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Process Optimization for Industrial Load Management

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Abstract – *Continuous process industries engaged in large scale manufacturing of chemicals and fertilizers are highly energy intensive and contribute significantly to system peak demand. Consequent to the introduction of TOU tariff rates by the utilities, industrial load management programs aimed at economic reduction of electric energy demand of the industries during utility's peak generation period , gained importance. This paper presents an optimization model and formulation for peak demand and electricity cost reduction in continuous process industries. The formulation utilizes non - linear programming technique for minimizing the electricity cost by rescheduling the loads satisfying the process, production, and maximum demand constraints. The proposed optimal schedules when applied to a typical chemical plant resulted in significant reduction in peak demand (about 16.8%) and electricity cost (about 4.6%) under the TOU tariff.*

Keywords – Load scheduling, non linear programming, peak demand, TOU tariff.

1. INTRODUCTION

Electrical energy today constitutes about 37% of the total annual energy consumption on a worldwide basis [1]. Demand for electricity is growing globally at a rate higher than that of economic growth. Electricity consumption rate continues to increase, due to the improvement in standard of living and changes in electricity usage pattern resulting from technological advancements. Consequently, the electricity supply industry is unable to keep pace with the increasing demands resulting in energy shortage and peak demand deficits, in many developing countries.

The industrial sector in India is a major energy user, accounting for about 35% of the electrical energy consumption. Among the various sub sectors, the fertilizer and chemical process industries is the second largest with 19.65% and iron and steel industry stands at the top with 21% of the total industrial electricity consumption, details of which are shown in Table 1 [2]. Load management (LM), which changes the shape of the load curve so that generations by costly peak load stations can be avoided or deferred, has emerged as an effective technique to handle the peak demand deficit faced by the electricity supply industry. Load management programs focus on reducing customer use at the time of high utility system loads.

Many utilities all over the world, have already implemented the TOU tariff rates as viable load management option to manage their peak demand problem. Since the industries consume a significant proportion of the total electrical energy generated, industrial load management (ILM) is a subject of active interest throughout the electricity supply industry. The process industries engaged in large scale manufacturing of chemicals and fertilizers are bulk consumers of electricity. Hence the LM action like load scheduling can result in significant reduction of peak demand, under TOU tariff. Application of industrial load management (ILM) using interruptible load control schemes by utilities have been reported [3].

A non linear model developed to obtain electrical demand behaviors of the electrolytic cell in a typical aluminum smelter plant has been discussed [4]. A comprehensive methodology for the dynamic modeling of aqueous electrolyte systems involving solid, liquid and vapor phases has been reported [5]. Data-driven modeling technique has been applied to the industrial grinding operation of a lead–zinc ore beneficiation plant to predict the output variables and key performance indicators [6]. Control and optimization techniques are proposed for enhancing the plant performance. Most of these models reported for process industries are aimed at process scheduling, to achieve the targeted production subject to the plant constraints and does not address the problem of peak demand reduction.

Table 1. Electricity consumption of selected industries in India

Industry	Electricity Consumption GWh	Percentage of total %
Iron and Steel	19 705.59	21.00
Chemicals and Fertilizers	18 459.24	19.65
Aluminium	12 481.98	13.30
Cement	9 883.07	10.53
Textiles	8 619.54	9.18
Minerals and Petroleum	6 899.66	7.35
Paper	3 986.48	4.24
Engineering	2 524.42	2.68
Others	1 132.75	12.07
Total	93 848.93	100.00

A study describing the pilot effort to measure load reductions from a residential electric water heater load control program, using low-cost statistically based measurement and verification approach has been presented [7]. A physically based load modeling methodology that allows independent consideration of individual load components use and response models and evaluation of its dynamic behavior has been reported [8].

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An optimization model based on an analytic load model of the load under control has been discussed [9]. It is an aggregated approach and cannot represent the characteristics of industrial loads. An optimization formulation of load side demand control has been presented [10]. As the model does not consider storage and process constraints, it cannot be applied to process industries. A general approach to solve the optimal contracting capacity for a petrochemical plant with an in-house cogeneration system has been reported [11]. The model optimizes the operation of cogeneration plant, to reduce peak demand and hence the electricity cost.

In this paper, a new approach for load modeling with an optimization formulation for load scheduling is proposed, which can be applied in deciding the optimal operating strategies of continuous process industries. This is done in continuation to the physical models proposed in previous papers. The formulation incorporates the non-linear characteristics of industrial loads. It is suitable for applying TOU tariff with differential pricing system for both energy and maximum demand. The formulation utilizes non - linear programming technique for minimizing the electricity cost by scheduling the loads satisfying the process, production, and maximum demand constraints.

