CHEMICAL ENGINEERING TRANSACTIONS

VOL. 52, 2016

A publication of AIDIC

The Italian Association of Chemical Engineering
Online at www.aidic.it/cet

Guest Editors: Petar Sabev Varbanov, Peng-Yen Liew, Jun-Yow Yong, Jiří Jaromír Klemeš, Hon Loong Lam

ISBN 978-88-95608-42-6; **ISSN** 2283-9216

DOI: 10.3303/CET1652171

Supervisory Control and Monitoring of a Hybrid High Temperature PEM Fuel Cell System with Li-Ion Batteries and an LPG Reformer

Chrysovalantou Ziogou[a,*], Damian Giaouris[b], Simira Papadopoulou[c], Spyros Voutetakis[a]

[a] Chemical Process and Energy Resources Institute (CPERI), Centre for Research and Technology Hellas (CERTH), 6th km Harilaou-Thermi rd, POBOX 60361, Thessaloniki, 57001, Greece

[b] School of Electrical, Electronic and Computer Engineering, Newcastle University, NE1 7RU, England, United Kingdom

[c] Department of Automation Engineering, Alexander Technological Educational Institute of Thessaloniki, PO Box 141, Thessaloniki, 54700, Greece

cziogou@cperi.certh.gr

In this work, the supervisory control and monitoring system of a hybrid energy production station is discussed. A functional architecture consisting of a continuous process system, a discrete data acquisition platform, and an automation infrastructure are integrated to introduce and describe supervisory concepts for the efficient online monitoring of such systems. To this end, a motivating system that consists of three main subsystems, an LPG reformer, a High Temperature Polymer Electrolyte Membrane (HT-PEM) fuel cell and a Lithium-Ion battery stack is used that was designed and constructed by CERTH/CPERI. The system explores the integration of the LPG reformer with the HT-PEM fuel cell and their ability to charge the battery stack upon demand. Overall the supervisory system enables the efficient operation of the involved subsystems and controls the power production which is used both to charge the battery stack and serve the local auxiliary subsystems.

1. Introduction

The past few years the development and use of the power generation systems with low environmental impact have gained significant attention. In case multiple sources can be combined then the resulted solution can deliver power in a reliable and efficient way (Hosseinzadeh et al., 2013). Fuel cell systems (FCs) can be a potential alternative to the power production using renewable hydrogen or hydrogen which is reformed by fuels such methanol, LPG etc. Furthermore when the application into consideration is at isolated places and not connected to the main power grid then the importance of autonomy is a very important (Degliuomini et al., 2014). In that context, the hydrogen fuelled FCs can play a major role as a part of the change towards the hydrogen economy. When FCs are combined with the right source of energy, they have high potential efficiencies and low emissions. Their combination with fuel processors (fuel reformers) provide an alternative option to address the issue of hydrogen availability (Authayanum et al., 2012). The operation of such an integrated system depends on the configuration selected for the subsystems and the extent of chemical and thermal integrations achieved.

Overall, the key motivation for the development and wider use of the hybrid power production systems are their benefits related to low carbon emission, improved power quality and reliability, and in cases where heat and power is available, e.g. Combined Heat and Power (CHP) the benefits are further increased (Menon and Marechal, 2012). However, the development and control of hybrid power generation system is a complex task as there are a number of challenges exist during the analysis, design and implementation of such systems that are related to interoperability and the connection of the multi-vendor subsystems into a common integrated platform. Also the selection of the appropriate automation and control system that will supervise the

Please cite this article as: Ziogou C., Giaouris D., Papadopoulou S., Voutetakis S., 2016, Supervisory control and monitoring of a hybrid high temperature pem fuel cell system with li-ion batteries and an lpg reformer, Chemical Engineering Transactions, 52, 1021-1026 DOI:10.3303/CET1652171

operation is important as it will be used for the monitoring and evaluation of the system's behaviour (Ziogou et al., 2015). Apart from the technical challenges, the selected system should also be able to incorporate a flexible decision making process in order to handle the generation and the distribution of the energy to charge the batteries and the auxiliary loads. Therefore, the aim of the current work is to initially describe the subsystems of the hybrid system with its automation infrastructure and subsequently the behaviour of the hybrid system is explored through some indicative results by a typical operation.

