On the Systematic Design and Optimization under Uncertainty of a Hybrid Power Generation System Using Renewable Energy Sources and Hydrogen Storage

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Abstract

This work addresses the optimal design and operation of a hybrid power generation system that uses renewable energy sources (RES) and hydrogen storage, while simultaneously accounting for associated design uncertainties in the form of stochastic variations in operating conditions. The considered hybrid system consists of photovoltaic panels, wind generators, accumulators, an electrolysis apparatus, hydrogen storage tanks, a compressor, a fuel cell and a diesel generator. The proposed design methodology involves the development of a power management strategy to determine all the feasible ways of dispatching power among the employed sub-systems. This is used in conjunction with an optimization method that considers design variables in the form of structural and operating parameters, as they directly affect the system performance. To emulate realistic operating conditions, the proposed design methodology is coupled with a systematic method to enable the efficient incorporation of uncertainties stemming from frequent external and internal system variations. Such uncertainties involve the fluctuating solar radiation and wind speed as well as the efficiency of the various energy conversion subsystems. The implementation of the design methodology results to robust and practically realizable system schemes, able to achieve high performance under a wide range of operating conditions.

Keywords: Renewable energy, hydrogen, systems design, uncertainty, optimization

1. Introduction

Systems that generate power using renewable energy sources (RES) are rapidly replacing power production based on conventional fuels. A major challenge that needs to be addressed in such systems is to facilitate the transformation into dependable and undisrupted power flows, of energy from sources that rely heavily on largely unpredictable natural phenomena. This goal is best served by the use of hybrid systems that combine multiple power generation units and storage media of diverse functionalities under an integrated power generation scheme. Such systems often involve photovoltaic panels and wind turbines to generate power that meets the demands of a targeted application. The intermittent nature of RES require the incorporation of batteries to store excess energy and release it under environmental condition variations. Whereas batteries are only able to serve short-term and limited power demands, hydrogen is emerging as an alternative, long-term and flexible energy storage medium that requires a rich infrastructure, to be integrated within hybrid power generation systems. Clearly, the involvement in the design of such systems of numerous
components with diverse operating characteristics causes significant complexities that require the implementation of efficient decision making methods. The intense presence of uncertainty due to fluctuating and unpredictable weather conditions or changes in the operational efficiency of the individual energy conversion units places additional requirements that need to be considered simultaneously with synergies developed among the employed sub-systems. Reported efforts to design systems with similar complexities are merely focused on the implementation of optimization algorithms on arbitrarily defined system characteristics [1-3], while the significant effects of uncertainty in the system performance have yet to be considered.

2. System description

The considered hybrid RES-based power system is shown in Figure 1. It consists of PV panels and wind generators for power generation. Surplus energy is supplied to an electrolyzer after the specified load demand for a targeted application is satisfied.

![Figure 1: Block diagram of the proposed hybrid RES-based power system.](image)

The produced hydrogen is stored in pressurized cylinders and in cases of energy deficit, is utilized in a fuel cell to provide the needed power to the system. Lead-acid accumulators (batteries) are used to regulate the power flows in the system through frequent charging and discharging cycles induced by the RES variability. In case of energy excess, units such as the hydrogen compressor utilize this energy to store hydrogen in long-term storage tanks. A diesel generator is also attached to the system and utilized only in cases of emergency (i.e. power demands of the application can not be covered by RES or stored hydrogen).

2.1. Power management

The system of Figure 1 involves several sub-systems with diverse requirements, that give rise to numerous operating options with regards to power utilization during system operation. The efficient integration of such subsystems requires the development of a power management strategy (PMS) to identify efficient operating decision alternatives, while maintaining a smooth system operation and protecting the individual components from irregular operating patterns that would eventually compromise their efficiency. Major operating parameters steering the generation of such alternatives are the state of charge (SOC) limits of the accumulator, the available system power (P) at any given time and the hysteresis band range (HBR), which determines the appropriate instance for initiation or termination of the operation of subsystems such as the electrolyzer and the fuel cells [4, 5]. The considered PMS involves the operating decision alternatives shown in Figure 2 for cases of power excess or deficit, depending on SOC values. In cases of power deficit (P ≤ 0), the power required to meet the load demand is provided directly by the accumulators, if there is sufficient power to avoid utilization of the fuel cell (SOC > SOC_{fc}). If there is no available power in the accumulators (SOC ≤SOC_{min}) the fuel cell is utilized, provided that hydrogen is available in storage. If SOC_{min} < SOC
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< SOC_{fc} and the fuel cell was operating in the previous time step (I_{fc}(t-1)≠0), the hysteresis band range (HBR=2%) enables prolonged operation of the fuel cell until the SOC reaches the limit SOC_{max} (defined as SOC_{min} + HBR). If the fuel cell did not previously operate (I_{fc}(t-1)=0), then it is not initiated to avoid frequent start-ups and shut-downs that could potentially lead to malfunction, and the load is covered by the accumulators. In case of power excess (P>0), the surplus power is used in the electrolyzer (SOC ≥ SOC_{max}) for the production of hydrogen, provided that the accumulators are charged to SOC_{max}. If the available power is higher than the power required from the electrolyzer (P > P_{max_elec}), the excess part is stored in the accumulators. This is possible due to the additional power storage available in the accumulator (over SOC_{max}) that is reserved to implement the hysteresis band policy. This extended SOC limit is in effect the sum of SOC_{max} and HBR and determines the point where only the auxiliary units may use the power excess. In case of insufficient power to enable operation of the electrolyzer (P < P_{min_elec}), the accumulators are used until P_{min_elec} is reached. In case of insufficient charge in the accumulators to enable operation of the electrolyzer (SOC < SOC_{elec}), the accumulators are charged. In case of SOC_{elec} ≤ SOC < SOC_{max}, if the electrolyzer did not operate at a previous instance then it is not initiated and the available power is routed to the accumulators.

