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Supervisory Control and Unattended Operation of an Off-grid Hybrid Power Generation Station with Hydrogen Storage

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The scope of this work is to present the architecture, structure and operation of a supervisory automation system that was designed and developed for an autonomous hybrid power generation station. In order to effectively address the issues that arise from the interactions of the various electrical and electrochemical subsystems, a dedicated Supervisory Control and Data Acquisition (SCADA) approach was selected. Such systems provide remote access, monitoring of the station and unattended operation which are very important when autonomy is required. The effectiveness and flexibility of the SCADA system is explored through the long-term operation of the station into consideration which reveals the salient features of the supervisory automation system.

1. Introduction

The use of renewable energy sources (RES) for the power production can significantly contribute to the reduction of greenhouse gas emissions and the development of an environmental friendly energy economy (Menon and Maréchal, 2012). In that context a polygeneration approach is a promising emerging approach that can concurrently address the need for power, fuel (in the form of hydrogen) and in some cases heating (Kyriakarakos et al., 2013), especially when isolated off-grid locations are considered. Although RES can be used for a wide range of applications, when off-grid power generation is required the most prominent and frequently used sources are solar and wind energy. Nevertheless, the intermittency of these renewable energy sources requires the utilization of intermediate storage systems. For this purpose accumulators are used to complement the infrastructure. Another recently emerging alternative for the storage of energy is the use of hydrogen production facilities that constitute a promising solution for the future's energy economy. When these approaches are combined, accumulators and hydrogen, the system's flexibility is increased and the long-term autonomy is improved.

However, the construction and control of hybrid power generation stations is not a trivial task as various challenges arise during the analysis, design and implementation of such systems that are strongly coupled with the interoperability and the exchange of information within the system boundaries. Thus, the selection of the appropriate automation and control system that will supervise the operation within the station is of paramount importance. 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, the transmission and the distribution of the energy to the end customer, which in the case of the off-grid stations is a specific load (Sechilariu et al., 2013). Therefore, the aim of the current work is twofold. Initially a brief description of the subsystems of a hybrid power generation station with its automation infrastructure is provided and subsequently the conceptual layout of the SCADA architecture is presented which is coupled with an

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energy management and decision making process. Finally the behaviour of the station is explored through some indicative results by a typical daily operation.

2. Description of the hybrid station and the automation system

The incentive for the design and development of a flexible and reliable supervisory framework originates from the operation requirements of an autonomous power generation station which is situated at Xanthi, Greece. 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 smart microgrid with an emphasis at the operations domain. The hybrid system integrates renewable energy sources and an energy storage subsystem combined with a subsystem that produces, stores and uses hydrogen. More specifically, the autonomous station consists of a PV array (10 kWp), three wind generators (1kWp each), a storage system based on lead–acid accumulators (4 strings of 750 Ah) and a long-term storage system that comprises of a Proton Energy Membrane (PEM) electrolyzer (4.2 kW), a PEM fuel cell (4kW) and the hydrogen storage system. A smart microgrid controls the transmission and distribution of the electricity flow, whereas its topology is based on a DC-Bus bar. Figure 1 illustrates the various subsystems of the station and the respective domains of the smart microgrid.

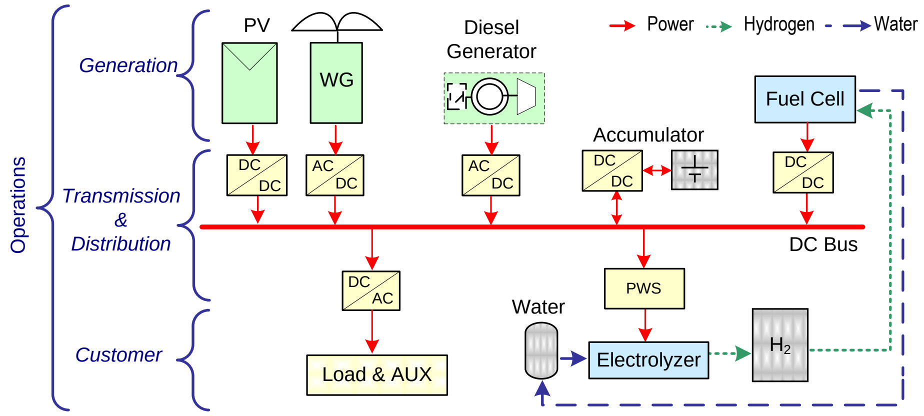


Figure 1: Conceptual domains of the smart microgrid and subsystems of the station

