Improved Taguchi Method Based Contracted Capacity Optimization for Power Consumer with Self-Owned Generating Units

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Abstract: - The paper proposes an improved Taguchi method to determine the best capacity contracts and dispatch the power output of the self-owned generating units from almost infinite combinations. To be achieved are savings of total power expenses of the consumers with self-owned generating units. Based on the different structures of power tariff in different periods and seasons, considered simultaneously are constraints on output ranges of the self-owned generating units, power factors, and fees of regulating capacity contracts, while searching the optimal capacity contracts. To verify the feasibility of the proposed method, the paper employs the practical data from an optoelectronics factory, which includes amounts of power consumption from the utilities, capacities of generating units, and load demand forecast in the months of planning period. Numerical results obtained are compared to the existing other algorithms. The simulation results reveal that about 12.95% in average of electrical power expenses per month can be saved through the proposed approach.

Key-Words: - Self-Owned Generating Units, Capacity Contracts, Improved Taguchi Method

1 Introduction

The high-tech industry in Taiwan has developed rapidly in recent years. Power consumption of a high-tech factory may usually reach up to more than ten-thousand kWs with about ten-billion dollar revenues created. However, if a power event happens, it often causes loss of ten-million dollars. As a result, requirements of power reliability are quite strict for the industry. In attempt to improve the power supply reliability, avoid voltage sag and interruption events, and reduce the impacts, often employed are the self-owned generating units interconnected with the power grid. In the mean time of enhancing power supply reliability, economic operations of the interconnected self-owned generating units are highly concerned.

Currently, the heuristic translation method [1] to determine the capacity contract is widely used in Taiwan Power Company (TPC). Different tariffs are designed for peak (including peak and semi-peak) and off-peak periods. To encourage load-shifting from the peak period to the off-peak one, per unit of peak contracted capacity can be shifted to off-peak one. The excessive load over the peak contacted capacity can be supplied by self-owned generating units. Different amounts of shifted capacity from the basis can thus be evaluated to have a lower and lower total power expenses.

Observing the nonlinear characteristics of the contracted capacity optimization, approaches of optimization, such as sequential search method [2], half interval search method [3], multi-pass dynamic programming [4], genetic algorithms [5,6], have been proposed to search the best combination of contracted capacities. Nevertheless, these methods usually need large amount of data [2], complicated calculation process [4], and long searching time [2-5].

In this paper, we propose the improved Taguchi method that includes traditional Taguchi method [7,8] and particle swarm optimization (PSO) method [9] to search effectively the best combination of contracted capacities and the dispatched output of self-owned generating units. To verify the effectiveness of the proposed method, employed are the real data from an optoelectronics factory with self-owned generators in Taiwan.

The remainder of the article is organized as follows. In Sec. 2, problem formulation of the contracted capacity optimization is described. Sec. 3 illustrates the proposed improved Taguchi method for contracted capacity optimization. Sec. 4 presents the solutions obtained and comparisons with the existing approaches. Finally, our conclusions are given in Sec. 5.

2 Problem Formulation

Generating units using fuel of heavy oil [10] are employed in this paper. The generating unit includes heavy-oil engine and generator. The peripheral apparatus of the generating unit consist of boiler system, air pollution treatment system, and cooling system. The expenses for power consumption include costs of TPC bill and the self-owned generating unit operations which involves the constant cost and variable cost.

2.1 Expenses for Power from TPC

In the current tariff structures of TPC, the electrical power expenses are composed of those for base load, variable load, regulated power factor, and excessive load over contracted capacity. The load demand over the contracted capacity would be charged additionally for over-capacity penalty.

To avoid over-capacity penalty, auxiliary power sources, like the self-owned generating units, can be used to supply the load demand over the contracted capacity with extra capital and operational costs needed. Therefore, an optimal contracted capacity exists with minimal total expenses of power consumption.

The electrical power expenses can be expressed as follows.