Figure 2: Operating decision alternatives represented by PMS

2.2. Uncertainty characterization
The design of a RES-based power generation system using solar and wind energy sources involves either the use of historical weather data or weather forecast methods to predict the future temporal evolution of the RES. Despite the use of such methods, the behavior of weather conditions always involves high uncertainty. Unless such uncertainty is accounted for during the system design, the performance of the RES-based system will only be optimum within the range of the considered weather conditions. Potentially unpredictable weather fluctuations will inevitably result to suboptimal system operation. In addition to the external variations propagated in the system operation, the efficiency of several subsystems, comprising the integrated power system, varies due to intense utilization or other exogenous factors throughout their anticipated life-term. For example, the efficiency of the electrolyzer and the fuel cell may faint during a prolonged system operation due to the utilization of delicate and prone to wear and tear materials such as membranes. The rate of efficiency degradation involves uncertainty as it is linked to the variable mode of equipment utilization, which is in turn affected by the considered weather conditions and the PMS employed to address them. The consideration of a constant system efficiency is expected to result in
suboptimal system performance, hence variations in efficiency should be considered during system design. Although these two types of uncertainty, namely external and system-inherent, are considered in this work for the parameters of solar radiation, wind speed and subsystem efficiencies, other types of uncertain parameters can be addressed using the design methodology presented in the following section.

3. Proposed design methodology

The design methodology illustrated in Figure 3 is based on the algorithm of Stochastic Annealing [6], which is used to address uncertainty in systems design and optimization. After the problem initiation, values must be assigned to the uncertain parameters. In case that uncertainty is considered to be of deterministic nature, it is described either by specific bounds imposed on the value range of the considered uncertain parameters or through a finite number of fixed parameter values. In case it is considered stochastic, uncertainty is represented by a probability distribution, showing the potential range of values for a parameter, in addition to accounting for the probability of occurrence of each value in the considered range. This attribute is suitable for the weather-associated uncertainty considered in this work. Intense unexpected variations in weather conditions are expected to be less frequent than milder ones, hence such type of uncertainty can successfully be represented through a normal distribution. As a probability distribution is a continuous function, it is represented by a finite set of discrete samples obtained using an appropriate sampling method [6].

![Methodology for optimization under uncertainty of hybrid power generation system](image)

The system is subsequently simulated for each sample corresponding to the uncertain parameters. The temporal dependence of parameters such as solar radiation and wind speed require discretization into several time steps of the entire time period for which calculations are desired. The number of required time steps can be equal to the rate for which time-dependent data are available. In this respect each sample, represented by a randomly drawn value from the probability distribution, is added to the value of the time-dependent parameter for the entire set of considered time steps, hence emulating the unpredictable behavior of the uncertain parameters for the entire desired time period. As each point of the time-dependent data set is different in each time step (e.g. different solar radiation), the produced power is also of different intensity, hence the rules imposed by the PMS result to utilization of different subsystems in each time step. This procedure is iterated for the entire set of samples drawn from the probability distribution and correspond to a certain set of design variables. After termination of this set of iterations, the optimization algorithm invokes the generation of a new set of design variables and the procedure is repeated, until the overall algorithmic termination criteria are satisfied.
4. Implementation

