PRODUCTION SCHEDULING OF AIR SEPARATION PROCESSES

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Abstract

Cryogenic air separation is an important industrial process, which separates air into pure gas and liquid products. The process is highly energy intensive and a major operating cost is electricity. Today the electricity markets in many regions are deregulated, which means the electricity price may fluctuate frequently. At the same time, many other key factors in plant operation may also change with time. These include customer demands, inventory levels, equipment conditions, etc. In this paper, a typical air separation process, previously discussed for the purpose of real time optimization (RTO), is reconsidered for production scheduling by taking the future profiles of these important factors into account without uncertainty. A combined RTO and scheduling strategy is proposed based on the characteristics of air separation processes to optimize the total profit margin in a certain time horizon. Several critical issues in practical operation such as switching on/off certain equipment within limited time are also addressed in one comprehensive optimization problem.

Keywords

Cryogenic air separation, real time optimization, production scheduling, rolling horizon method, mixed integer nonlinear programming.

Introduction

Air separation is an important industrial process that provides pure air components in both gas and liquid product forms to many industrial, environmental and medical applications such as refineries, metallurgy, glass, electronics, waste water treatment, and hospitals (Vinson, 2006). Among different air separation techniques, cryogenic distillation is an important one, which can provide high purity products in large production rates. There are 3 major components in the air, i.e. nitrogen (78%), oxygen (21%) and argon (0.9%). In a cryogenic air separation unit (ASU), air is first compressed to a high pressure and then liquefied at a very low temperature. The liquefied air is separated into oxygen, nitrogen and argon of high purity through a series of distillation columns and other equipment. Except argon, which is usually liquid, the final products can be either in the gas or liquid phase depending on the type of use and the design of the process. The gas products usually serve customers nearby, referred as over-the-fence customers, or pipelines, which typically connect a number of ASU plants and customers. And the liquid products are usually first stored in cryogenic tanks and then delivered to customers through truck trailers. The production rates of gas and liquid products of an ASU are often linked through certain relationships including mass and energy balances, although the specific functions are usually different based on different process designs (Air Liquide, 2005).

In general, cryogenic air separation is a very energy intensive process where a great amount of electricity is consumed in air compression and gas product liquefaction if there are liquefiers. The Air Liquide Group, for example, has more than 400 ASUs worldwide, and the group's total

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electricity consumption in 2010 corresponds to more than one thousandth of the world's total electricity consumption according to published data (Air Liquide, 2011 and BP, 2011). The electricity bill is one of the major operating costs of cryogenic air separation plants. So optimizing the operation is important in improving an industrial gas company's profit and competitiveness while reducing energy consumption and carbon footprint.

Currently, many air separation plants are operated in a dynamic economic environment. The electricity market is deregulated in many regions, so the electricity price changes hourly. Figure 1 shows the published settle point power price at each hour in the Houston, Texas area on July 25, 2011 (ERCOT, 2011). It can be seen that the highest price is about 10 times the lowest price. Under such a condition, in order to maximize the operating profit, an optimal operation schedule would most likely produce more liquid when electricity price is low and store the excess in tanks, and produce less or no liquid when electricity price is high as long as customer demands can be met. However, in practice, most ASUs are still operated only to meet their major production targets in real time, and this kind of price profile is not considered. Although the real time optimization of air separation plants is dealt with by Li, et al. (2011), the solution only optimizes the current operating condition and does not consider the conditions throughout a time horizon into the future. So the profit can be further improved by considering such a horizon.