The electricity is primarily generated by the PV array and the wind generators (WG) according to RES availability, whereas a PEM fuel cell system (FC) is used to produce the requested power when the accumulator's voltage drops below a certain predefined level. The necessary hydrogen for the PEM fuel cell operation is produced by the respective subsystem (PEM electrolyzer, EL) which is present at the station and the necessary energy is supplied by a power supply (PWS). Furthermore, the infrastructure is complemented with a diesel generator (DG) for backup purposes. Besides the power generation, the station is equipped with the PEM electrolyzer that produces hydrogen when excess energy is available from RES. In first stage hydrogen is stored in a low pressure cylinder (buffer tank- BF, max 5.5 bar) and subsequently hydrogen is compressed through a compressor (CP) to a high pressure cylinder array (final tank - FT 30 bar). Also a water purification subsystem (WT) is employed since the electrolysis demands high water purity. The end user of the electricity is a predetermined load (LD) and the auxiliaries (AUX) which are necessary to support the autonomous operation of the station. These auxiliaries include the power requested by the components of the control cabinet, the ventilation system and the air-conditioning system which is present to maintain the temperature within the station.

Based on this analysis it is necessary to monitor and control these subsystems in order to provide the requested load demand and ensure that the station operates according to the predetermined design specifications. Thus, a respective automation infrastructure is employed to initially create a homogeneous basis for the information exchange between the system components and to handle their diversity.

2.1 Automation System Development

Among the most important challenges that the automation system should address are the handling of the complex interactions between the electrical and the electrochemical subsystems and the communication between the subsystems which is a key element for the formulated microgrid that facilitates the exchange of information between the various components. Thus, 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 (Ziogou et al., 2011). 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. As such, the SCADA system is selected for the implementation of the necessary operations that coordinate the generation, distribution and use of the produced energy. More specifically the Proficy iFix SCADA from GE communicates with all the necessary components in order to gather the required information (from sensors and devices). The information flow is shown at Figure 2.

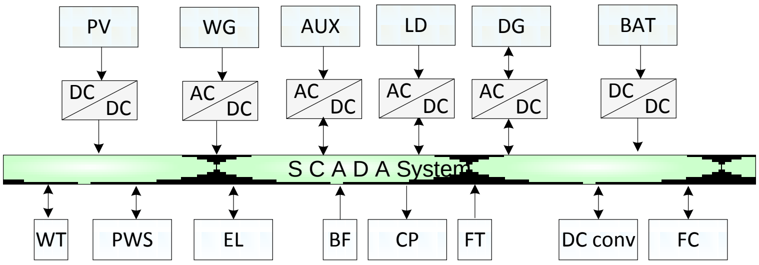
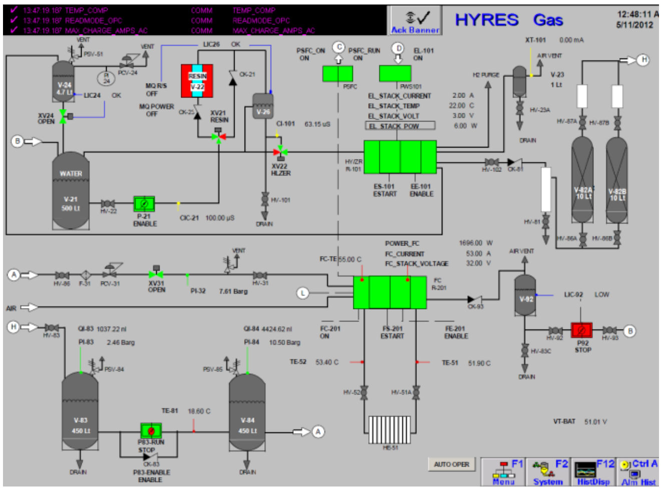


