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Design And Optimization Of A Stand-Alone Power System Based On Renewable Energy Sources

Dimitris Ipsakis[1,2], Garyfallos Giannakoudis[3], Athanasios I. Papadopoulos[1],
Spyros Voutetakis[1], Panos Seferlis[3]

[1]*Chemical Process Engineering Research Institute (C.P.E.R.I.), Centre for Research and Technology Hellas (CE.R.T.H.), P.O. Box 60361, 57001 Thessaloniki, Greece*
[2]*Department of Chemical Engineering, Aristotle University of Thessaloniki, P.O. Box 1517, 54124 Thessaloniki, Greece*
[3]*Department of Mechanical Engineering, Aristotle University of Thessaloniki, P.O. Box 484, 54124 Thessaloniki, Greece*

A stand-alone power system for small to medium scale applications requires the exploitation of renewable energy sources (RES), such as solar and wind energy, in conjunction with a hydrogen production and long-term storage system. Surplus energy is supplied to a PEM electrolyzer and the produced hydrogen is used in a PEM fuel cell to provide power in cases of energy deficit. In order to account for short-term needs, a lead-acid accumulator is employed and charged by the RES or the fuel cell depending on the availability of the RES and the accumulator State-of-Charge, SOC. Power management strategies that aim at the efficient operation of every subsystem are developed. Moreover, the current study presents a novel design approach that optimally determines the capacity requirements for all subsystems and further calculates the optimal operating conditions of the power management strategies. An optimization method in the form of simulated annealing is employed to identify the solution to the resulted large scale, discontinuous and discrete optimization problem.

1. Introduction

The design of an autonomous power system requires a number of subsystems to be considered. PV-systems and wind generators for power production, accumulators to suit short-term needs and a hydrogen based system that will meet long-term needs, are of usual interest in stand-alone applications. Ulleberg (1998), developed and validated mathematical models to investigate the operation of stand-alone power units consisting of single components (i.e. PV system, electrolyzer etc.), however the integration of subsystems was not considered. The integration of all the potentially available subsystems within a flowsheet consisting of RES components, requires the development of power management strategies (PMSs) based on the monitoring of a process system

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variable, such as the SOC of the accumulator (Ipsakis et al. 2008a, 2008b, Ghosh, 2003). The main purpose of these strategies, is the protection of every subsystem from over- or under-utilization that might be detrimental to the system overall costs.

In this work, a combined study of optimal design and operation of integrated systems that exploit RES is presented. Initially, two basic PMSs are presented and their main objective is the smooth flow of power in the system based on the power excess or shortage and on the SOC operation limits. The lower limit, SOC_{min}, dictates the operation of the fuel cell in cases of power shortage, while the upper limit, SOC_{max}, dictates the operation of the electrolyzer in periods of power excess. A hysteresis band zone in these limits, is used to ensure that the fuel cell and the electrolyzer will operate continuously and frequent start-ups and shut-downs will be eliminated (Ipsakis et al. 2008a, 2008b). Furthermore, the system design will define the optimal selection of the subsystems capacity (e.g. nominal power level, accumulator capacity etc) by minimizing a cost related objective function. This objective function, takes into account the annualized costs of purchase, replacement and operation. The parameters in the PMS strongly influence the operating pattern of the subsystems and subsequently the operation and maintenance costs of the overall system. The solution of the optimal design problem is performed through an optimization method in the form of simulated annealing (Papadopoulos and Linke, 2004) that allows the screening of numerous design alternatives within the integrated power system flowsheet and enables the identification of optimal design targets.

2. Description of the main principles of the stand-alone power system

The stand-alone power system under study is shown in Fig.1. It mainly consists of a PV and wind generators systems. Surplus energy is supplied to a PEM electrolyzer after the specified constant load demand is satisfied.

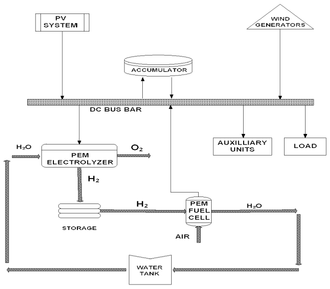


Figure 1: Block diagram of the proposed stand-alone power system

The produced hydrogen is stored in cylinders under pressure and in cases of energy deficit, a PEM fuel cell is used to provide additional power to the system. Also, in order to account for short-term needs, a lead-acid accumulator is used and charged by the RES or the fuel cell depending on the availability of the renewable sources and the SOC levels. In case of energy excess not used in any other subsystem, then the auxiliary units (e.g., hydrogen compressor) of the integrated system may utilize this energy.

