

INDUSTRIAL LOAD SCHEDULING IN SMART POWER GRIDS

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ABSTRACT

Recently deployment of advanced metering and automatic load management methods make it possible to optimize energy consumption, and to release generation capacities for the purpose of providing sustainable electricity supply. The subject addressed in this paper, is proposing a practical demand response program for industrial load management in smart power grids. The main focus of the paper is modelling industrial loads and proposing a novel load scheduling algorithm to achieve a near optimal scheduling by taking into account industrial users satisfaction, dynamic electricity pricing, and constraints regarding to electricity generation capacity. An industrial plant containing 17 devices in its production line is used for simulation studies. The high convergence speed and the appropriate results are also clarified by comparing the proposed algorithm with Particle Swarm Optimization (PSO) algorithm.

INTRODUCTION

Demand Response program (DR), which is known as an efficient load management strategy for customer side, works basically by encouraging customers to alter their habits reasonably according to electricity price variation during daytime [1]. This strategy has been facilitated by developments of smart meters that enable customers to simultaneously have access to data of their appliances' rate of electricity consumption, real time electricity pricing, and utilities generation capacity [2].

Focusing on Industrial customers, because of considerably amount of industrial loads in compared to total network loads, managing these loads can play an important role in network management in both normal and emergency states of network operation [3, 4]. Besides, industrial loads have more potential to participate in load management schemes since the benefit gained from DR programs to them are high enough [4].

Industrial loads management has been studied in recent researches. In [3], two factors: production of the industrial unit, and reserve capacity has been modelled in DR Program. In [4], the concepts of customer satisfaction, energy storage possibilities, and industrial unit production were considered in DR model. In [5], power production part and heating system were considered in the model to decrease the final cost of production in industrial units. In [6], a load encouraging response program has been studied and the effect of electricity price and the role of reserve units on optimization of customer bill cost and in peak load reduction has been examined.

In this paper, industrial load management is studied with a novel point of view. This study considers industrial load main features such as sequence of devices operation, and limitation in load shifting. The method proposed in this paper has a benefit over most of the earlier works cited in this literature, in the sense that it takes a multi-objective optimization problem to maximize the customer satisfaction, and to minimize industrial sector's cost. This optimization problem is also solved by proposing a novel algorithm and the results are compared with particle swarm optimization (PSO) algorithm to confirm its validation and potential.

The rest of the paper is organized as follows: In section II some the optimization problem is introduced. In Section III, description of the proposed scheduling method and its respective optimization technique are discussed. In section IV, outputs of the technique are illustrated by simulation. In final section the paper is concluded.

OPTIMIZATION PROBLEM

In this section, two main factors in industrial load management which are Electricity bill cost and Load shifting index are discussed. Additionally, the objective function for optimization problem will be defined.

Electricity Bill Cost

Generally, electricity consumption cost can be computed by (1) [7]:

$$C = \sum_{k=1}^{24} [\sum_{i \in A} L_{i,k}] \times P_k \quad (\$/\text{day}) \quad (1)$$

in which P_k is electricity price in time slot k . $L_{i,k}$ is consumed power of i_{th} device in time slot k , and A is the set of all devices.

In global cost model of power market when consumed power increases the price increases too and when the generation capacity increases the price reduces. These functions are convex and nonlinear. Accordingly, (2) can be used for modelling electricity price in the market. For detailed proof see [8].

$$P_k = \gamma_k \cdot \left(\frac{\sum_{i \in A} L_{i,k}}{C_{k,max}} \right)^\alpha \quad (\$/KWh) \quad (2)$$

γ_k is weighting coefficient in time slot k . α shows nonlinear relation between rate of power consumption and price, and can be determined based on previous data of the power market [8]. $C_{k,max}$ is electrical power available for the customer in time slot k .