Figure 2: Information flow towards the SCADA system

Various network and industrial protocols (CANBus, Profibus, Ethernet, RS232) are used to integrate the system devices into one central control entity. The overall 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 knowledge extraction capabilities. For this purpose, respective user interfaces are developed and Figure 3 illustrates a representative interface for the online monitoring of the station.



✓ 13:47:19.187 TEMP_COMP COMM TEMP_COMP
✓ 13:47:19.187 READMODE_OPC COMM READMODE_OPC
✓ 13:47:19.187 MAX_CHARGE_AMPS_AC COMM MAX_CHARGE_AMPS_AC

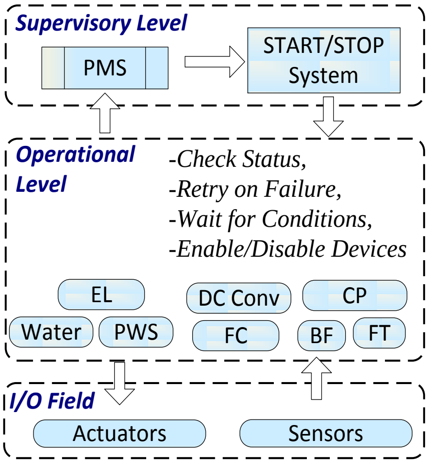


Figure 3: SCADA – System Monitoring

Figure 4: Conceptual layered framework

Overall the SCADA system is responsible for the flow of electricity and for the implementation of the necessary operations that distribute and control the energy flow within the microgrid. From the information point of view, the SCADA enables data sharing for exchange and integration purposes with other systems, whereas the characteristics of its architecture ensure the interoperability between the subsystems, the devices and the applications of the station. Furthermore components can be added, replaced or modified without affecting the rest of the system since a modular and expandable approach is employed.

3. Layered Control System Architecture

In order to define the levels of the decision making process with respect to the logical domains of the conceptual information exchange framework the SCADA architecture is analyzed. At the core of the SCADA system there is a process database where the values of the various variables are collected and organized. Also the algorithms and the decision making actions are developed inside the database using appropriate structures. The variables or tags are identified according to the information type and flow with respect to the SCADA. More specifically, we determine whether a variable is analog (A), discrete (D) or logical (B, Boolean). In the case of analog tags a further categorization is based on the direction of the information flow, input (I) or output (O) and a set of analog constraints (AC) are determined that act as the boundaries, physical or operational, for the input and output tags. These sets constitute the main elements of the SCADA database and all actions are performed based on their values. Each input tag has a sampling time, alarm limits and a dedicated scanning procedure which is executed in parallel for the data acquisition of the tags. The tags within the database include all the available signals from the field area network (FAN). The resulting sets of tags for the power generation station are represented by eq. 1.

$$\begin{aligned}
&AI=\left\{P_{PV},P_{WG},P_{LD},P_{aux},P_{EL},P_{FC},V_{Bat},W_{\mathrm{Re}s},PT_{BF},PT_{FT},ST_{EL},ST_{FC},ST_{FCDC}\right\}\\
&AO=\left\{I_{PWS},V_{PWS},I_{FC,Allow},I_{DC,SET},V_{DC,SET}\right\}\\
&DO=\left\{WT_{ON},PWS_{ON},PWS_{EN},EL_{SET},FC_{SET},CP_{ON},CP_{EN},FC_{ON},FC_{EN},FC_{SET}\right\}\\
&AC=\left\{PT_{CP,k},WT_{RES,k},V_{FC,k},V_{EL,k},PT_{FC,k},PT_{EL,k}\right\},k\in[HI,LOW]\\
&BL=\left\{B_{RES},B_{PT,CP},B_{V,Bat,FC},B_{V,Bat,EL},B_{PT,FC},B_{PT,EL}\right\}
\end{aligned} \tag{1}$$