2. Development and Supervision of Hybrid Powered Systems

Prior to the analysis of the hybrid system the operation prerequisites need to be established for the development of the automation and supervisory control of the system. The objective is to develop a modular infrastructure that will be used not only by the system into consideration but also from similar systems as well. In general, a supervisory control and automation system can improve the efficiency, safety and reliability of integrated hybrid systems while it can also provide indications about the operating cost. The automation system needs to handle the complex interactions between the electrical and the electrochemical subsystems and the communication between them which is a key element for the formulated hybrid system that facilitates the exchange of information between the various components.

2.1 Supervisory Monitoring and Control

Overall, the architecture of the automation system must rely on a flexible, adjustable and parametric structure with supervisory features enabling the unattended operation and concurrently handle the heterogeneity of the subsystems. Supervisory control is a layer of the automation system structure that is responsible for setting the reference values of the low-level control loops. Additionally, the supervisory controller can incorporate information from soft sensors (e.g., model-based efficiency calculation) and estimate the status of the hybrid system. In order to design and develop a supervisory control system it is necessary to perform the following activities:

- Define detailed requirements of all equipment (sensors, acquisition modules, equalization mechanism, data management, supervisory system) and process subsystems (reformer, fuel cell, battery, power electronics)
- Determination of the synergies among system components
- Derive a suitable architecture and a set of technical specifications of all components

After the determination of the aforementioned activities the process equipment is interconnected and the selected automation infrastructure is developed. Subsequently the deployment of the selected monitoring interfaces along with the respective energy management is integrated to the software platform (Ziogou et al., 2013a). At this stage the communication through appropriate middleware of the involved components is realized and finally the operability of the entire system is tested as an integrated small-scale unit. Typically, an automation and control system needs to determine and assign appropriate actions for each subsystem while keeping its output at the desired level. Overall, the control structure of such systems can be classified into three categories: centralized, distributed, and hybrid (Nehrir et al., 2011). In all three cases, each subsystem is assumed to have its own controller which determines the operation of the local components. In this work the hybrid approach is selected. A suitable solution able to effectively fulfil these requirements and constraints is a dedicated Supervisory Control and Data Acquisition (SCADA) system. The need for data acquisition and information management along with the diversity of the devices, dictated the use of a control system able to provide high level monitoring functions and discrete control (Ziogou et al., 2013b). The supervisory control system is designed to operate unattended and to provide remote monitoring features for the supervision of the unit along with a wide range of reporting and information extraction capabilities.

3. Integrated hybrid system – Topology and Infrastructure

The design of complex system can be viewed as a decision making process which involves the identification of possible design alternatives and the selection of the most suitable one. A good design is one that meets the design requirements and represents a trade-off among the different design objectives. For a fuel cell system, the requirements and objectives may include efficiency, size and weight, output power, emissions, quick startup and fast response to load changes and lifetime. A subset of these requirements will be considered in the current work and more specifically the data acquisition and measurement will be considered for each particular application. This specific system is used as a motivating example for exploring in small scale the technical issues and challenges which are present during the development procedure, from design to construction, of a hybrid power production system with particular emphasis at the supervision of the operation. The integrated hybrid system consists of a FC stack, an LPG reformer, a Li-Ion battery stack, various electromechanical and electronic supporting devices, different valves and pipelines and a control system that enables the proper functioning of the entire system in an efficient, safe, and reliable manner within predefined constraints.

3.1 Flow diagram and Specifications of the subsystems

The main objective for the integrated system is to be able to operate in a hybrid mode depending on the origin of the hydrogen that can be either from a gas reformer or from the hydrogen tanks. Another important objective is to be able to charge the battery stacks and to self-sustain the auxiliary subsystems along with the demanded load. Finally the entire operation should be automated and autonomous and should consider the protection of the lifetime of the involved subsystems (reformer, fuel cell, battery stack). The objective is to preserve the lifetime of the battery while using the optimum amount of fuel either hydrogen from LPG or pure hydrogen. The basic flow diagram of the hybrid system and its subsystems is shown at Figure 1 and Figure 2 depicts the overall integrated subsystem.

