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A Novel and Flexible Energy Management Strategy with Application in a Hydrolytic Solar Hydrogen Autonomous System

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The aim of the current work is to present a novel energy management strategy (EMS) which constitutes the core of a supervisory control framework. The proposed approach formalizes the knowledge of the system operation using a Finite State Machine (FSM) combined with a propositional-based logic to describe the transitions between the different states of the integrated system. The use of the proposed framework is derived by the operation of a hydrolytic solar hydrogen production unit. Furthermore an optimization study was performed to determine the values of important operating parameters and finally the efficiency of the system is explored.

1. Introduction

The field of energy management in integrated renewable energy systems is of increasing importance due to the necessity for optimum operation of the various interconnected subsystems that constitute a unit (Friedler, 2009; Martins, 2009). As the role of hydrogen in a sustainable energy environment increases, an optimum management strategy is required in order to exploit the intrinsic features of the hydrogen production system into consideration. Proper EMS is a prerequisite for optimal use of the devices constituting the presented autonomous hydrogen production system also supporting their proper operation and maintenance. The primary incentive of the proposed technology for producing hydrogen from solar energy is to reduce the overall production cost and improve the associated sustainability of a process converting used cooking oil to 2nd generation biofuel through catalytic hydrotreatment (Bezergianni, 2012). Therefore the main purpose of the unit is to produce high-pressure hydrogen required for the above process. In this way, system integration and novel technologies are combined towards sustainability.

2. System Description

The method of hydrogen production via water electrolysis and solar energy requires the utilization of several subsystems, which formulate an autonomous and eco-friendly integrated system. The electrical

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architecture of the system is based on an AC-bus architecture, meaning that all transfer of energy is made through a three-phase system. A 10 kWp peak power photovoltaic array (PV) supplies energy for a PEM electrolyzer that is rated at maximum of 7.5 kWp supplying up to 7 bar of hydrogen. The produced hydrogen is stored in pressurized tanks at both low and high pressure utilizing a compressor between the two stages. In order to maintain a smooth operation despite weather fluctuations, a 1000Ah/24V lead-acid accumulator stores temporarily electrical energy and provides it when needed in a controlled way (Ziogou, 2011b). Figure 1 presents the connection of the subsystems and in Figure 2 the information flow of the automation system is represented.

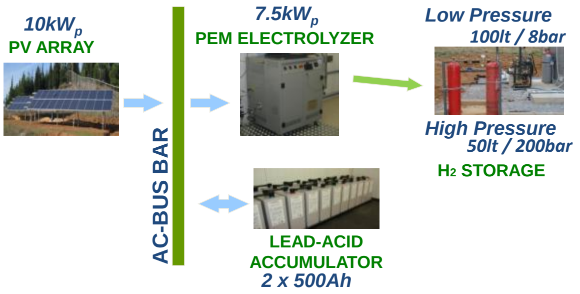


Figure 1: Subsystem's interconnection

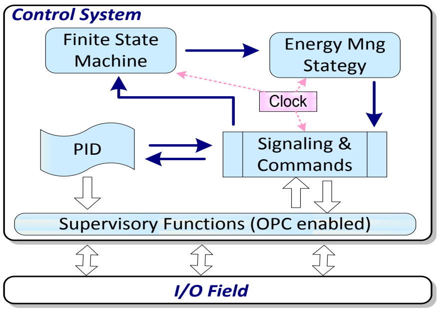


Figure 2: Information flow

The system monitoring and control is implemented through a Supervisory Control and Data Acquisition system (SCADA), while the complex interactions among electrical and chemical subsystems are addressed by the automation infrastructure and lead to the appropriate control structure development. Various network and industrial protocols (CANbus, Profibus, RS485, TCP/IP etc.) are used to integrate the system devices into one central control entity, managing this way the heterogeneity between the chemical and electrical subsystems (Ziogou, 2012). The main challenge for the overall control system is to guarantee that power will be available whenever needed, without compromising reliability and maintain system integrity both for the hydrogen production period as well as for the part of the day with no insolation, as the system is autonomous, and all that at a reasonable cost.