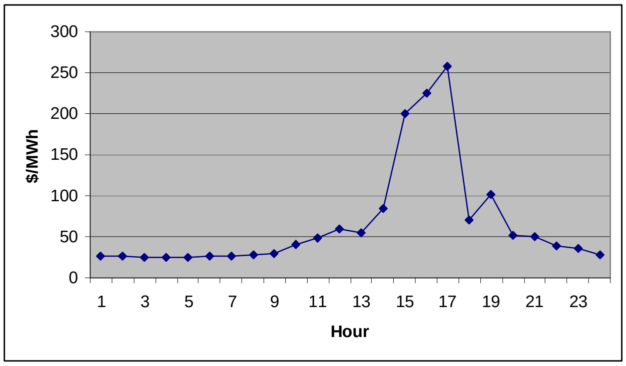

Figure 1. Houston electricity price over a 24 hour period on July 25, 2011

In practice, based on specific contracts between plants and power suppliers, sometimes the hourly electricity price over the coming days can be known in advance. Even if the exact information is not available when the electricity price is decided in real time by the regional spot market, certain forecasting models and techniques can be used to forecast the future hourly electricity price from current and historical information (e.g. Ierapetritou et al, 2002). Customer demand prediction is similar. For some plants, the demands are very stable so that they can be predicted very accurately. For others, the demands are more difficult to predict so that certain models should be used to forecast the future demands (e.g., Heath and Jackson, 1994). Anyhow, price and demand forecasts and incorporation of corresponding probabilities into optimization are beyond the scope of this paper, so it is assumed that all future profiles can be known without uncertainty for the rest of the discussion.

In principle, the scheduling can only be applied for the liquid production because cryogenic tanks storing liquid serve as buffers. For the gas production, unless there are pipelines with large volumes (which become cases of higher complexity), there are usually no such buffers so that real time optimization still needs to be carried out. As mentioned above, the production rates of gas and liquid are usually linked so that the problem becomes an integration of real time optimization of the current plant condition and production scheduling for a future time horizon. It will be seen that this feature is represented in the optimization problem formulation.

In this paper, the example studied by Li et al. (2011) will be revisited as a typical ASU process to illustrate the formulation of its scheduling problem and the strategy in applying the time-dependant results. Special issues related to equipment constraints, which are common in ASU operations, are also addressed.

Process Description

Over more than 100 years of improvements and optimization, the cryogenic air separation process has a variety of designs (Air Liquide, 2005). Some ASUs produce both gas and liquid, while others mainly produce gas products. For plants with the latter type of ASUs, there are often liquefiers which liquefy some of the gas into liquid. In certain designs, a liquefier can be even integrated with an ASU so that most of the products from such an ASU are liquid.

Although there are different designs, they share certain similarities providing a foundation for studying production scheduling. Li et al. (2011) presented an ASU plant model as a typical process for real time optimization study. The plant has two ASUs (I and II), and produces both gas and liquid products. The gas products include oxygen (GOX), nitrogen (GAN) and, specifically to this plant, compressed air (CA), and directly serve the over-the-fence customer. The liquid products include oxygen (LOX), nitrogen (LIN), and argon (LAR). They are first stored in cryogenic tanks and then delivered to customers by trucks. Each ASU has a main air compressor, which consumes most of the electricity. Only ASU I produces argon. Additionally, ASU II has a turbine which can be turned on or off. If the turbine is turned on, it generates additional refrigeration so that more liquid can be produced. For the purpose of real time optimization, the following degrees of freedom, or called manipulated variables (MV), are identified based on the process design:

1. Air flow rate to the ASU I (MV_1);
2. GOX production rate of ASU I ($MV_2/Q_{GOX,I}$)
3. Compressed air production rate of ASU I ($MV_3/Q_{CA,I}$)
4. LIN production rate of ASU I ($MV_4/Q_{LIN,I}$)
5. Air flow rate to the ASU II (MV_5)
6. LIN production rate of ASU II ($MV_6/Q_{LIN,II}$)
7. The on/off status of the turbine (MV_7)
8. The flow rate through the turbine if it is on (MV_8)

The rest of the process variables involved can be derived from these MVs directly or indirectly. The key variables involved and corresponding functions are:

$$Q_{LOX,I} = f_1(MV_1, MV_2, MV_4) \tag{1}$$

$$Q_{LOX,II} = f_2(MV_5, Q_{GOX,II}, MV_6, MV_7, MV_8) \tag{2}$$

$$Q_{LAR,I} = f_3(MV_1, MV_2) \tag{3}$$

$$k_I = f_4(MV_1, MV_3) \tag{4}$$

$$k_{II} = f_5(MV_5, Q_{CA,II}) \tag{5}$$

where $Q_{LOX,I}$, $Q_{LOX,II}$, $Q_{GOX,II}$, $Q_{LAR,I}$, k_I, k_{II}, $Q_{CA,II}$ are the LOX production rates of ASU I and ASU II, GOX production rate of ASU II, LAR production rate of ASU I, power of the air compressors of ASU I and ASU II, and flow rate of compressed air from ASU II respectively. Since ASU I and ASU II serve the same customer with GOX and compressed air, $Q_{GOX,II}$ and $Q_{CA,II}$ can be easily calculated as:

$$Q_{GOX,II} = Q_{GOX,customer} - Q_{GOX,I} \tag{7}$$

$$Q_{CA,II} = Q_{CA,customer} - Q_{CA,I} \tag{8}$$

where $Q_{GOX,customer}$ and $Q_{CA,customer}$ are the total customer demands of GOX and compressed air. In addition, the ASU plant provides GAN to the customer. But the production of GAN from the process is usually abundant so that it is not considered in the production optimization or scheduling.