2. MATHEMATICAL FORMULATION

Discrete time representation is used in the formulation and the entire time horizon T of interest (say one day) is split into K intervals of equal duration (for example 30 minutes). The time horizon T is partitioned to different time slots to facilitate the billing by a time differentiated tariff, both for maximum demand and energy. In a typical TOU tariff, it is partitioned to three slots; normal time, peak time and off peak time:

$$T = T_n + T_p + T_o \tag{1}$$

where, T_n, T_p and T_o are normal, peak and off peak time periods respectively.

Normal time period:

$$T_n = \sum_{i=1}^{m} t_i \tag{2}$$

where, m is the number of time intervals during the normal time.

Peak time period:

$$T_p = \sum_{i=m+1}^{m+n} t_i \tag{3}$$

where, n is the number of time intervals during the peak time.

Off peak time period:

$$T_o = \sum_{i=m+n+1}^{K} t_i \tag{4}$$

However, if the TOU tariff followed by the utility stipulates the partition of time horizon into more than three slots, it can be incorporated in the model.

The entire manufacturing plant is split into E sub plants and all the electrical equipments with controllable loads in a sub plant are grouped together and considered as a single unit. L_{ei}, the fractional loading of the electrical equipments of e^{th} sub plant at any interval i is taken as the decision variable such that:

$L_{ei} = 0$; If the electrical equipment of e^{th} sub plant is off in the interval i : (5)

$0 < L_{ei} \le 1$; If the electrical equipment of e^{th} sub plant is on in the interval i : (6)

The power factor $\cos\phi_{ei}$ and efficiency η_{ei} of the electrical equipment of e^{th} sub plant at any interval i is obtained from a quadratic fit to the manufacturers' data:

$$\cos\phi_{ei} = A * L_{ei}^2 + B * L_{ei} + C \tag{7}$$

$$\eta_{ei} = P * L_{ei}^2 + Q * L_{ei} \tag{8}$$

where, A, B, C, P, and Q are coefficients of the electrical equipment of any sub plant e.

The electrical power input KW_{ei} in kW to the electrical equipment of any sub plant e at any interval i:

$$KW_{ei} = (R_e * L_{ei}) / \eta_{ei} \tag{9}$$

where, R_e is the rated capacity of the electrical equipment of sub plant e in kW.

Maximum demand in kVA of any sub plant e at any interval i is:

$$MD_{ei} = KW_{ei} / \cos\phi_{ei} \tag{10}$$

Maximum demand of the entire manufacturing plant in kVA at any interval i is:

$$MD_i = \sum_{e=1}^{E} MD_{ei} \tag{11}$$

Maximum demand of the plant in kVA during the normal time T_n :

$MD_n = Max.\left[MD_i\right]$; for all intervals i, $1 \le i \le m$ (12)

Maximum demand of the plant in kVA during the peak time T_p :

$MD_p = Max.\left[MD_i\right]$; for all intervals i, $m+1 \le i \le m+n$ (13)

Registered maximum demand of the plant in kVA:

$$RD = Max.\left[MD_n, MD_p\right] \tag{14}$$

Maximum demand charge for the billing period:

$$MC = RD * CD \tag{15}$$

where, CD is the cost of maximum demand (Rs./kVA), during the billing period.

The objective of load scheduling operation is to minimize the electricity cost satisfying the production, process, storage and maximum demand constraints. The objective function minimizing the monthly electricity cost is:

$$Min.\left[\sum_{i=1}^{K}\sum_{e=1}^{E}\left(KW_{ei} * t_{ei} * D * CE_i\right) + MC\right] \quad (16)$$

where, t_{ei} - time of operation of the electrical equipment of

e^{th} - sub plant for any interval i

D - number of days in a month.

CE_i - cost of energy (Rs./kWh) for the interval i

Production constraint to ensure that specified minimum production level TD is achieved in the time horizon under consideration is:

$$\sum_{i=1}^{K}\sum_{e=1}^{E} TH_{ei} * t_{ei} * L_{ei} \geq TD \quad (17)$$

where, TH_{ei} is the production rate (tons/hour) of the sub plant e at any interval i.