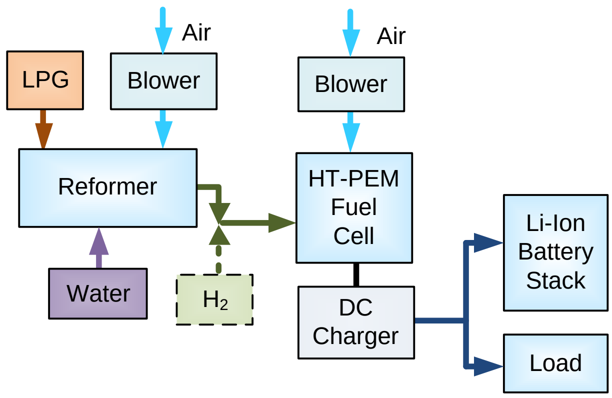

Figure 1: Topology of the hybrid system

Figure 2: Overview of the integrated system

When the system starts it is sustained by using power from a battery and subsequently, when necessary, the integrated fuel cell – reformer subsystem provides the requested power to charge the battery or to serve the load. The hydrogen for the operation of the fuel cell is supplied either from presssurized hydrogen stored in cylinders or from the LPG fuel reformer. In the system into consideration the hydrogen production is achieved via the LPG steam reforming of the feeding fuel by its reaction with steam. The produced stream contains high percentage of hydrogen (70 - 73 %), along with carbon monoxide and dioxide, as well as traces of hydrocarbons. A High Temperature PEM Fuel Cell (HT-PEM) is selected to be used because of the stable and reliable operation and the absence of the water management subsystem, compared to LT-PEM fuel cells. Also the increased tolerance to CO (up to 2 %) is an advantage of the HT-PEM fuel cells, which could lead to simpler reforming systems with less CO clean-up stages. The HT-PEM produces power up to 1 kW (36 cells, current: 2 - 45A, voltage: 21 - 30V) and its nominal temperature is 170 - 190 °C. The battery subsystem consists of a Lithium-Ion stack for forklift vehicles. A local load exists which is served by the hybrid system. The aforementioned integrated system is designed and constructed, from the Process and Instrumentation Diagram (P&ID) to the commissioning phase, by the Laboratory of Process Systems and Design Implementation (PSDI lab) at CERTH/CPERI. The control strategy and system monitoring is based on an industrial SCADA system (GE Proficy iFIX) which communicates with all the necessary components to gather the required measurements, the sensors and the control elements. Also the SCADA system is responsible for the analysis of the information and the notification of the operator (though the HMI) or the connected subsystem (M2M communication) when an abnormal situation or an alarm occurs based on the pre-defined conditions.

3.2 Battery Management System (BMS) and Voltage Cell Equalization

As Lithium-Ion batteries are used, the charging and discharging functions needs to be carefully monitored. Therefore, the developed BMS is of major importance. The BMS has a protection subsystem of each individual cell of the battery stack. More specifically, the system is developed for a battery stack that consists of 15 Li-ion battery cells of 3.2 V / 120 Ah each, which are connected in series to produce a 48 V. In order to protect the battery and the individual cells a state of the art BMS has been designed, implemented and tested. The main requirements for this BMS are the monitoring of the state and the protection from overcharging of each individual cell and at the same time the reduction of the overall cost as much as possible.
The information from the battery cells is organized in a database that holds both static information of each cell (regarding production date, installation date, capacity, voltage, maximum current etc.) along with the dynamic (regarding state of health, state of charge, voltage, current etc). Similarly, other available dynamic data are utilized in the developed battery model so as to evaluate the state of each cell. As far as the static information

is concerned, the database is updated both by the individual user through an interface and automatically by the data collected from the unit that incorporates the cells. For the realization of these functions a software platform is designed and implemented that establishes a communication link to the collection of the field data. Figure 3 shows part of the BMS with detailed information from each battery cell (voltage and temperature) while Figure 4 shows the battery stack.