According to (1) and (2), cost function can be rewritten as (3):

$$C = \sum_{k=1}^{24} [\sum_{i \in A} L_{i,k}]^{\alpha+1} \times \frac{\gamma_k}{C_{k,max}^\alpha} \quad (3)$$

Besides, for simplification, parameter v_k and total load in time slot k are defined in equations (4), (5) as follow:

$$v_k = \frac{\gamma_k}{C_{k,max}^\alpha} \quad (4)$$

$$L_{tot,k} = \sum_{i \in A} L_{i,k} \quad (KWh) \quad (5)$$

Equation (3) can be written as (6):

$$C = \sum_{k=1}^{24} [L_{tot,k}]^{\alpha+1} \times v_k \quad (6)$$

By applying (6), daily bill cost for each single customer will be computed.

Load Shifting Index

In practical DR programs, it is imperative to pay attention to the customers' satisfaction and to model it mathematically [4, 9]. In industrial load management because of many constraints on different devices, analysis of satisfaction function cannot be done for each device separately [4]. If industrial user does not participate in DR scheduling program, he runs the production line regularly. But by participating in DR program, he has to change usage time of specified

devices during the day. In these conditions load shifting index, which is defined as (7), shows changes in time of operation for all devices during the day.

$$S = \sum_{k=1}^{24} [T_{k,after} - T_{k,before}]^2 \quad (7)$$

In this equation $T_{k,after}$ and $T_{k,before}$ are respectively the midpoints of time intervals of k_{th} device operation period before and after applying DR program.

Objective Function

Objective function is weighted summation of consumed power cost function and load shifting index as it is shown in (8) regarding to starting time of operation of each device.

$$f = \text{Min} (\mu_1 \cdot C + \mu_2 \cdot S) \quad (8)$$

In the above equation the weighting coefficients μ_1 , μ_2 are used to scale the load shifting index and power consumption cost. The optimization problem (4) is subjected to following conditions.

- 1- Conditions in which some devices should work one after another (consecutively).
- 2- Conditions in which some devices should start to work simultaneously (parallel).
- 3- $\sum_{i \in A} L_{i,k} \leq C_{k,max}$ (9)

SCHEDULING ALGORITHM

The proposed algorithm for solving industrial load management problem consists of three steps:

Step 1) Load modelling: industrial devices do not operate separately from each other. Their operation times may be simultaneously or consecutively. Fig. 1 shows four industrial devices with average power rates of P_1 , P_2 , P_3 and P_4 which have been modelled with one equivalent device operating within a five hour time period. Power rating of this equivalent device is $P_1 + P_2$, P_1 , $P_3 + P_4$, P_4 , and P_4 , during five hours of operation. Similarly, the other dependent devices used in a industrial unit can be modelled with equivalent loads, each of which can be shown by a $1 \times k$ array, (P_1, P_2, \dots, P_k) . Each entry of this array shows the operating power of the equivalent device in each time slot, and K is operation period of the equivalent device.

Step 2) Load Scheduling: The Proposed algorithm to find optimized times of usage for equivalent loads is comprised of following two steps:

Step 2-a) In the first stage, the data of all devices will

be sent to data center by using smart meters.

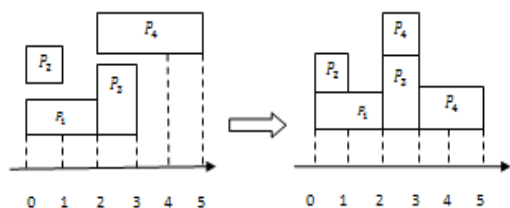


Fig.1. Equivalent load (device) model of four devices.

In data center, all equivalent loads will be sorted in descending order according to their respective rate of energy consumption. Then, appliances with higher energy consumption will be scheduled firstly in times with lower electricity price; and hence, it is expected that the results of scheduling will be more optimum at the end. This method, in some aspects, is similar to the technique called the priority list method which is widely used in unit commitment problems [10].

