Journal of Process Control 24 (2014) 1318–1327

Contents lists available at ScienceDirect

Journal of Process Control

journal homepage: www.elsevier.com/locate/jprocont

An economic receding horizon optimization approach for energy management in the chlor-alkali process with hybrid renewable energy generation

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ARTICLE INFO

Article history:
Received 3 March 2014
Received in revised form 21 April 2014
Accepted 21 April 2014
Available online 23 May 2014

Keywords:
Hybrid renewable energy systems
Chlor-alkali process
Hydrogen
Receding horizon
Operational optimization

ABSTRACT

This paper presents a methodology for the application of receding horizon optimization techniques to the problem of optimally managing the energy flows in the chlor-alkali process using a hybrid renewable energy system (HRES). The HRES consists of solar and wind energy generation units and fuel cells to supply energy. The HRES is also connected to the grid and allows for buying or selling electricity from and to the grid. Initially, detailed models of each system component are introduced as the basis for the simulation study. Energy management strategies are then developed to realize the objectives of meeting production requirements while minimizing the overall operating and environmental costs. Sensitivity and uncertainty analyses are carried out to elucidate the key parameters that influence the energy management strategies. Finally, production demand response is integrated into the proposed methodology.

1. Introduction

The chlor-alkali process produces chlorine, caustic soda and hydrogen through the electrolysis of sodium chloride solution. The corresponding industry is one of the most important segments of chemical industries, the products of which are used in over 50% of all industrial chemical processes [1]. The chlor-alkali industry is also among the highest energy consuming processes due to the high electricity utilization with correspondingly high pollutant emissions that have serious impact on the environment and human health. It consumes approximately 10 GW of electrical energy per year, amounting to nearly 2% of the total electric power generated in the United States [2]. About 90% of the electric current is used as raw material which cannot be substituted, while the remaining 10% is used for lighting and operating pumps, compressors and other necessary equipment. Energy consumption of the plant is so large that it becomes the key issue to determine profitability. Significant research work has been conducted on how to reduce the environmental impacts and improve the energy efficiency of the process (e.g., see [3–6]).

Production of 1 kg of chlorine is accompanied by the production of 1.1 kg of caustic soda and 0.03 kg of hydrogen, which are also important products with a very wide range of applications [7]. However, the hydrogen is treated as a by-product by the chlor-alkali industry and most of it is not recovered for further use and thus wasted. One of the most innovative energy applications is to recover the hydrogen from industrial processes through fuel cells. Not only can this produce clean electricity, but it can also build up the complete supply chain to reuse the electrolytic hydrogen. The direct integration of fuel cells in an electrochemical plant by means of bus bars without interposition of any voltage converter or adjuster can efficiently take advantage of energy resources and significantly reduce investment and maintenance cost. There are several research and small-scale industrial applications on the direct connection of fuel cells to electrolyzers of electrochemical plants producing hydrogen as a by-product [8]. The benefits of combining fuel cells and electrolyzers to form a complementary system [9] have been observed previously; however, further research is needed to address the fundamental problems of economic system design, energy supply and optimal operational strategies of an electrolysis plant, such as the chlor-alkali process considered in this work.

On the other hand, faced with the increasing energy crisis, optimization of the design and operation of the next-generation

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http://dx.doi.org/10.1016/j.jprocont.2014.04.017
0959-1524/

industrial chemical plants may have to consider how to increase efficiency and reduce cost of the energy network. With utilization of existing infrastructures, how to add new renewable or co-generation units is one research direction [10]. The integration of multiple production processes to form a complete supply chain is also a meaningful approach to the problem. As a specific case of Enterprise-wide Optimization (EWO) that involves optimizing the operations of material and utility supply, manufacturing and distribution activities of a company to reduce costs and inventories [11], the concept of Enterprise-wide Energy Optimization (EWEO) is proposed to consider the optimal dispatch of electricity generation among all available resources as well as the operation of manufacturing facilities that often requires extensive energy use. In this work, the electrolysis can be conducted using any energy source, while renewable energy has become most attractive and also feasible to be integrated into existing infrastructures, making it one of the solutions to sustainable energy supply and the so-called "hydrogen economy" [12]. An additional advantage is that the cost of solar and wind energy has fallen sharply in recent years. Electricity from small or medium-scale photovoltaic (PV) installations costs around 12–30 cents/kWh, and these prices continue to demonstrate accelerating decline. It is even predicted that the cost of solar power will drop below retail electricity rates in many parts of the United States between 2013 and 2018 [13]. Similarly, the cost of wind energy has come down 85% in the last 20 years. According to the U.S. Department of Energy, the average cost of wind farms in areas with excellent wind resources and thus top performance varies about 7 cents/kWh, making wind the most cost competitive source of non-hydroelectric renewable electricity [14].