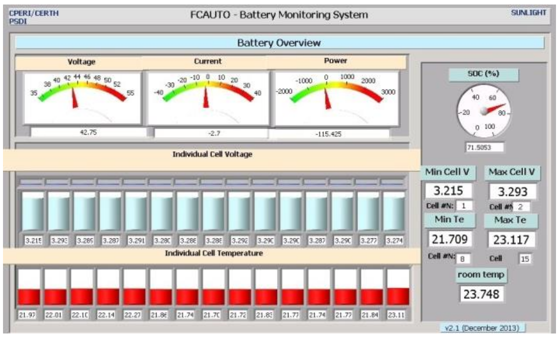

Figure 3: BMS interface of the Battery stack

Figure 4: Lithium-Ion Battery stack of the hybrid system

When a resistance is placed in parallel to a cell its state of charge and voltage should remain constant i.e. all the charging current goes through the resistance. However, due to transient phenomena it was observed that the voltage is not remaining constant but is oscillating between two values. One of them is the value where the resistance is placed in parallel to the cell and the other one is a lower value where the resistance is removed when the cell voltage drops. It was observed that the frequency of this oscillation is different for each cell and that it is greatly depended on its state of charge and health. Moreover, it was found after several charging cycles and in case that a cell is overcharged, that its voltage continues to increase even above the limit where the resistance is placed. In this case a second safety limit is used by the BMS and when this limit is exceeded the charging process is interrupted. After all using the BMS, it is possible to balance the state of charge of all the cells and therefore to protect the state of the battery.

3.3 Monitoring of the LPG Reformer Operation

The supervisory monitoring of the integrated system is performed through respective Human Machine Interfaces (HMIs) that present signals, condition and operational status.

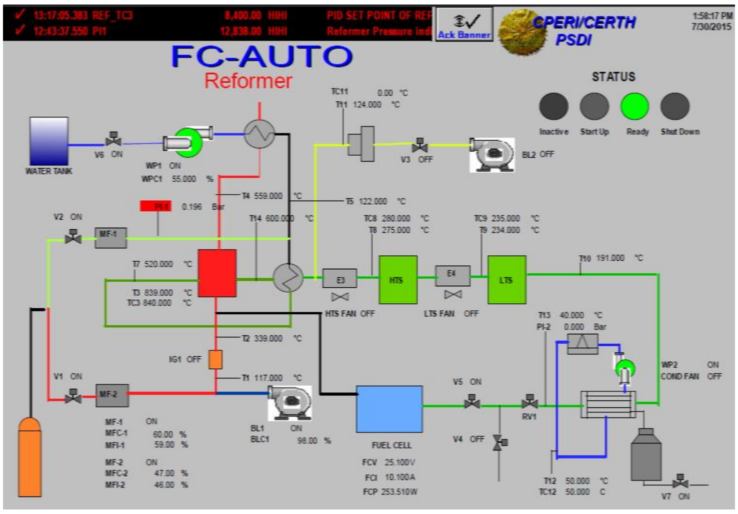

Figure 5: HMI of the LPG reformer

The developed HMIs provide online information about the integrated system and the operator is informed about any abnormal condition that might appear. Figure 5 shows an indicative HMI that is related to the detailed monitoring of the LPG reformer. During the operation of the system various status or error checks are performed and respective actions are implemented in case of a subsystem errors. The automation system is able to respond to failures caused by unplanned operation of a subsystem and takes into consideration various aspects of device failures. The HMIs provide a detailed view of all involved subsystems, devices and components and through appropriate notification indications it is possible to protects the equipment from possible malfunctions.