Step 2-b) Consider the least time unit is a half an hour. Thus, the whole of day and night is divided to 48 time intervals of 30 minutes duration. Since changes in generation and price are not fast, it can be assumed that the price of electricity and the capacity of generation in each time slot are constant.

For each equivalent load, parameter q_n is defined as the total time slots in which the device operates. For example if a device operates 3.5 hrs, then q_n is 7. The operating power of n^{th} device in different time intervals is an array which consists of q_n entries $(P_{1,n}, P_{2,n}, \dots, P_{q_n,n})$. Consider that $(i + 1, i + q_n)$ is the proper time interval for operation of the device n . If this time interval is practically the best, therefore, by running the device during this time the increase in cost shown in (10) will become minimum.

$$\mu_1 \Delta C + \mu_2 \Delta S = \sum_{k=i+1}^{i+q_n} \mu_1 v_k (L_{tot,k} + P_{k,n})^{\alpha+1} - \sum_{k=i+1}^{i+q_n} \mu_1 v_k L_{tot,k}^{\alpha+1} + \mu_2 \Delta S \quad (10)$$

In scheduling device n , ΔS can be calculated from (7) in that it is only depends on operating time of that device before scheduling and is not depended on other devices. ΔC in (10) can be written as follows:

$$\Delta C = \sum_{k=i+1}^{i+q_n} v_k (L_{tot,k} + p_{k,n})^{\alpha+1} - \sum_{k=i+1}^{i+q_n} v_k L_{tot,k}^{\alpha+1} \quad (11)$$

Using Mc Lauren Series, (11) is estimated by (12):

$$\Delta C = \sum_{k=i+1}^{i+q_n} v_k L_{tot,k}^{\alpha+1} \left[\left(1 + \frac{p_{k,n}}{L_{tot,k}} \right)^{\alpha+1} - 1 \right] \cong (\alpha + 1) \cdot \sum_{k=i+1}^{i+q_n} v_k p_{k,n} L_{tot,k}^{\alpha} \quad (12)$$

Substituting equation (12) in (10) gives:

$$\mu_1 \Delta C + \mu_2 \Delta S \cong (\alpha + 1) \cdot \sum_{k=i+1}^{i+q_n} \mu_1 v_k p_{k,n} L_{tot,k}^{\alpha} + \mu_2 \Delta S \quad (13)$$

According to (13), to find optimum q_n sequential time intervals, it is enough that above linear equation become minimized. Hence, for device n the product of two vectors $(P_{1,n}, P_{2,n}, \dots, P_{q_n,n})$, $(\mu_1 \cdot L_{tot,i+1}^{\alpha} v_{i+1}, \mu_1 \cdot L_{tot,i+2}^{\alpha} v_{i+2}, \dots, \mu_1 \cdot L_{tot,i+q_n}^{\alpha} v_{i+q_n})$ is computed. The result is added to $\mu_2 \Delta S$ and at last q_n sequential time intervals for which $\mu_1 \Delta C + \mu_2 \Delta S$ is minimum will be selected. Such work from the aspect of programming is easy and spends minimum computational time. By performing the above steps for all devices, the near optimum time of operation for each equivalent device will be determined.

SIMULATION AND THE RESULTS

In this section, different features of proposed algorithm will be examined. This problem has also been solved by applying particle swarm optimization algorithm for comparison [11]. Besides, it is assumed that maximum generation capacity in each time slot is 10 Mega watts, $\alpha = 2$ and $\gamma_k = 1$. The proposed algorithm is studied on an example factory with seventeen devices. Operating power and time interval of each device (before scheduling) and also sequence of operation between devices are listed here:

- Devices 1, 2 and 3 with operating powers and operating times of (3.5Mw, 2Mw, 2.5Mw: 1-2:30, 3:30-5:30, 5:30-7) are used consecutively.
- Devices 7 (1Mw: 1:00-2) and 1 are used consecutively
- Devices 8 (1.5Mw: 5:30-6) and 3 are used simultaneously.
- Devices 4, 5, 6 (1.5Mw, 2Mw, 2.5Mw, 4-5:30, 5:30-8, 8-10:30) operate simultaneously.
- Devices 9 (2.5Mw: 5:30-7) and 5 operate simultaneously.
- Devices 9 and 10 (1.3Mw: 7:00-8) operate consecutively.
- Devices 11, 12 (1Mw, 2Mw, 5:00-6, 6:00-7) operate consecutively.
- Device 12 should be switched off before the operation of device 13 (1.5Mw: 8-9:30).
- Operation times of Devices 13, 14 (2Mw: 9-10:30), 15 (1.5Mw: 10-11:30), 16 (1.5Mw: 12-13:30), and 17 (1.5Mw: 13-14:30) is not related to the other loads.
- The whole devices within a fourteen hours period should finish their operation

Above conditions simulate the model of an industrial unit production line. Some devices should operate consecutively some in parallel in time and the others can be used with no limitations. Three cases are considered in examination of optimization algorithm:

Case 1: without DR program: $\mu_1=0$, $\mu_2=1$.

Case 2: with DR program, for peak shaving and without considering load shifting index: $\mu_1=1$, $\mu_2=0$.

Case 3: with DR program, for peak load shaving and with considering load shifting index $\mu_1=1$, $\mu_2=100$.

Fig. 2 shows load profile curve by applying both proposed algorithm and PSO algorithm for above three cases. Although this comparison does not prove the optimality of the method, it can be helpful in observing the potential of the proposed algorithm in convergence rate and accuracy. According to this Figure, in case one there is high peak load in times 5, 9, and 13 but the devices are utilized in periods based on regular bases of production line. In case two the peak shaving by using both algorithm is fully achieved but shifting index which shows dissatisfaction becomes 75. Besides the results of proposed algorithm and PSO are 128¢ and 114 ¢ which are very close to each other. In case three shifting index is reduced to 43 but the peak shaving is not as perfect as in case two; besides, bill cost increases to 163 ¢ when the proposed algorithms applied and 149¢when PSO is used. Again the results of both algorithms are close. Each of these three cases has its merits and demerits. Thus, depending on the goal of the DR program, proper values for μ_1 , and μ_2 can be determined to run the scheduling algorithm. The closeness of proposed algorithm to PSO confirming that the proposed method results is near optimum, while the convergence speed of the method is significantly higher than the PSO-based algorithm (less than 1 second versus about 8 minutes). This advantage is of prime importance in practical cases and makes the proposed algorithm more viable in real world DR programs with numerous numbers of customers and devices.

CONCLUSION

In this paper a new industrial load management strategy based on a modified cost function was introduced. Besides, customers' satisfaction is modeled by defining load shifting index. This approach reduces peak load, regarding the impacts of load rates on the price and customer satisfaction. A fast algorithm is also presented to solve the proposed optimization problem.

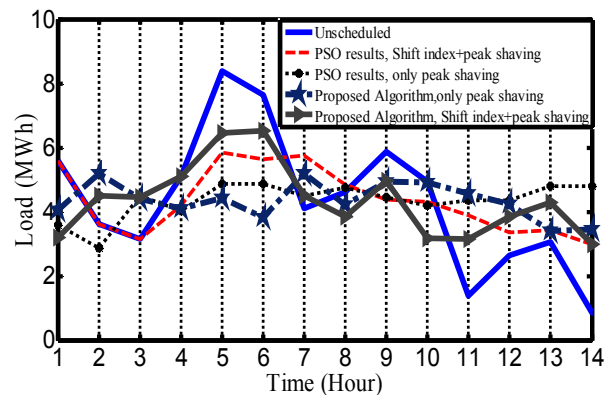


Fig. 2. Total load before and after scheduling: proposed algorithm and PSO.

The algorithm is compared with PSO to show its accuracy and speed of convergence. Simulation results show that the method has near-optimum results with the high convergence speed.

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