From the above equations, it can be easily seen that the production of gas and liquid products are linked and the production of different liquids are also linked. This is quite typical among different ASU process designs without liquefiers. Even for those ASU plants with liquefiers, which give them more flexibility in producing liquid, the liquid production rates are usually not totally independent.

Problem Definition

The operating cost in such a process is mainly the electricity used by the air compressors. So for real time optimization, the objective is to maximize profit margin at the current time (Li, et al. 2011), which is

$$\max \begin{bmatrix} (Q_{LOX,I} + Q_{LOX,II}) \cdot P_{LOX} + (Q_{LIN,I} + Q_{LIN,II}) \cdot P_{LIN} \\ + Q_{LAR,I} \cdot P_{LAR} + (Q_{GOX,I} + Q_{GOX,II}) \cdot P_{GOX} \\ + (Q_{CA,I} + Q_{CA,II}) \cdot P_{CA} - (k_I + k_{II}) \cdot P_e \end{bmatrix} \tag{8}$$

where P_{LOX}, P_{LIN}, P_{LAR}, P_{GOX} and P_{CA} (€/normal m^3) are the prices of LOX, LIN, LAR, GOX and compressed air, and P_e is the electricity price at this hour (€/kWh). The constraints are derived from specifications of the process design and equipment limits, e.g.

$$MV_{1,\min} \le MV_1 \le MV_{1,\max} \tag{9}$$

where $MV_{1,\min}$ is the lower bound of the air flow rate to ASU I, which is the minimal amount of air flow needed in order to run the process properly based on its design, and $MV_{1,\max}$ is the upper bound, which is determined by the limit of the air compressor and thus a function of ambient temperature. Eq. (1) – (5) and other equations in the model are either linear or nonlinear, and binary variables, e.g. MV_7, are involved in the model. As a result, the problem is a mixed integer nonlinear programming (MINLP) problem, which can be solved with an MINLP solver, e.g. AOA (Paragon Decision Technology, 2010).

When the above real time optimization problem is extended as a scheduling problem in a future time horizon, the objective function in Eq. (8) can be formulated as:

$$\max \left[\begin{array}{l} \left(\sum_t Q_{LOX,I}(t) + \sum_t Q_{LOX,II}(t) \right) \cdot P_{LOX}(t) \\ + \left(\sum_t Q_{LIN,I}(t) + \sum_t Q_{LIN,II}(t) \right) \cdot P_{LIN}(t) \\ + \sum_t Q_{LAR,I}(t) \cdot P_{LAR}(t) \\ + \left(\sum_t Q_{GOX,I}(t) + \sum_t Q_{GOX,II}(t) \right) \cdot P_{GOX}(t) \\ + \left(\sum_t Q_{CA,I}(t) + \sum_t Q_{CA,II}(t) \right) \cdot P_{CA}(t) \\ - \left(\sum_t k_I(t) + \sum_t k_{II}(t) \right) \cdot P_e(t) \end{array} \right] \tag{10}$$

where t is the index of discrete time points, e.g. hour, and $P_e(t)$ is the electricity price of the specific hour, which may change as in Figure 1. Although product prices do not change as frequently as electricity does, they are expressed as functions of time for generality. Most of the constraints can be adapted in a straightforward way. For example, the constraint in Eq. (9) becomes a series of constraints as:

$$MV_{1,\min}(t) \le MV_1(t) \le MV_{1,\max}(t) \tag{11}$$

The important constraints that link all the variables at all the time points are from the storage tank limits. Usually, these storage tanks should not be overfilled or emptied. So these constraints can be formulated as:

$$V_{LOX,\,\text{truck}} \le \left(\sum_{t=1}^{N_1} Q_{LOX,I}(t) + \sum_{t=1}^{N_1} Q_{LOX,II}(t) \right) + L_{LOX}(0) \tag{12}$$

$$\left(\sum_{t=1}^{N} Q_{LOX,I}(t) + \sum_{t=1}^{N} Q_{LOX,II}(t) \right) + L_{LOX}(0) \le V_{LOX,\,\text{tank}} - V_{LOX,\,\text{truck}} \tag{13}$$