4. Operation Results of the Integrated System

As mentioned earlier the scope of the system is to produce hydrogen in the most efficient way while protecting the life time of the subsystems that support the hydrogen production in conjunction with the full utilization of the available renewable energy. Thus, the determination of the value for important operating parameters is of paramount importance. The integrated HT-PEMFC and the LPG reformer along with all the necessary auxiliary equipment including air compressor, cooling subsystem, battery overcharging protection and power electronics are developed and commissioned. A set of preliminary operation results are presented and show that the integrated system is able to charge the battery stack and also that the involved subsystems can operate according to their design requirements. Figure 6 shows the voltage of the battery stack and Figure 7 the applied current.

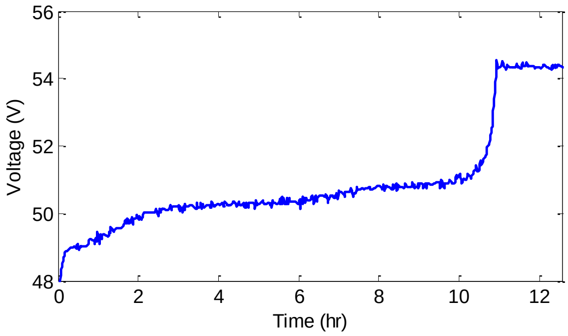

Figure 6: Battery voltage during charging

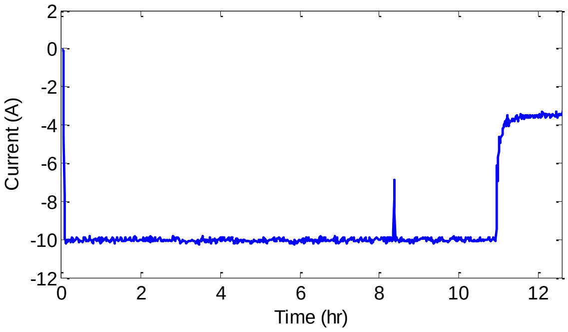

Figure 7: Applied current for battery charging

The battery stack was charged with 10 A, whereas during equalization the charging was performed with 3.8 A. The equalization of the cells was initiated when one of the cells reached a predefined limit and was concluded when each battery cell reached a predefined maximum voltage level. The duration of the equalization phase was 1h and the battery stack capacity reached 114 Ah.
Besides the charging of the battery stacks the operation of the other subsystems is shown at Figure 8. The specific experiment was performed in order to test the operation of the fuel cell and the reformer.

