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学 位 論 文 題 目

Study on Electric and Hydrogen Hybrid Energy Storage System for Improving Performance of Reliable and Sustainable Supply of High Quality Power

高品質電力の長時間安定供給能力の向上を目指した
電力・水素複合エネルギー貯蔵システムに関する研究

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論 文 内 容 要 約

Because of the booming demands of the reliable and sustainable supply of the high quality power against long-time outages for the essential infrastructures such as water purification plants, this research proposed the establishment method of a reliable and sustainable EPS technology. This EPS adopts the conception of the HESS, which was proposed for utilization of renewable power generation in former researches.

Chapter 2 investigated the conception and configuration method of the proposed EPS using the HESS. The initial conception of the HESS was introduced at first. The HESS consists of high-response-speed electric energy storage and large-energy-capacity hydrogen system to satisfy the high response speed and large capacity demand at the same time. The hydrogen system consists of fuel cell (FC), electrolyzer (EL), and hydrogen storage. In order for the EPS application, in the ordinary time, the HESS should utilize the real-time fluctuating PV power generation and public grid power input, maintain sufficient energy reserve while keeping reliable power to the load consumption. When the power outage happens, the HESS can mostly utilize the PV power and supply sustainable high-quality power to the load consumption. The basic energy dispatch method of this HESS used Kalman filtering prediction algorithm. This research took the Moniwa water purification plant, which experienced the outage over than three days in the Great East Japan Earthquake, as the specified research object. Hence, this chapter investigated the configuration of the HESS in order for the EPS in the water purification plant, by a pre-simulation using recorded 1-year PV power data and load data. Fig. 1 shows the view of a 20-kW model system, which was designed and fabricated based on the simulation results.

However, the former researches only achieved the short-time demonstration of the HESS on the utilization of the PV power generation. To achieve the establishment of the EPS for the reliable and sustainable supply of the high quality power using the HESS, there are several issues requiring solutions:

1) During the long-time fluctuation compensation work of the HESS, the state-of-charge (SOC) of the electric energy storage should be maintained within the permitted working range. Otherwise, the work of the electric energy storage and the entire HESS would break off. However, the appropriate control method on the SOC was not established.
2) Since the HESS has to run alone as the EPS during the long-time power outage, the sufficient hydrogen energy reserve needs to