In order to maintain production, a specified minimum quantity of raw material flow has to be maintained. This can be ensured by the constraint:

$$L_{ei} = 0 \text{ ; If } F_{ei} \leq a_r \text{ for } r = 1 \text{ to } N \quad (18)$$

where, F_{ei} - the flow rate of raw material flowing through the sub plant e at any interval i.

a_r - minimum flow rate of the r^{th} raw material.

N - number of raw materials.

Total production of the manufacturing plant during the time period under consideration shall not exceed the total storage capacity and it is ensured by the constraint:

$$\sum_{i=1}^{K}\sum_{e=1}^{E} TH_{ei} * t_{ei} * L_{ei} \leq \sum_{j=1}^{M} S_j \quad (19)$$

where, S_j - storage capacity of j^{th} storage.

M - number of storages.

In continuous process chemical industries, the quality of the raw material flowing through the production stream is an important parameter. Considering as a general case, it can be modeled as:

$$L_{ei} = 0 \text{ ; If } Q_{ei} \geq b_r \text{ for } r = 1 \text{ to } N \quad (20)$$

where, Q_{ei} - the impurity content in the raw material flowing through the e^{th} sub plant at any interval i.

b_r - maximum limit of impurities in the r^{th} raw material.

Maximum demand limit is an important factor to be considered in load scheduling, because most of the industries are subjected to peak demand restrictions. Maximum demand of the entire plant in kVA at any interval i :

$$\sum_{e=1}^{E} MD_{ei} \leq KVA_i \quad (21)$$

where, KVA_i is the maximum demand limit in kVA, imposed by the utility at any interval i.

The solution to the above non linear programming formulation for minimizing the electricity cost satisfying the constraints, provides the optimal operating strategy for the process under consideration, for a given production target and electricity tariff rate.

3. CASE STUDY

A case study of a typical caustic soda manufacturing plant in Kerala, India is presented here, to illustrate the methodology proposed. Caustic soda (sodium hydroxide) is manufactured by the electrolysis of salt brine using membrane cell technology. The process is energy intensive and electricity cost accounts for almost 60% of the total cost of production. Hydrogen and chlorine gases are by-products and they are combined in a controlled atmosphere to produce hydrochloric acid. Compressed chlorine gas is bottled in high-pressure cylinders. A simplified process flow diagram of the plant is shown in Figure 1. The connected load of the plant is 40 MW with 25 MVA contract demand. Average daily electricity consumption is about 460 MWh with specific energy consumption of about 2600 KWh/t [12]. The load curve of the plant for a typical day is shown in Figure 2. Power supply is at 110 KV from Kerala State Electricity Board (KSEB) grid.

With the present TOU tariff rate followed, the base demand charge is Rs. 245/KVA/month of billing demand while the base energy charge is Rs. 2.90/KWh [13]. The utility follows differential pricing for both energy and maximum demand. As per Tariff 1, the TOU tariff applicable to the industry, the demand and energy charges are approximately in the ratio1:1.8:0.75 for normal, peak and off peak periods. The impact of load scheduling under a demand flat and energy differential tariff (Tariff 2), followed by another utility company is also evaluated for comparison. Details of the tariff rates are shown in Table 2.

The optimization model as per Equation 16 is developed, based on the equipment and process data. The corresponding non linear programming formulation is solved using Hyper LINGO [14].