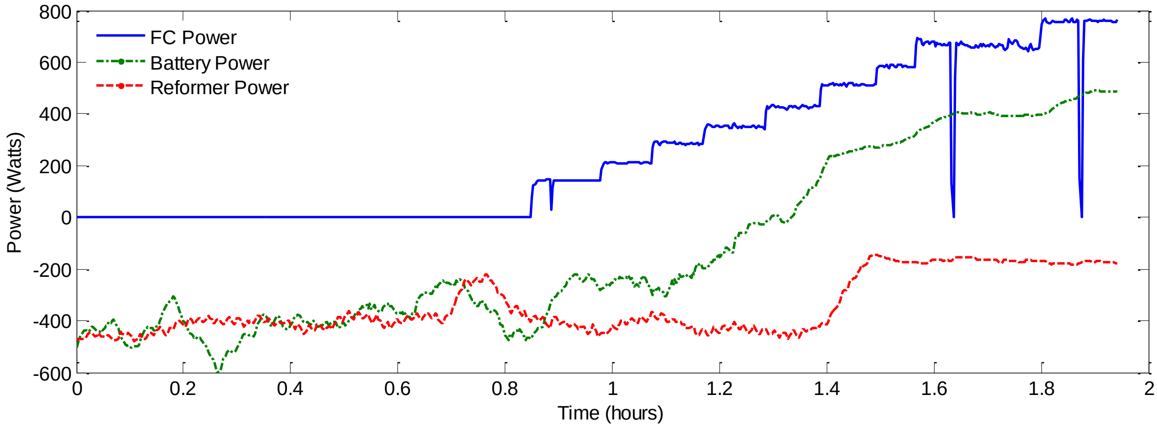

Figure 8: Fuel cell and reformer operation

Figure 8 shows that the initial requested power necessary for the start-up and stabilization of the operation was used from the battery stack and subsequently when both subsystems, the LPG reformer and the FC, were ready and fully operational they were able to produce the necessary energy and so it is observed that the charging of the battery started (positive values of the battery power). The maximum delivered FC power was 780 W. The integrated system utilized the energy that was stored to the battery stack for the first 45 min which was the necessary amount of time for the FC to be heated and the reformer to start producing hydrogen. The LPG reformer during its initial phase it requested an average of 430 W and when it reached its stable operation mode this was reduced to 190 W. Also the FC gradually produced power as we wanted to explore its response to varying load demands and supply.

It is observed in both cases that the automation system was able to control all subsystems and that the overall requested energy was produced by the fuel cell and the reformer.

5. Conclusions

The main results of this work focus on the operation of the integrated hybrid system and the automation system, that relies on SCADA architecture, supervises the involved components successfully. This automation framework besides the main subsystems, fuel cell, reformer and the charger of the lithium-ion battery stack, monitors all the involved power electronic components that are necessary for the energy conversion and the distribution. The monitoring features combined with the supervisory capabilities enable the optimum utilization of the battery pack and the available fuels (LPG or pure hydrogen). Finally the SCADA system provides informative decisions to the user that monitors the integrated process and enables proactive maintenance operation to ensure that the system will provide the maximum of its capabilities. Also the modular BMS system can be applied to a wide range of traction and stationary battery applications since the involved platform is generic and can be adapted upon demand. The preliminary operation results demonstrated that the automation system can manage the thermal and power load in real-time and is able to fulfil the objectives for effective supervisory control of the involved subsystems. In order to further optimize the operation the future actions include the development of model-based control strategies and the development of optimization based energy management strategies.

References

Authayanum S., Mamlouk M., Scott K., Arpornwichanop A., 2012, Design and analysis of HT–PEMFC systems with different fuel for stationery applications. International Conference on Renewable Energies and Power Quality (ICREPQ-12), 28–30 March2012, Spain.

Hosseinzadeh E., Rokni M., Advani S. G., Prasad A. K., 2013, Performance simulation and analysis of a fuel cell/battery hybrid forklift truck, Int J.Journal of Hydrogen Energy, 38, 4241-4249.

Degliuomini L. N., Cunningham M., Ferreyra F., Luppi P. A., Basualdo M. S., 2014, Energy Management of a Hybrid Controlled Process with Renewable Sources, Computer Aided Chemical Engineering, 33, 2014, 1141-1146.

Menon R.P., Maréchal F., 2012, Optimal predictive control strategies for polygeneration systems, Optimal predictive control strategies for polygeneration systems, Chemical Engineering Transactions, 29, 913-918.

Nehrir M.H. , Wang C., Strunz K., Aki H., Ramakumar R., Bing J., Miao Z., Salameh Z., 2011, A Review of Hybrid Renewable/Alternative Energy Systems for Electric Power Generation: Configurations, Control, and Applications, IEEE Transactions on Sustainable Energy, 2 (4), 392-403.

Ziogou, C., Elmasides, C., Papadopoulou, S., Voutetakis, S., 2013, Supervisory control and unattended operation of an off-grid hybrid power generation station with hydrogen storage, Chemical Engineering Transactions, 35, 529-534.

Ziogou C., Giaouris D., Yfoulis C., Stergiopoulos F., Voutetakis S., Papadopoulou S., 2015, Behaviour Assessment of a Fuel Cell - Battery System Using a Supervisory Control Methodology Empowered by a Hybrid Timed Automaton (HTA), Computer Aided Chemical Engineering, 37, 2327-2332.

Ziogou C., Ipsakis D., Seferlis P., Bezergianni S., Papadopoulou S., Voutetakis S., 2013b, Optimal production of renewable hydrogen based on an efficient energy management strategy, Energy, 55, 58-67