1. Base power expenses B_j

$$B_j = B_{j,1} + B_{j,2} \tag{1}$$

$$B_{j,1} = \begin{cases} X_{j,1} \times Y_{j,1} + X_{j,2} \times Y_{j,2} \\ \quad + X_{j,3} \times [Y_{j,3} - (Y_{j,1} + Y_{j,2}) \times 0.5] & \text{, otherwise} \\ 0 \text{ ,} \quad Y_{j,3} - (Y_{j,1} + Y_{j,2}) \times 0.5 < 0 \end{cases}$$

where $B_{j,1}$ is the regular load tariff in *j*th month; $X_{j,1}$, $X_{j,2}$, and $X_{j,3}$ are the tariff of the peak, semi-peak, and off-peak contracted capacities in *j*th month; $Y_{j,1}, Y_{j,2}, Y_{j,3}$ are peak, semi-peak, and off-peak contracted capacities in *j*th month;

$$B_{j,2} = B_{j,1} \times 0.15 \tag{2}$$

where $B_{j,2}$ is the reserve capacity fees.

2. Variable power expenses (S_j)

Variable power expenses are based on real power consumption in peak and semi-peak load periods, Saturday non-peak period.

3. Regulated power factor expenses (R_j)

$$R_j = \begin{cases} (B_j + S_j) \times 0.003 \times (0.8 - pf) \text{,} \\ \qquad pf_{average} \le 0.8 \\ (B_j + S_j) \times 0.0015 \times (0.8 - pf), \\ \qquad pf_{average} > 0.8 \end{cases} \tag{3}$$

where pf is the power factor.

4. The penalty of excessive load (F_j)

$$F_j = \begin{cases} 2 \times B_j \text{ ,} & Y_{j,k} < D_j \le 1.1 \times Y_{j,k} \\ 3 \times B_j \text{ ,} & D_j \ge 1.1 \times Y_{j,k} \end{cases} \tag{4}$$

where D_j is the highest load demand in *j*th month.

5. Contracted capacity expenses (P_j)

Based on the original capacity contracted with the utilities, the consumers can also adjust it subject to adjusting charge per the capacity adjusted, except shifting the peak contracted capacity to the off-peak one [11]. The shifting of the peak contracted capacity to the off-peak is actually encouraged as mentioned before.

2.2 Expenses for Power from Self-Owned Generating Units

To avoid the over-capacity penalty, the self-owned generating units can be employed to supply the load demand over the contracted capacity with extra capital and operational costs needed, which are further illustrated below.

1. Constant cost (G_{con})

The constant costs needed for self-owned generating units are given in Table 1 with depreciation of twenty years. The monthly cost items encompass infra-structure needed, generation equipment, and constant operation and maintenance (O&M) costs. For example, the monthly constant cost of one self-owned generating unit is NT$ 730.79M in average of 7 units.

2. Variable cost (G_{var}=sum{$U_{1,n}$+ $U_{2,n}$})

The variable costs of generating units are the fuel cost and the variable O&M costs. Fuel costs are calculated according to Eqs. (5), (6), and (7).

$$x = \frac{P_{Gi}}{P_{Gi,\max}} \tag{5}$$

Table 1. Composition of constant costs

Cost item	Cost (NT$M)	Average cost (NT$M/month)
Building	10,330	43.04
Construction	21,200	88.33
Equipment	125,860	524.42
Personnel	-	75

Table 2.Composition of variable costs

Item	Cost (NT$/kWh)
Pollution prevention	0.03
Boiler maitenance	0.007
Cooling water tower maintenance	0.006
Lubricating oil	0.007
Consumables	0.03
Total	0.08

$$d = 0.0000025625x^2 - 0.29725x + 282.7 \quad (6)$$

$$U_{1,n} = d \times P_{Gi} \times 0.9317\ (l/kg) \times C_{mp} \quad (7)$$

where x is the generating factor of the generator, P_{Gi} (kW) and $P_{Gi,\max}$ (kW) are the power output and maximum power output of each generator, d(g/kWh) is the fuel consumption, $U_{1,n}$(NT$) is the variable cost of the nth generator, and C_{mp} (NT$/$l$) is the market fuel price for one liter. In this paper, we set here C_{mp} equal to 8 (NT$/$l$).