A Hybrid Renewable Energy System (HRES) combines solar, wind and other energy generation and storage units to deal with the intermittent generation and scarce supply of a single renewable resource [15]. Various methods for control and optimization have been applied to HRES [16]. Compared with traditional approaches, the combination of Receding Horizon Optimization (RHO) and hybrid renewable generation proves to be an effective approach to improve the economic and environmental performance [17,18]. RHO has been widely used in the development of planning and scheduling strategies for the process industries [19,20]. As the first layer of Model Predictive Control (MPC), the real-time receding horizon optimization performs a steady-state economic optimization of the plant variables, updated on a timescale of hours or days, and returns results for further advanced control systems [21]. The consideration of an economic objective aims at determining optimal strategies for the plant operation and achieving optimal solutions in an economic sense. Economic receding horizon optimization is also able to better manage uncertainties and reduce computational complexity, and thus can be a promising approach for the management of various process industries [22].

This paper focuses on the optimal design and operation of a grid-connected HRES comprising PV panels, wind turbines and fuel cells, to supply power to a chlor-alkali plant. The overall system structure and chlor-alkali process are first described in Section 2. A detailed modeling of each energy supply component is presented in Section 3. The formulation of the optimization problems and a base case study are discussed in Section 4. Then in Section 5, additional scenarios including uncertainties, demand management considerations and other factors are considered to guarantee that the production requirements are stably satisfied and that the overall system economic and environmental costs are minimized.

2. Process description

A schematic of the HRES considered in this work is depicted in Fig. 1. Wind and solar energy conversion systems are independently operated and supply electricity based on control set points. The stacks of fuel cells not only take advantage of the hydrogen directly produced from electrolysis, but also use hydrogen in storage tanks which is purchased from outside sources, along with air to supply oxygen to the cathode. Moreover, the plant is connected to a smart grid, so that either purchasing or selling electricity is allowed to profit and stabilize the whole system.

As the core part of the chlor-alkali plant, the series of electrolyzers compose the main electricity demand. The reaction at the anode of the electrolyzer is:

$$2Cl^-(aq) \rightarrow Cl_2(g) + 2e^- \tag{1}$$

The reaction at the cathode is:

$$2Na^+(aq) + 2H_2O + 2e^- \rightarrow H_2(g) + 2Na^+(aq) + 2OH^-(aq) \tag{2}$$

The total reaction is:

$$2Na^+(aq) + 2Cl^-(aq) + 2H_2O \rightarrow 2Na^+(aq) + 2OH^-(aq) + Cl_2(g) + H_2(g) \tag{3}$$

The chlor-alkali process is a specific electrolyzing system, which converts electrical energy into chemical energy, as well as producing certain useful products. The decomposition of water into hydrogen and oxygen can be achieved by passing an electric current (DC) between two electrodes separated by an aqueous electrolyte with good ionic conductivity. Similarly, using brine as the raw material, chlorine and hydrogen, as well as caustic soda can be produced as products.

The electrolyzer model in this work is based on the modeling approach presented in [23], which is developed for alkaline water electrolysis – the same process as chlor-alkali, but using aqueous potassium hydroxide (KOH) solution in water as an electrolyte. Since the system-wide optimization is the main focus of this work, the model of alkaline electrolysis cell will be adopted here to approximate the chlor-alkali process, which may result in minor differences in values but still maintains similar trends and characteristics with real conditions. Such an electrolysis cell works as follows: two electrodes (anode and cathode) are placed in an electrolyte (usually a 20–30% aqueous KOH solution) separated by a diaphragm. An electrolyzer consists of a stack of cells; i.e., several cells linked in series, with operating temperatures varying from 343 K to 373 K.

The model consists of three parts: thermodynamic, electrochemical and thermal. Assuming hydrogen and chlorine to be ideal gases, water to be an incompressible fluid, and the gas and liquid phases to be separated, the Gibbs energy ΔG can be calculated at standard pressure and temperature (1.013×10^5 Pa and 298 K). The change in Gibbs energy describes the reversible work in order to operate a chemical process, in this case to split water. The electrical energy needed for this process is calculated using Faraday's law. The reversible cell voltage U_{rev} is therefore given by:

$$U_{rev} = \frac{\Delta G}{zF} \tag{4}$$

where F=96,485 As/mol is the Faraday constant and z is the number of electrons exchanged (2 electrons in this case). Since the reaction is irreversible and heat is produced, the total amount of energy required for the process is described by the change in enthalpy ΔH. The thermoneutral cell voltage U_{tn} describes the voltage related to the change in enthalpy:

$$U_{tn} = \frac{\Delta H}{zF} \tag{5}$$

Since U_{rev} changes only slightly with changing pressure and temperature, and U_{tn} changes even less, both are considered