3. Main characteristics of the power management strategies

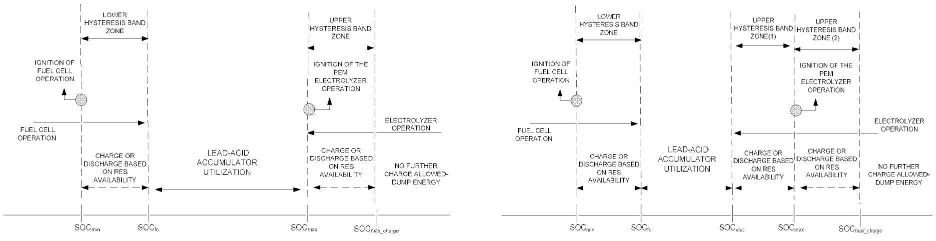
To facilitate efficient integration of the previously described subsystems within a stand-alone power system we propose the development of two power management schemes (PMSs).The proposed PMSs essentially provide venues for the development of efficient decision alternatives in the operation of the integrated power system. The two major operating parameters steering the generation of such alternatives are the SOC limits of the accumulator and the value of P (Watt), which is defined as the difference between the power produced by the PV and wind generators system and the load demand.

3.1 Power Management Strategy 1, PMS1

PMS1 considers the operating decision alternatives shown in Fig. 2a for cases of power deficit or excess within certain ranges of the accumulator SOC. In cases of power deficit ($P \leq 0$), the necessary power to satisfy the load is provided by the lead-acid accumulator ($SOC_{min} < SOC$) or the fuel cell ($SOC_{min} > SOC$) and in cases of power excess ($P > 0$), the surplus power is used in the electrolyzer ($SOC_{max} < SOC$) for the production of hydrogen or to charge the accumulator ($SOC_{max} > SOC$). A characteristic of the hysteresis band range (HBR=2%) is that if $SOC_{min}<SOC< SOC_{fc}$ and in the previous time step the fuel cell was operating and still shortage of power exists, then the fuel cell does not shut down, but rather continues to operate until the SOC reaches the limit SOC_{fc} (defined as SOC_{min} + HBR) or until the RES can fully meet the system demands. It is noticed that the electrolyzer may only operate if the available power from the RES is higher than its minimum power level ($P_{min,elec}$). The limit SOC_{max_charge} (defined as SOC_{max} + HBR) is specified as the point where no further charge is allowed and only the auxiliary units may use the power excess.

3.2 Power Management Strategy 2, PMS2

The main difference of PMS2 (shown in Fig.2b) from PMS1 is that the electrolyzer in PMS2 is allowed to operate at $P_{min,elec}$ using power provided by the RES in conjunction with power from the discharge of the accumulator. Thus, the accumulator is subject to more intense utilization in PMS2. Regarding the hysteresis band, if $SOC_{elec} < SOC < SOC_{max}$ and in the previous time step the electrolyzer was operating and still excess of power exists, then it continues to operate, but the accumulator cannot be discharged below SOC_{elec} (defined as SOC_{max} - HBR)



(a) **(b)**

Figure. 2: Decision alternatives in the operation of the integrated system for (a) PMS1 and (b) PMS2

4.Design and optimization method

To determine the capacity of all the subsystems within the integrated power system and to calculate the optimal operating conditions of the PMSs, we propose the use of optimization-based technology. The employed technology utilizes numerous subsystems, as well as design parameters affecting their operating and economic performance, as design variables in the performed optimization in order to capture major synergies and interactions among the participating energy producing and storage components. The selected design variables are as follows: a) number or capacity of PV panels (given a fixed surface area of each panel), b) number of wind generators (given a fixed capacity of each wind generator), c) number of accumulators (given a fixed capacity of each accumulator), d) maximum power of the electrolyzer, e) hydrogen buffer tank capacity, f) maximum produced power of the fuel cell, g) SOC_{min} limit and h) SOC_{max} limit. It should be noted that for the simulation of the system at hand, the mean hourly values of the solar radiation and the wind speed per annum are used. This time span is considered a sufficient period to use, since it captures all the necessary changes during the day and is considered satisfactory for the purpose of our study.

The operating and economic performance of the integrated power system is evaluated through a comprehensive objective function that is developed in this work. The proposed objective function involves costs such as investment, installation, operation, maintenance and replacement, as well as costs that may occur during the system operation, such as energy expenses in case of hydrogen deficit. Hence, the objective function takes the following form and is expected to determine the requirements of the components for the optimum operation of the integrated system:

$$f = C_{invest} + C_{oper.\&maint.} + C_{replace} + C_{deficit} \tag{1}$$

where: f is the final cost (€/yr), C_{invest} is the investment cost (including depreciation of purchase and installation cost for every subsystem) (€/yr), $C_{oper\&maint.}$ is the operation and maintenance cost (€/yr), $C_{replace}$ is the replacement cost, (€/yr), $C_{deficit}$ is the energy purchase cost in case of hydrogen deficit (€/yr).