Where *P, V, I* are the power, voltage and current measurement, *PT, W* are related to pressure and water quality indications and *ST* is the status of the respective device. The subscripts *ON, EN, SET* are for turning on/off a device, for enabling the operation and for setting the desired value. As far as the logical variables are concerned, they are formulated by the combination of the other tags and they determine the resulting action for each component within the station. The value of a tag can be easily propagated to another using the concept of the chain which is embedded at the SCADA system. When two tags are connected using a chain, the output value of the first tag is the input value of the second one.

This structure facilitates the bridging between the diverse nature of the subsystems and the development of generic decision making algorithms and energy management strategies, since a unified approach is used for all subsystems. From the integration point of view, the complexity of the interaction is handled by the automation system that provides an interface where the information is represented uniformly regardless of its origin. To enhance this approach a two level top-down conceptual structure is used that isolates the upper level from the details of the lower one. A conceptual framework is designed and deployed which is layered into the supervisory level and the operational level as shown in Figure 4. At the supervisory level a decision making process enables or disables the operation of the fuel cell (FC), the electrolyzer (EL), the compressor (CP) and the diesel generator (DG). At the operational level, an equipment specific algorithm is developed that handles the operation of each device inside each subsystem. For example, the actions at the supervisory level enable the operation of the electrolyzer system and subsequently, at the operational level, this action is translated into a set of commands that prepare the water purification equipment (WT), set the electrolyzer to the proper state, enable the power supply (PWS) and start the water pump. Although the analysis of the proposed architecture focuses on a station with specific subsystems, the overall approach is a generic one and can be easily deployed to other similar systems or can be used to extend existing infrastructures that are already equipped with other automation systems or operate in a manual mode.

3.1 Supervisory Level

At the supervisory level the conditions for the decision making process are represented using a propositional-based logic by utilizing the set of the Boolean tags. For the case of the power generation station which is considered by the SCADA system, the supervisory actions enable or disable the operation of a subsystem (FC, EL or CP) based on the status of its energy storages. More specifically the level of energy of the accumulators (BAT), the low pressure hydrogen buffer tank (BF) and the high pressure final tank (FT) are associated with Boolean variables. The voltage of the accumulator and the level of the pressure at the hydrogen storage tanks are the main parameters that drive the operation actions for the FC, the EL and the CP.

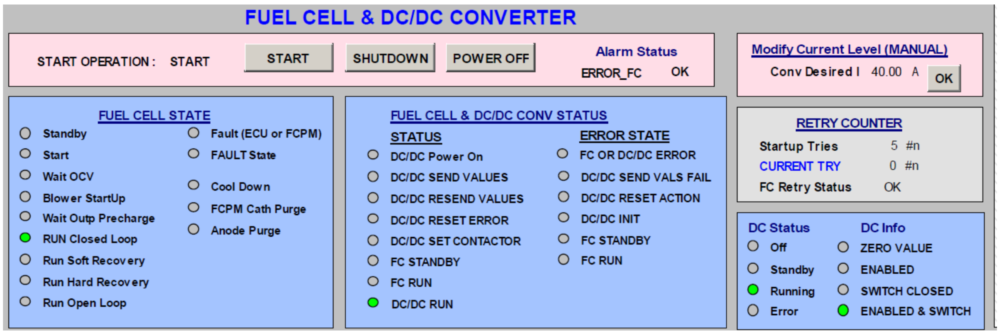
Table 1: Decision making process for the operation of the compressor