3. Energy Management Framework

Energy management strategies (EMS) are needed to supervise the operation of the various subsystems. The purpose of the EMS is twofold, to supervise the status of each subsystem and to be able to adjust to system operational modes. The derived set of rules is used for the control of the operation of the subsystems, namely the electrolyzer (EL), the compressor (CP) and the water tank and purification subsystem (WT). The EMS consists of a series of switching actions in order to drive the system from its initial state to an operating mode appropriate for every subsystem, taking into consideration the device specifications and the respective constraints. There exist a number of methodologies that can describe an EMS, such as if-then rules, fuzzy logic, Petri nets, state-flow charts and automata or finite state machines. In our work we selected the finite sate machine approach due its applicability in the SCADA environment.

3.1 Finite State Machine

A finite-state machine (FSM) or finite-state automaton is commonly used in computer science (eg. for parsing, compiler design and formal verification) and in the design of digital logic circuits (Hierons, 2001). In this work a FSM is used to describe the realization of the EMS for the operation of our solar hydrogen production system. Particularly, a FSM can be extremely helpful in the study of the behavior of the autonomous solar hydrogen system due to its inherent hybrid structure. A FSM is a dynamic approach that describes the evolution in time of a set of discrete and continuous state variables. The solar hydrogen system exhibits two kinds of dynamics completely different in nature, namely discrete (eg. start or stop of the compressor) and continuous dynamics (eg State Of Charge of the accumulators). The interaction between discrete and continuous operating states motivates the use of the hybrid approach and thus the FSM appears as an appropriate and powerful representation and analysis tool for the realization of a generic EMS. A FSM M is defined by a tuple $(Q, q_0, \delta, \lambda, \mathrm{X}, \mathrm{Y})$ in which Q is a finite set of states, $q_o \in Q$ is the initial state, δ is the state transfer function, λ is the output function, X is the finite input alphabet; and *Y* the finite output alphabet. The alphabet (X, Y) represents the rules of operation that will be explained in the following section. If M receives input $x \in X$ while in state q it produces output $y = \lambda(q, x)$ and moves to state $q' = \delta(q, x)$. This defines a transition $(q, q', x / y)$. In our system the finite set of states (Q) describes the unit's operation cycle.

3.2 Propositional Logic

The transitions between the states (q : state of the operation cycle) are implemented using a formal propositional-based logic that aims to present a systemic and generalized approach able to be applied in the SCADA system. The output function can enable or disable (start, stop) the operation of a subsystem (EL, CP, WT) based on the status of its energy/mass storages, the accumulator (BAT), the low-pressure hydrogen buffer tank (BF) and the high-pressure final tank (FT). The State Of Charge (SOC) of the accumulator and the level of the hydrogen storage tanks are the main factors that drive the operating decisions concerning the EL and CP. The level of energy of each storage subsystem (BAT, BF, FT) defines a set of Boolean variables (*β*), which are related to the statuses of the subsystems. The value of each Boolean variable can be true or false and based on these variables a set of rules are formed.

The propositional based approach is easily deployed at the SCADA system since every logical function can be expressed as a combination of the logical operations ($AND: \wedge, OR: \vee, NOT: !$). The status of each subsystem or the level of stored energy can be subsequently compared to a predefined level using the appropriate operand ($Greater :>, Less :<, Equal :=$). Furthermore a hysteresis band is used in the boundary limits of the accumulator to avoid irregular operation (reduction of frequent start-ups and shut-downs). For example the operation of the CP depends on the level of H_2 pressure in the BF. A Boolean variable (β_{BF}) represents the level of H_2 pressure in the BF (Table 1).

Table 1: Buffer Tank Status Variable

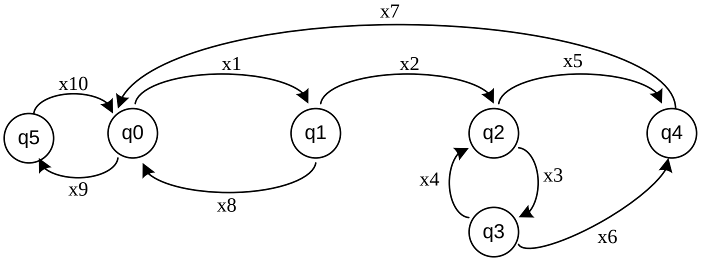
Variable status	Description
$[\beta_{BF} = 1] \leftrightarrow [BF \geq BF_{high}]$	Variable β_{BF} is true (=1) if and only if (iff) the pressure of H_2 in the BF is greater/equal to BF_{high} (4bar)
$[\beta_{BF} = 0] \leftrightarrow [BF \leq BF_{low}]$	Variable β_{BF} is false (=0) iff the pressure drops below BF_{low} (3bar)