The previously presented objective function and optimization variables are employed in an optimization algorithm in the form of Simulated Annealing (SA), (Papadopoulos and Linke, 2004). SA is a stochastic search method that is based on probabilistic search of the optimum solution. At each step of the method, a new value of the objective function is calculated by invoking random transitions on the design variables. Each calculated value of the objective function is either accepted directly if it improves the previously calculated value of the objective function or it is accepted with a certain probability if it deteriorates the previously calculated objective function value. The utilized probability value depends on the objective function values, as well as, on an algorithmic parameter called annealing temperature. As the annealing temperature decreases through the implementation of the algorithm, each new state of the design variables is selected based on states of the design variables corresponding to the previously accepted design solution. At higher annealing temperatures, more optimum or potentially optimum solutions are accepted, while at lower temperatures the algorithmic search is intensified only closer to solutions that improve the objective function value. Overall, the main aim of this method is to investigate and identify diverse operation and cost effective schemes and address significant design issues and operating limits that emerge from the integration of power production and storage components of varying requirements.

5.Results from the design and optimization process

As pointed out in Ipsakis et al. (2008a, 2008b), despite the fact that in PMS2 the electrolyzer and the fuel cell operate longer than in PMS1, PMS2 exhibits the advantage of using the accumulator to support the operation of the electrolyzer if the RES are not sufficient and reliable enough to fully meet the electrolyzer minimum operation point. Thus, in geographical regions such as Neo Olvio in Greece, where solar and wind energy fluctuate constantly, PMS2 is the most reliable for selection in order to design and optimize the integrated, stand-alone system. An installed application in the region of interest is selected (initial approach) and its economic and operating characteristics are calculated to enable a comparison of the system performance obtained through the employed optimization-based and the initial approach. In the latter case the design is performed heuristically by iterative selection of suitable capacities for the involved subsystems with the aim to decrease the cost. The aim of the optimization-based method is to minimize this cost by adjusting the design variables for the involved subsystems. For the integrated system optimization, the following values have been considered: load demand: 1kW, wind generator nominal power: 80W, PV panels nominal power 122.4 W, initial accumulator capacity: SOCinit=90% (855Ah), minimum operation power level of electrolyzer ($P_{min,elec}$): 25% of the nominal power level kW, initial hydrogen storage capacity: 60.5 Nm^3.

Table 1. Technical characteristics obtained for the integrated system

Design variables	Installed system characteristics	Optimization-based approach	Design variables bounds
Capacity of wind generators, kW	3	0.08	0 to 20
Capacity of PV-panels, kW	5	6	0 to 200
Capacity of accumulators, Ah	3000	1900	2 to 20
Buffer Tank Capacity, Nm^3	4.6	0.1	0.1 to 2
Maximum electrolyzer Operation level, kW	4.2	0.25	0.25 to 7.5
Fuel cell operation power level, kW	2	1	1 to 5
SOC_{min} limit	84%	74%	65% to 78%
SOC_{max} limit	91%	89%	82% to 96%
F, objective function €/yr	22,220	9,850	-

Table 1 shows results obtained using the initial and the optimization-based approach. The value of the objective function for the initial approach is found to be 22,220€/yr The results obtained using the optimization-based approach reveal that the optimum solution gives a value of 9,850€/yr in the objective function which is approximately 56% lower than the value obtained for the installed system. The main difference is observed in the wind generators capacity which should be lower than the installed one due to low wind speed conditions in the specified region. Subsequently, in the optimal design the PV capacity is increased to meet the specified load demand, while the accumulator capacity is decreased because of the lower imposed SOC limits. Furthermore, the optimal design results in an electrolyzer of smaller capacity, since power excess is not often observed. The fuel cell is operated at lower levels in order to protect the system from possible hydrogen deficits. It should be noted that the upper and lower bounds employed for the design variables were implemented based on research regarding the technical characteristics of the employed subsystems and the optimization method utilized is independent of the range of such bounds.

6. Conclusions

In this paper, a combined study of operation, design and optimization in integrated systems that exploit RES for a small scale application (up to 1kW) is performed. The investigations point out that prior to construction of such a complicated system, it is necessary to perform a systematic design analysis based on economic and other operational criteria for the selection of suitable subsystems capacity levels. The optimal design framework will further consider additional decision variables associated with the power management strategies for an overall system optimization.

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