Action	Description
$[B_{PT,CP}=1]\leftrightarrow[PT_{BF}\geq PT_{CP,HI}]$	Tag $B_{PT,CP}$ is true (=1) if and only if (iff) the H_2 pressure is greater/equal to $PT_{CP,HI}$ (5.5bar)
$[B_{PT,CP}=0]\leftrightarrow[PT_{BF}\leq PT_{CP,LOW}]$	Tag $B_{PT,CP}$ is false (=0) iff the pressure drops below $PT_{CP,LO}$ (2bar)
$CP_{EN}=B_{PT,CP}$	Set the value of tag $B_{PT,CP}$ to the digital output tag CP_{EN}

This tag based approach which is embedded at the SCADA system represents the logical actions as a combination of the appropriate operators ($AND:\wedge, OR:\vee, NOT:!$) with the status of each subsystem or the level of stored energy and it is compared with predefined constraints using the respective operand ($Greater:>, Less:<, Equal:=$). Each logical expression can be evaluated as true or false and based on that the respective subsystem is allowed to operate or not. For example the operation of the compressor depends on the level of H_2 in the BF (Boolean tag B_{CP}) as described at Table 1. Similarly all the elements of the Boolean set (BL) are defined and the actions that control the energy flow are applied when the respective conditions are met. These actions are subsequently sent to the lower level of the framework.

3.2 Operational Level

At the operational level, device specific algorithms are developed that receive the supervisory request for the start or stop of a subsystem and proper actions are taken in order to implement the requested command at the FAN. For each subsystem a set of pre-run and preparative actions are considered. The preparative actions include the establishment of the communication with the equipment and the reset of any errors that might appear before the enabling of the main operation. Also, proper conditions should be met in order for a subsystem to run, e.g. the water resistivity should be below a predefined level otherwise the electrolyzer is not allowed to run. During the operation of the system various status or error checks are performed and respective actions are implemented in case of device or communication errors. The algorithm is able to respond to failures caused by unplanned operation of a subsystem and takes into consideration various aspects of device failures, e.g. the prime pump of the EL fails to start or the communication of the power supply is not enabled and protects the equipment from possible malfunctions. The procedure which is related with each subsystem is able to repeat the list of the predefined preparatory actions in case of a failure and notifies the supervisory level using a proper alarming mechanism in an automated manner.



START OPERATION : START

Alarm Status
ERROR_FC OK

Modify Current Level (MANUAL)
Conv Desired I 40.00 A

FUEL CELL STATE
○ Standby
○ Start
○ Wait OCV
○ Blower StartUp
○ Wait Outp Precharge
● RUN Closed Loop
○ Run Soft Recovery
○ Run Hard Recovery
○ Run Open Loop
○ Fault (ECU or FCPM)
○ FAULT State
○ Cool Down
○ FCPM Cath Purge
○ Anode Purge

FUEL CELL & DC/DC CONV STATUS

STATUS
○ DC/DC Power On
○ DC/DC SEND VALUES
○ DC/DC RESEND VALUES
○ DC/DC RESET ERROR
○ DC/DC SET CONTACTOR
○ FC STANDBY
○ FC RUN
● DC/DC RUN

ERROR STATE
○ FC OR DC/DC ERROR
○ DC/DC SEND VALS FAIL
○ DC/DC RESET ACTION
○ DC/DC INIT
○ FC STANDBY
○ FC RUN

RETRY COUNTER
Startup Tries 5 #n
CURRENT TRY 0 #n
FC Retry Status OK

DC Status
○ Off
○ Standby
● Running
○ Error

DC Info
○ ZERO VALUE
○ ENABLED
○ SWITCH CLOSED
● ENABLED & SWITCH

Figure 5: FC and DC/DC Converter Status Monitoring and Error Handling Screen

Figure 5 is a part of the monitoring interface where the preparatory actions are shown along with the possible errors. As the operation proceeds to the next predetermined step, the status is updated and the user is able to monitor the state of each subsystem. More specifically in Figure 6 the DC Converter is running and the FC operates in closed loop. The user is able to bypass the automatic operation of the system and can manually control the station and its subsystems. The proposed conceptual framework is applied to the hybrid power generation station and its operation is monitored online.