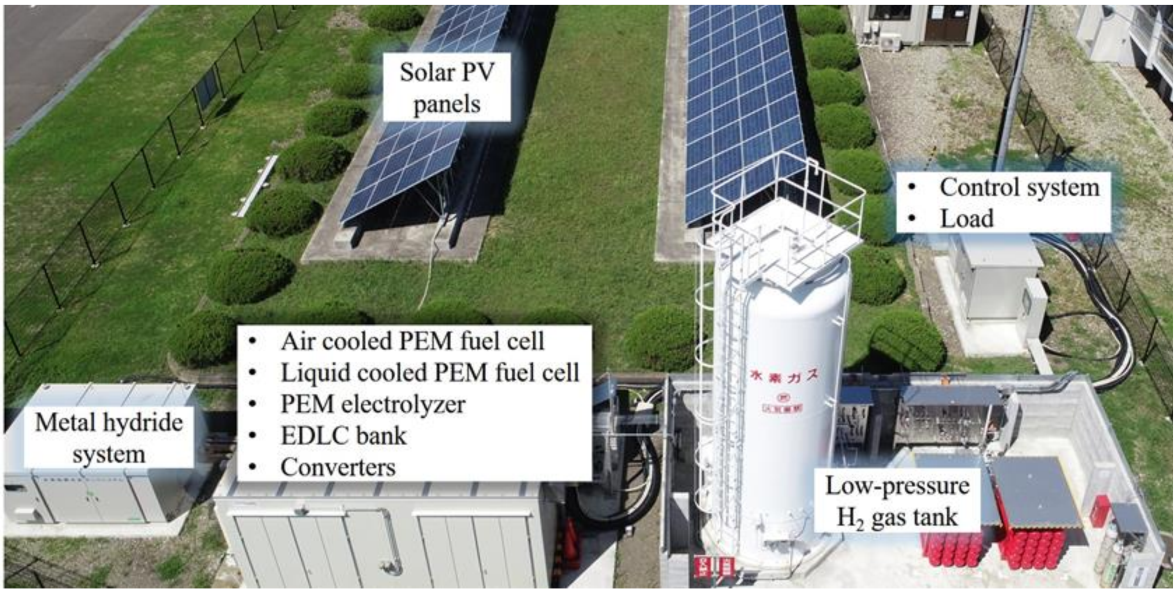

Fig. 1 View of the 20-kW model EPS system using electric and hydrogen hybrid energy storage system

be maintain in the ordinary time. However, the appropriate control method on the hydrogen reserve was not established yet.

3) Hydrogen metal hydride (MH) tank has large volume hydrogen gas storage density and is usually used as connected to the FC directly. However, the gas flow regulation of the MH tank is low. If the instant power of the FC gets high and the required gas supply gets high, the MH tank can hardly maintain the required gas supply.

4) Inside the HESS, the auxiliary power and the energy loss takes a quite large part. Such as the auxiliary power for the heat supply to the MH tank, in order for the hydrogen gas supply from the MH tank. In the ordinary time, the auxiliary power can be supplied from the public grid or other systems. However, during the emergency operation of the HESS, the auxiliary power costs the energy reserve, and influence the long-time power supply to the load consumption.

5) The FC power should be regulated to satisfy the fluctuation compensation. However, during the long-time running of the HESS, the power variation and the open circuit voltage (OCV) state would led to the early performance degradation of the FC cell stack. Thus, the running has to be paused for the FC cell stack exchange, and the long-time continuous running cannot be achieved.

Against the issues above, we investigated the system configuration and control methods as followings:

Chapter 3 discussed the appropriateness of different electric energy storages to the HESS, by the quantitative evaluation on the power compensation accuracy and real-time SOC estimation accuracy of different electric energy storages. The Superconducting Magnet Energy Storage (SMES), lithium-on battery (LiB), and electric double-layer capacitor (EDLC) are the three most possible candidates, because of their outstanding power characteristics. At first, a novel control method of the SMES was proposed, to solve the problem of temperature rise in the SMES coil with the former control method. Then a demonstration verified the proposed threshold control method on solving the continuous temperature rise in the SMES coil, and achieved the 20-minute continuous operation of the

HESS using the SMES. After then, demonstration of the HESS with the SMES, LiB and EDLC were operated respectively, in order to compare their power fluctuation compensation performance and their SOC estimation accuracy. The results showed that the fluctuation compensation performance of the SMES is limited by its immature control technologies, and the real-time SOC estimation accuracy of the LiB is disadvantageous because its flat voltage characteristic. Thus, the most appropriate electric energy storage should be EDLC at the present stage. In the future, it is necessary to evaluate the appropriateness of difference electric energy storage against different system scales and configuration.

Chapter 4 investigated the management of the SOC of the EDLC and the hydrogen energy reserve, in order for the long-time continuous operation of the HESS and the highly accurate power fluctuation compensation by it. Against the only Kalman filtering prediction control and the EDLC SOC feedback control method based on the proportional control, this thesis firstly proposed the structure of the entire system control. This system control structure realized the management of the hydrogen energy by regulation of the public grid power input before the Kalman filtering prediction control, and realized the management of the EDLC SOC by minor regulation of the energy dispatch inside the HESS. To realize the accurate management of the hydrogen gas reserve, this research took the real-time running states and efficiencies of the FC and EL into consideration. On the side of the EDLC feedback control method, we improved the control by introducing an extra integral control. This integral control makes the varying auxiliary power and system loss can be accurately compensated. To verify the proposed control methods, a simulation of the HESS ordinary running was operated. The running results showed that the hydrogen energy reserve and the EDLC SOC were correctly and stably managed, by the proposed control methods. Then an experimental demonstration of the HESS emergency running was operated. The running results showed that the high-quality power supply can be achieved while the EDLC SOC was correctly managed. Comparing the EDLC SOC with the proposed EDLC SOC feedback control method, the former one, and without control, the results showed that the newly proposed method has the better ability on management of the EDLC SOC. In the future, it is necessary investigate the method of the control parameter settings, according to different system scales and the specified practical conditions.