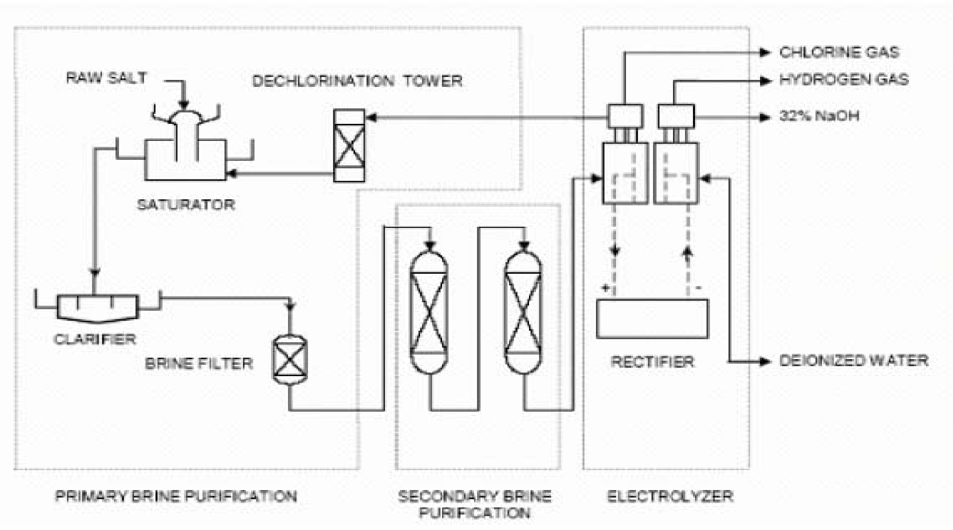

Fig. 1. Process flow diagram

Table 2. Tariff rates

Tariff	Base M D Charge Rs./KVA	Base Energy Charge Rs./KWh	Time Partition	Differential Rate	
				Demand	Energy
Tariff 1	245	2.90	Normal: 6am-6pm Peak:6pm-10pm Off peak:10pm-6am	Differential	1:1.8:0.75 (for normal, peak and off peak periods)
Tariff 2	350	2.65	Partial peak:6am-9am Peak:6pm-10pm Off peak:10pm- 6am Normal: rest of the day	Flat	1:1.23:1.37:0.68 (for normal, partial peak, peak and off peak periods)

Table 3. Results of load scheduling

Description	Tariff 1		Tariff 2	
	Normal Operation	Load Scheduling	Normal Operation	Load Scheduling
Maximum Demand (Peak) MVA	19.60	16.30	19.60	15.95
Electricity Charge (Rs. million /month)	46.87	44.72	42.80	42.12
Annual Saving (Rs. million)		25.80		8.16
Annual Saving (%)		4.59		1.59
Peak Demand Reduction (%)		16.84		18.59

4. RESULTS AND DISCUSSION

Results of load scheduling operation under two different tariffs - the demand and energy differential tariff (Tariff 1) and demand flat and energy differential tariff (Tariff 2) are shown in Table 3. Figure 2 shows the comparison of load curves for existing operation and load scheduling under two different tariffs.

It can be seen that under the prevailing tariff (Tariff 1), the load re-scheduling will result in an annual saving of Rs.Million. 25.80 (4.59%) in the electricity cost. Maximum demand of the plant during the system peak gets reduced from 19.60 MVA to 16.30 MVA (16.84%). During the peak hours, at an average of 5.02 MW of load gets reduced which results in a reduction of 20.08 MWh/day in electricity consumption. In order to maintain the same level of production, corresponding load is increased during off peak hours, resulting in valley filling.

In respect of demand flat and energy differential tariff (Tariff 2), the load re scheduling results in peak demand reduction from 19.60 MVA to 15.95 MVA (18.59%). But the savings in electricity cost achieved is not that significant. The load scheduling operation results in an average load reduction of 5.29 MW during peak hours and 2.78 MW during partial peak hours. This in turn results in a reduction of about 21.18MWh/day and 0.83 MWh/day during peak and partial peak hours respectively, in electricity consumption. Here also the reduction in load during peak and partial peak hours is compensated by corresponding increase during off peak and normal hours, resulting in valley filling.

Attempt has been made to assess the impact of load scheduling on the utility's load curve, if all the major process industries connected to the utility grid resort to load scheduling, as per the developed optimal operating strategy. It is estimated that, in the state of Kerala, India, the industries coming under this category accounts for about 26% of total electrical energy consumption [15]. For a typical day, the utility's load curve has been plotted from the data collected. It is observed that, on that particular day the average system peak demand is about 2151 MW and the contribution of major process industries towards system peak demand is about 559 MW. The effect of load scheduling operation on the utility's load curve is shown in Figure 3 and it can be seen that, at an average the peak demand of the utility company gets reduced by 115 MW (5.3%). This results in a reduction of 460 MWh of electricity consumption during the peak hours.

Optimal load scheduling operation by all the major process industries, results in shifting of a considerable amount of load from the utility's peak to off peak and normal periods, resulting in valley filling. At an average, 43 MW and 3 MW of load has been built up and results in corresponding increase in energy consumption, during the off peak and normal periods respectively. Thus by strategic load shifting operation, the optimal schedule tries to flatten the system load curve and improves the system load factor.

Load factor of the industry is 0.9841, in the existing operation. It is observed that, consequent to the load scheduling, the load factor of the industry gets reduced under both the tariffs. New values of load factor are 0.9042 and 0.9208 under Tariff 1 and Tariff 2 respectively. But it is seen that, the system load factor gets improved from 0.6541 to 0.6868, in the event of all the major process industries connected to the utility grid resort to load scheduling, as per the optimal schedules developed. Hence it is observed that, even though the load scheduling operation results in reduction of industry's load factor, it helps to improve the system load factor.