4. Online Operation and Results

The operation of the station is presented through the results of two typical days during last year (March 2012). Figure 6 shows a) the power from the PV array, the load demand and the requested power from the EL, b) the battery voltage and c) the hydrogen pressure at the BF and FT. The provided power by the PV not only fulfilled the power demand but also charged the accumulators at their maximum level. Thus, the excess of energy was transformed into hydrogen. Also the compressor was activated as the intermediate pressure at the BF reached its maximum level (5.5 bar). Similarly the same variables are shown at Figure 7 for a day that the fuel cell was used. Thus the power of the EL is replaced by the power of FC at the diagram. The results indicate that the station can operate within the predefined specifications under environmental or operational variability based on the decisions which are taken by the SCADA system. Furthermore some indicative statistics from the weekly operation of the station during the same period (March 2012) are shown at Table 2.

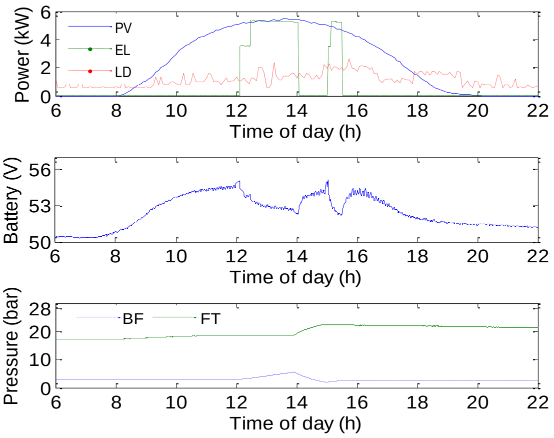


Figure 6: Daily operation using the electrolyzer

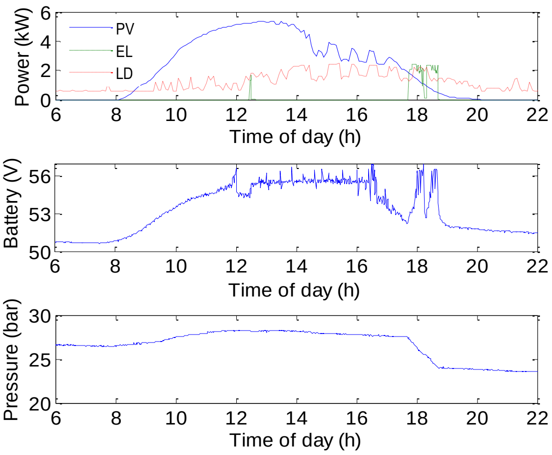


Figure 7: Daily operation using the fuel cell

Table 2: Weekly operation statistics of the station

	Minimum	Maximum	Mean	Absolute Meas. Error
Load Demand (kWh/d)	28	34	31	±0.5
PV Power (kWh/d)	21	42	36	±0.5
Fuel cell power (kWh/d)	2.2	5.2	3.6	±0.5
Fuel cell Operation (h)	1.2	2.9	1.5	-
Electrolyzer Operation (h)	1.2	3.2	2.6	-
H_2 produced (L/min)	5.1	12.3	10.8	±0.06
Bat. Power (W)	-1216	6383	683	±36
Bat. Current (A)	-34.5	83	45	±1

The experimental results, short-term and long-term, reveal that the station can operate unattended for long periods of time based on the automated actions which are applied by the SCADA system and it is observed that the station fulfils the power demand and exploits the available energy from RES as the hydrogen subsystem is also activated when there exist an excess of energy.

5. Conclusions

This work presented the structure and architecture of an automation system which was developed to supervise and control a hybrid RES power generation station. The conceptual multi-layered framework was analyzed along with the decision making elements that are responsible for the unattended automated operation. Furthermore, the complex interactions among the electrical and the chemical subsystems are addressed effectively enabling the distribution of energy through a smart microgrid and a set of interfaces were also developed at the SCADA system in order to enable the monitoring of the station. Overall the implementation of the conceptual framework reveals that the employed automation infrastructure handles adequately and reliably the synergy among the various subsystems.

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