In a similar way a set of Boolean variables are defined for the water purity (β_{WT}), the pressure at the final tank (β_{FT}) and the SOC of the accumulator $(\beta_{BUP}, \beta_{ELoff}, \beta_{prep}, \beta_{ELon}, \beta_{\max})$. In order to define the input alphabet X and subsequently the transfer functions δ of the FSM these variables are combined into propositional rules to provide the reasoning behind the subsystems operation. In Table 2 a subset of the FSM's input alphabet is presented that corresponds to the transitions for the hydrogen production from preparation state (q_1) and compression from production state (q_2).

Table 2: Propositional Rules and Input alphabet

Propositional rule	Description
$x_2 : \beta_{WT} \wedge \beta_{ELon} \wedge ! \beta_{FT}$	The water resistivity is at the required level (>2MΩ) and the accumulators are charged to the point where the electrolyzer is allowed to operate while the final tank pressure is lower than its maximum level (200bar)
$x_3 : \beta_{BF} \wedge ! \beta_{FT}$	The pressure at the buffer tank has reached the upper level (4bar) and the final tank pressure is lower than its maximum level (200bar)

Each rule constitutes a letter of the input alphabet. These set of rules are derived by the engineering knowledge of the operation of the unit's subsystems and their constraints. The FSM that describes the operation of our system is shown in Figure 3.



q0: System standby
q1: Preparation for H_2 production
q2: Produce H_2
q3: Compress H_2
q4: Stop H_2 production
q5: Use backup to self-sustain the system

Figure 3: Finite State Machine for the operation of the system

The use of the FSM that realizes the EMS enables the study of the behavior of integrated systems in a flexible way due to its adaptability. Overall the proposed EMS is able to incorporate engineering and computational knowledge and techniques for the application on the actual system and it can incorporate various operating modes. Additionally, it offers a theoretical context for the analysis and design of complicated energy systems involving multiple energy sources and loads.

4. Optimal Operation and efficiency

The scope of the system is to produce hydrogen in the most efficient way while protecting the lifetime of the subsystems that support the hydrogen production in conjunction with the full utilization of the available renewable energy. Thus the specification of the value of important operating parameters is of paramount importance. An optimization-based framework is used for this purpose that utilizes mathematical models of the interconnected subsystems (photovoltaic array, accumulator, electrolyzer, compressor). These models were experimentally validated utilizing data collected during the operation of the various unit subsystems (Ziogou, 2011a). Furthermore the efficiency of the overall system operation through a typical daily period is explored.

4.1 Optimization problem and results

The proposed optimization framework dictates the operation of the subsystems in terms of reliability and aims at the increase of their life expectancy. The utilization pattern for the accumulator and the electrolyzer determines the frequency of equipment replacement and maintenance requirements and therefore the operating costs, over the lifespan of the overall system (Ipsakis, 2008). To this end, the optimization problem focuses on these operation parameters, which are considered as the decision variables for the optimization problem. A sensitivity analysis was performed and we concluded that the operation parameters that mainly influence hydrogen production and operation of the system are the SOC levels $(SOC_{el,on}, SOC_{el,off})$, a prerequisite to initiate and stop hydrogen production, the maximum allowable power drawn from the accumulator $(P_{bat,\max})$ and the minimum power for the operation of the electrolyzer $(P_{el,\min})$. Based on these requirements and as the subsystems are described by deterministic, non-linear, well-defined and experimentally validated models (Ziogou, 2012) a constrained medium-scaled optimization problem is formulated, which is solved utilizing a deterministic optimization method. The feasible area that the optimizer explores is determined by the variables' bounds and the operational constraints of each subsystem. The optimization presented here, was performed for one month (March 2011) and the resulting values of the decision variables are shown in Table 3.

Table 3: Optimization results

Optimization Variables	
$SOC_{el,on} = 75\%$	$P_{bat,HI} = 1400W$
$SOC_{el,off} = 60\%$	$P_{el,\min} = 2415W$

4.2 Daily operation

The autonomous system operates unattended every day and the hydrogen is stored in cylinders. In Figure 4 the typical daily operation of all subsystems of the unit is shown.