In Chapter 5, the hybrid use of the buffer gas tank with the MH tank, and the FC waste heat utilization were proposed. These proposals are in order for the sufficient hydrogen gas supply and the decrease in the auxiliary power in the HESS, for reliable and sustainable power supply. An experimental demonstration to verify the validness of the buffer gas tank and the FC waste heat utilization was operated. By the buffer gas tank, the sufficient hydrogen gas supply to the FC was achieved even the hydrogen gas release from the MH tank was late. Meanwhile, by the FC waste heat utilization, the MH tank released sufficient hydrogen gas in long time even without the 1kW auxiliary power for the heat supply to the MH tank. These results implies that the proposed hybrid use with buffer tank and the FC waste heat utilization can improve the performance of the HESS reliable running and the whole system efficiency (considering all the auxiliary power). In the future, further investigation in the optimization of the buffer gas tank capacity and the utilization of the FC waste heat is necessary.

In Chapter 6, the method of suppressing early FC performance degradation was investigated, which is an obstacle before the achievement of the stable long-time continuous system operation in order for the reliable and sustainable supply of high quality power. The causes of the early degradation under the former control method was clarified at first. The ramping and frequent FC power variations and the open circuit voltage states (low load-ratio running states) are main causes of the early degradation. To suppress the degradation causes, this chapter proposed a FC and EL simultaneous operation method. This method was expected to suppress the FC's performance degradation by setting parameters, including minimum output power, maximum power sweeping rate, and constant FC power time interval. An experimental demonstration of the proposed energy management method was realized in a 1-kW scale model system. A simulation was performed, and the results showed that the proposed energy management method performed well in terms of both reducing FC power variation cycles and ensuring system efficiency. The results show that the proposed energy management method can effectively prevent FC's open circuit voltage state, and cut down ramping and frequent power variations, even this method may sacrifice about 10% system efficiency. To verify this proposed simultaneous operation method further, degradation experiments of the FC should be operated for investigation in the quantitative effectiveness of this method.

After the investigation in the issues above, in Chapter 7, a 72-hour continuous emergency operation demonstration of the EPS was operated using the 20-kW model system, supposing a long-time power outage due to a large natural disaster. By this demonstration, it was verified that the improved HESS is able to provide the reliable and sustainable supply of high quality power against the long-time power outage, while utilizing real-time fluctuating PV power generation. Also, this demonstration verified the performances of the EDLC, the EL, the FC, and the hydrogen storage, verified the effectiveness of the series hydrogen storage, the waste heat use, the simultaneous operation method, and the EDLC's SOC feedback control method. From the performance of the hydrogen storage, we recognized that the further investigation in configuration of the series hydrogen storage and the waste heat use are necessary. We discussed on the electricity generation and consumption share in the operation, and learned that the improvement on the efficiency of the EL and FC facilities, and the further decrease in the auxiliary power are important on the improvement of the entire system efficiency. In addition, from the investigation results on the system efficiency and power (voltage) characteristics of the EDLC, EL, and FC, it was clarified that the control method of the HESS should also be improved for reduce the necessary capacity of the facilities. Moreover, demonstrations were performed under different weather or control conditions, and load peak shift conditions, hence the effectiveness of the reliable and sustainable EPS for the water purification plant using the HESS was further verified.

By this research, the establishment method of the EPS using the HESS is achieved, in order for the reliable and sustainable supply of the high quality power supply to the water purification plant, against possible long-time power outage due to the large natural disasters. In the future, this kind of EPS technology using the HESS could be implemented in different applications and condition, guaranteeing the energy security.