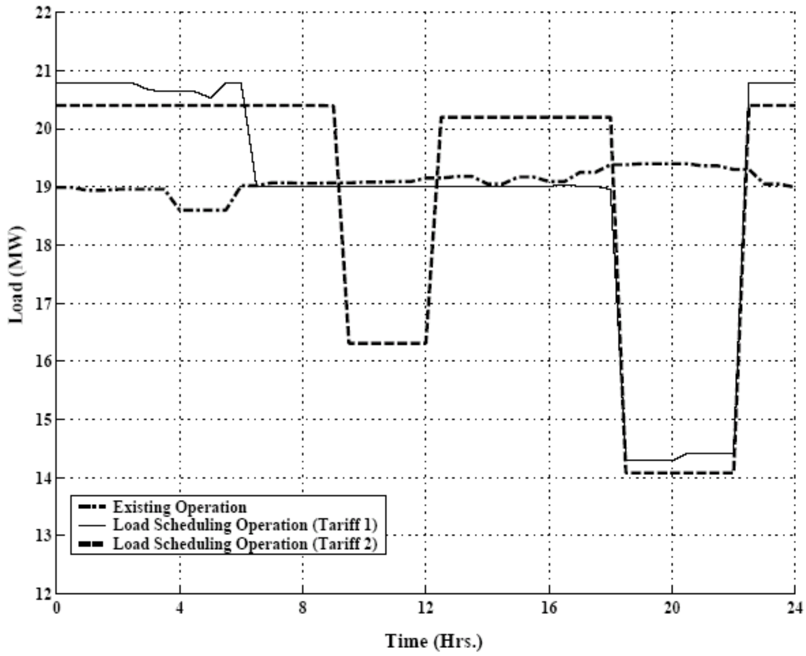

Fig. 2. Load curve

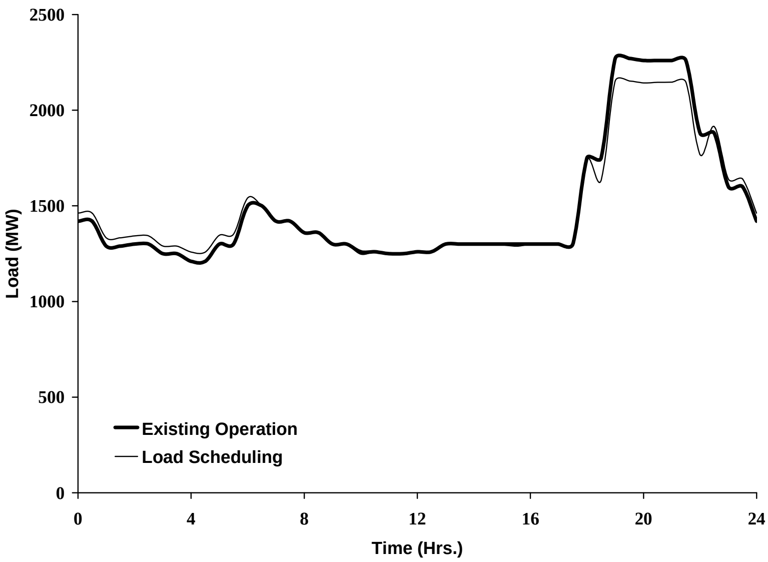

Fig. 3. Impact of load scheduling on utility's system load curve

5. CONCLUSION

An optimization formulation for load scheduling, based on load model incorporating production, process, storage, and maximum demand constraints has been developed. The industry's response to different TOU tariffs can be evaluated using the model. The case study for a typical caustic soda manufacturing plant shows that reduction of total electricity cost is possible by optimal process scheduling. The optimal schedule under the prevailing TOU tariff results in about 4.6% saving in electricity cost. The saving achieved is significant, because the process is energy intensive with almost 60% of cost of production accounts for electricity cost. The peak coincident demand gets reduced by 16.8%. In the event that all the major process industries re-schedule their operation, it is observed that, utility's system peak demand gets reduced by 5.3%.

The optimization technique can be extended to any type of continuous process industries with controllable loads. If the process industries re schedule their process according to the optimal schedules developed, their operating cost can be reduced considerably. The utility company is also benefited due to significant reduction achieved in system peak demand.

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