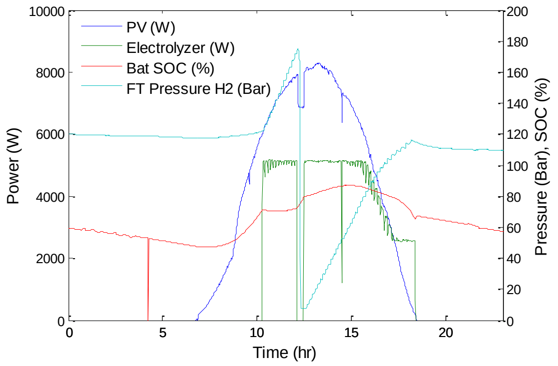


Figure 4 Typical daily operation

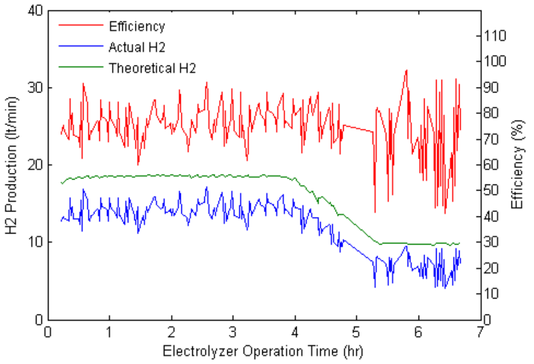


Figure 5 Hydrogen Production and efficiency

When the pressure reaches the maximum allowable level the high-pressure cylinder is switched over to an empty one. In Figure 4 a sudden drop of hydrogen pressure illustrates the changeover of the cylinder. During the nighttime the SOC decreases, as the system has to support its auxiliaries subsystems (air-condition, control and automation infrastructure). The electrolyzer operates continuously for 7 hours and the required power is adjusted according to the SOC of the accumulators using a PID controller. In Figure 5 the produced hydrogen compared to the theoretical hydrogen is shown, along with its efficiency.

4.3 System Efficiency

One of the major concerns in all energy systems and particularly in renewable energy exploitation is the calculation of subsystem efficiency. In the presented unit, the analysis focuses on the evaluation of the operating efficiencies of photovoltaics, PEM electrolyzer and lead-acid battery. The efficiency of the photovoltaics, derived as the ratio of energy coming out/energy coming in, is given as:

$$n_{PV} = \frac{P_{pv}}{G_s \cdot A_{pv}} \qquad (1)$$

where n_{pv} the PV efficiency, P_{pv} the power output in W, G_s the incident solar radiation on the tilted panel in W/m^2 and A_{pv} the total PV are in m^2. The accumulator efficiencies in the cases of charging and discharging are:

$$P_{bat,tot,(charge)} = P_{pv} - P_{load} \quad \text{and} \quad P_{bat,tot(discharge)} = P_{load} - P_{pv} \qquad (2)$$

$$n_{bat} = \frac{P_{bat,real}}{P_{bat,tot}} \qquad (3)$$

where n_{bat} the accumulator efficiency, $P_{bat,real}$ the accumulator power (derived from the measurements of current and voltage) in W, $P_{bat,tot}$ the total power supply or demand from the AC-bus (derived from the balance of loads and PV power) in W. The electrolyzer efficiency is provided as:

$$n_{elec} = \frac{H_{2,real}}{H_{2,theoretical}} \quad \text{and} \quad H_{2,theoretical} = \frac{n_c I_{elec}}{nF} \qquad (4)$$

where n_{elec} the electrolyzer efficiency, $H_{2,real}$ and $H_{2,theoretical}$ the real and theoretical hydrogen produced respectively in Nm^3, n_c the cell number, F the Faraday's efficiency in Cb/mol, I_{elec} the operating current and n the number of electrons. Table 4 presents efficiencies of the above the subsystems for the solar-hydrogen unit.

Table 4: Subsystem Efficiencies

Subsystem	Efficiency
Photovoltaics	12.22 %
Accumulator	70.95 % (discharge) – 86 % (charge)
PEM Electrolyzer	73.24 %

5. Conclusions

In the current work the basic components and methodology required for the unattended operation of a stand-alone renewable hydrogen production unit are presented, namely the automation structure and the energy management strategy (EMS). The EMS was based on a finite state machine (FSM) in conjunction with propositional based reasoning. An optimal framework was used to assess the system's ability to follow specific operating targets regarding the hydrogen production and the preservation of the life of the accumulator taking into account the minimization of the total operating cost of the whole unit, leading to a more economical overall system operation.

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