$$V_{LIN,\,\text{truck}} \le \left(\sum_{t=1}^{N_2} Q_{LIN,I}(t) + \sum_{t=1}^{N_2} Q_{LIN,II}(t) \right) + L_{IN}(0) \tag{14}$$

$$\left(\sum_{t=1}^{N} Q_{LIN,I}(t) + \sum_{t=1}^{N} Q_{LIN,II}(t) \right) + L_{IN}(0) \le V_{LOX,\,\text{tank}} - V_{LIN,\,\text{truck}} \tag{15}$$

where $t = 1, \cdots, N$ is the full scheduling horizon, N_1 and N_2 are the time points when the LOX and LIN trucks come, $V_{LOX,\,\text{truck}}$ and $V_{LIN,\,\text{truck}}$ are the volumes of the trucks separately, and$V_{LOX,\,\text{tank}}$ and $V_{LIN,\,\text{tank}}$ are the volumes of the LOX and LIN tanks. If there are more than one truck comes, Eq. (12) to (15) can be easily extended. Because of these constraints, the optimization at each time point cannot be solved by itself, and the whole scheduling problem must be solved as a whole.

Switching Costs and Constraints

In the ASU scheduling problems, switching certain equipment, e.g. compressors or turbines, on/off, is often associated with costs and subject to constraints. Instead of introducing switching variables as proposed by Ierapetritou et al. (2002), they can be directly expressed by using the binary variables representing the on/off states of the equipment.

Cost of Turning on/off Equipment

Here it is assumed that turning on the turbine is associated with a certain cost C_{on}, while there is no cost to turn it off. Then this cost should be included in the objective function by using MV_7:

$$C(t) = \frac{1}{2} C_{on} \left[MV_7(t) - MV_7(t-1) \right] \left[MV_7(t) - MV_7(t-1) + 1 \right] \tag{16}$$

where $C(t)$ is the cost at time t. So the total cost is

$$C_{Total} = \sum_{t=1}^{N} C(t) \tag{17}$$

where N is the length of the time horizon. Specially, when $t = 1$, $MV_7(0)$ is the current status of the turbine, which is a known value. This total cost can then be subtracted from the objective function in Eq. (10).

Limitation of Turning on/off Equipment

Certain equipment such as a compressor or turbine cannot be turned on/off too frequently even if the optimization result indicates that this can increase the profit. So in addition to the cost in the objective function mentioned, certain constraints need to be added based to limit the change of binary variable values representing its on/off status. For example, if the turbine can only be turned on or off n times within the scheduling horizon, the constraints can be formulated as:

$$\sum_{t=1}^{N} \left[MV_7(t) - MV_7(t-1) \right]^2 \le n \tag{18}$$

Although the above formulations use the turbine as the example, similar formulations can be used for the costs and constraints associated with switching other equipment, such as compressors, liquefiers, a whole air separation unit within a plant with multiple units, or even an air separation plant connected to a pipeline.

Solving and Implementing Solutions

The scheduling problem is still an MINLP problem but with a larger size, so it can still be solved by using an MINLP solver such as AOA. If $N = 10$, the problem is about 10 times larger in terms of numbers of variables and constraints. In general, such a problem is non convex, so a global solver or certain global optimization strategy should be used to increase the chance of finding global optimum. AIMMS offers the multistart technique for global optimization (Roelofs, M. and Bisschop, J., 2010). The multistart technique tries different starting points in solving the optimization problem. The advantage is that users can define the number of starting points. With more points, the chance of global optimization is higher, but the solving time is also longer. So users can choose a suitable number based on the balance between optimality and time constraint, which is important in real time optimization applications.

Because the gas production still needs to meet customer demands in real time, the production rates should be still from the optimization based on real time information. The scheduling is mainly for the liquid production. Since there is always uncertainty in future time information including customer demands and ambient condition, only the solution corresponding to the first time point should be applied to the current plant operation. Then a rolling horizon strategy should be adopted at each time step (Li and Ierapetritou, 2010).

Conclusion

In the paper, the special features of the scheduling problem of a typical ASU process producing both gas and liquid are presented, including the formulation of special constraints commonly seen in such a scheduling problem. The optimization feature and corresponding solution strategy are discussed. Not only can the solution be easily extended to other types of air separation plants, but also adapted for other similar processes where both real time optimization and production scheduling without uncertainty are needed.

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