of future research topics.

Acknowledgement

This work was supported by the Energy Efficiency & Resources Core Technology Program of the Korea Institute of Energy Technology Evaluation and Planning (KETEP) granted financial resource from the Ministry of Trade, Industry & Energy, Republic of Korea (No. 20162010103900).

References

[1] M. Lee, “Design of an intelligent system for autonomous groundwater management,” *Journal of Convergence*, vol. 5, no. 1, pp. 26-31, 2014.

[2] A. Pughat and V. Sharma, “A review on stochastic approach for dynamic power management in wireless sensor networks,” *Human-centric Computing and Information Sciences*, vol. 5, article no. 4, 2015.

[3] S. Maity and J. H. Park, “Powering IoT devices: a novel design and analysis technique,” *Journal of Convergence*, vol. 7, article ID. 16071001, 2016.

[4] X. Luo, J. Wang, M. Dooner, and J. Clarke, “Overview of current development in electrical energy storage technologies and the application potential in power system operation,” *Applied Energy*, vol. 137, pp. 511-536, 2015.

[5] A. A. Akhil, G. Huff, A. B. Currier, B. C. Kaun, D. M. Rastler, S. B. Chen, A. L. Cotter, D. T. Bradshaw, and W. D. Gauntlett, “DOE/EPRI 2013 electricity storage handbook in collaboration with NRECA,” Sandia National Laboratories, Livermore, CA, *Sandia Report SAND2013-5131*, 2013.

[6] *IEEE Standard Conformance Test Procedures for Equipment Interconnecting Distributed Resources with Electric Power Systems*, IEEE Standard 1547.1-2005.

[7] *IEEE Recommended Practice for Emergency and Standby Power Systems for Industrial and Commercial Applications*, IEEE Standard 446-1995.

[8] IEC 60050 International Electrotechnical Vocabulary [Online]. Available: http://std.iec.ch/iev/iev.nsf.

Young Gon Kim https://orcid.org/0000-0003-0562-7964

He received M.S. degree in Electrical Engineering from Myungji University in 1996. He had been in the energy industry for more than 10 years, where he had been involved in a few research and development projects. He joined Incheon National University as a senior researcher in 2016. His current research interests include energy management system and energy storage system.

Dong Hoon Kim https://orcid.org/0000-0003-1431-8776

He received B.S and M.S. degrees in Information and Telecommunication Engineering from Incheon National University in 2011 and 2013, respectively. He is now pursuing a doctoral degree at the same institution. His current research interests include microgrid communication and radar signal processing.

Eun-Kyu Lee https://orcid.org/0000-0003-1459-5458

He is an assistant professor in the Department of Information and Telecomm. Engineering of Incheon National University (INU). Before joining INU, he had worked for Symantec Research Labs (LA, USA) and Electronics and Telecommunications Research Institute (Daejeon, Korea) for several years. He has been involved in many research projects in the fields of smart grid, smart building, electric vehicle network, location-based services, and Telematics. He received M.S. and Ph.D. degrees in Computer Science from the University of California, Los Angeles in 2011 and 2014, respectively. His research interest includes Internet of Things, cyber-physical systems, wireless networks, cybersecurity and privacy, and pervasive physical computing.