4.1. Background
The aim of the performed optimization is to minimize the net present value (NPV) of investment for a ten year operating period. The considered costs involve initial purchase and installation capital and additional expenditures for the operation, maintenance and replacement of the employed equipment. The highest possible system autonomy from fossil fuels is also required, hence the use of the diesel generator is penalized during system optimization. The considered decision variables involve the number of PV panels \( n_{pv} \), the number of the wind power generators \( n_{wg} \), the nominal capacity of the accumulators \( n_{acc} \), the maximum operating power of the electrolyzer \( P_{max,e} \), the capacity of the intermediate \( V_b \) hydrogen storage tanks, the nominal power of the fuel cell \( P_{op,fc} \) and the upper (\( SOC_{max} \)) and lower (\( SOC_{min} \)) limits of the stage of charge of the accumulators. The considered uncertain parameters involve the solar radiation \( u_s,t \), the wind speed \( u_w,t \) as well as the efficiencies of the electrolyzer \( u_e \) and of the fuel cell \( u_{fc} \). The weather data are taken from a database in the form of hourly averaged data for a year, corresponding to the conditions observed in a particular geographical area. The uncertainty in the weather data is implemented through samples drawn from a normal distribution that enable a random deviation of maximum ±12% from the hourly averaged points. The uncertainty in the efficiencies is implemented through an one-sided normal distribution that enables random deviation of maximum -8% from a pre-specified efficiency. In this case the uncertainty is not time-dependent and is only allowed to decrease, to emulate the probability of fainting equipment performance. The load demand of the targeted application is allowed to vary within the range of 0.6-1.3 kW throughout the year.

4.2. Discussion of results
The addressed cases involve system design without consideration of uncertainty (C1) and design considering uncertainty (C2) in order to compare the system performance. Table 1 shows the design results obtained for both cases. The major differences between the two involve the significantly larger number of PV-panels \( n_{pv} \) required in C1 and the significantly larger intermediate storage tanks \( V_b \) required in C2.

Table 1: Design results for cases C1 and C2

<table>
<thead>
<tr>
<th>Case</th>
<th>( n_{pv} )</th>
<th>( n_{wg} )</th>
<th>( n_{acc} )</th>
<th>( P_{max,e} ) (kW)</th>
<th>( V_b ) (Nm(^3))</th>
<th>( P_{op,fc} ) (kW)</th>
<th>( SOC_{max} ) (%)</th>
<th>( SOC_{min} ) (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>C1</td>
<td>49</td>
<td>5</td>
<td>7</td>
<td>0.5</td>
<td>0.2</td>
<td>1</td>
<td>96</td>
<td>66</td>
</tr>
<tr>
<td>C2</td>
<td>45</td>
<td>6</td>
<td>6</td>
<td>0.5</td>
<td>0.9</td>
<td>2</td>
<td>93</td>
<td>68</td>
</tr>
</tbody>
</table>

Based on Table 1 the aim is to compare the economic performance of the designs corresponding to cases C1 and C2 in response to variations, hence a sample of variations is imposed only in the wind speed, the solar radiation and the fuel cell efficiency, and the results are shown in Figure 4a. The negative NPV of the investment is due to the widely acknowledged fact that such technologies are still under intense development and unable to compete the prices of conventional energy sources. In any case, it appears that under intensely favorable wind speed variations, unfavorable solar variations and high fuel cell efficiency, the design of C1 performs better than C2. However, as the wind speed deviates towards an increasingly negative direction and the fuel cell efficiency drops, a steep decrease is observed in the NPV for the design of C1, while the design of C2 remains unaffected and even presents a slight improvement. This shows that highly unfavorable operating conditions are addressed with increased efficiency when uncertainty has been accounted for during the design stages.
Figure 4: System performance under uncertainty in variations of wind speed, solar radiation and a) fuel cell efficiency, b) electrolyzer efficiency.

Figure 4b shows the effects of varying wind speed and solar radiation considered simultaneously with variations in the efficiency of the electrolyzer for C2. For negative variations in the solar radiation and positive variations in the wind speed, high efficiency in the electrolyzer leads to increased production of hydrogen that is stored in the long-term (final) storage tanks, which result in a higher required investment. In case of unfavorable wind conditions and favorably high solar radiation, the system requires a high efficiency in the electrolyzer in order to maintain decreased investment costs. The storage and consumption profile of hydrogen is also shown in Figure 4b. In the case of 89% electrolyzer efficiency, the capacity of the long-term hydrogen storage tanks is over 5m$^3$ (for compressed hydrogen), while as the wind conditions deteriorate the available hydrogen is gradually consumed.

5. Conclusions
The presented work addresses the optimal design of a hybrid RES-based power production system under uncertainty. The proposed design methodology determines the values for structural (i.e. equipment capacity) and operational (i.e. parameters of the PMS) design variables that optimize a performance criterion over the life span of the system under uncertainty due to unpredictable variation of weather phenomena and potential fainting equipment efficiency. In particular, the temporal variation of the weather conditions is addressed through an efficient power management strategy. The proposed methodology provides a reliable tool for the design of realistic and highly performing hybrid energy systems of complex structure in any geographical location.

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References