The variable O&M costs, $U_{2,n}$, can be calculated bu using the data in Table 2 for different power generations.

As described above, the contracted capacity would determine the power expenses to pay the utilities and the operation cost of the generator. In this paper, the use of self-owned generating units is regarded as an alternative to the supply the load demand over the contracted capacity. The constant costs of the self-owned generating units are hence taken into account in the optimization problem, as expressed in (8):

$$\text{Min} \quad \{J_M\} = \sum_{i=1}^{j}(B_i + S_i + R_i + F_i + P_i + G_{con,\,i} + G_{\text{var},\,i}) \quad (8)$$

where J_M is the total power expenses.

3 Proposed Improved Taguchi Method

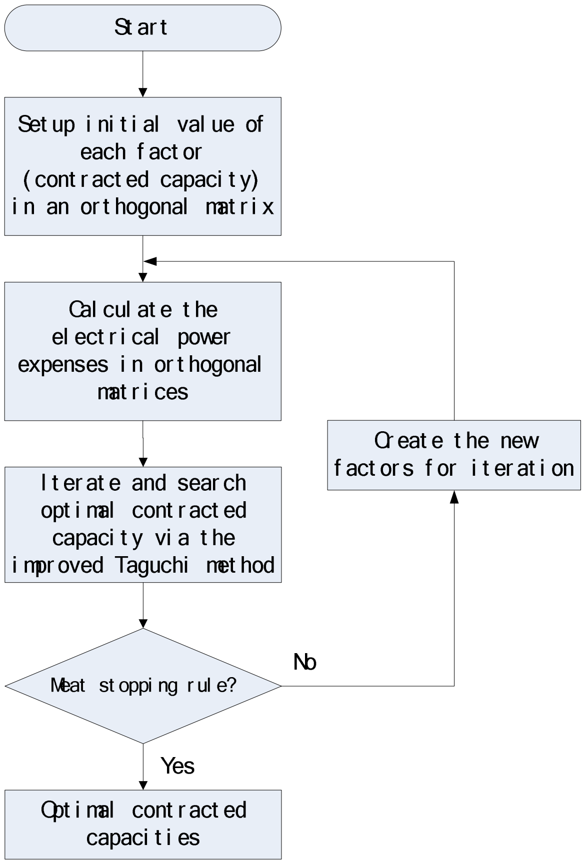

Fig. 1. Flowchart of the contracted capacity optimization.

Taguchi method has been applied in the quality engineering to have the least variances of products or processes and the high quality outcome with lowest costs. To improve the optimization efficiency, the PSO is integrated into of the existing Taguchi method in this paper. The solution steps are delineated in the optimization structure as shown in Fig. 1 and addressed below.

3.1 Initialization

Initialization of the solution scheme of the Taguchi method is to set up a suitable orthogonal matrix, $L_M(q^m)$ where L is Latin squares (as shown in Table 3.) which is a n by n square matrix, M is the number of experiments, q is the number of levels, and m is a parameter of factor.

In this paper, the orthogonal matrix is shown in Table 3. Each factor (decision variable) of the orthogonal matrix has three levels. Initial values of the levels are selected randomly in an ascending order, i.e., Level 1 < Level 2 < Level 3. Each factor in the matrix has to meet the following two rules:

1. Each level of every factor appears the same number of times in each column of the matrix,

e.g., each level of each column in Table 4 appears 27 times.

2. Each combination of factors between any two columns appears the same number of times, e.g., each pair between every two columns in Table 4 appears once.

With the orthogonal matrix built up, different total costs (e.g., $J1$ - $J81$) for different contracted capacity combinations can be calculated by (8).

3.2 Integrated Search Scheme

In search scheme, the PSO method is used to create the next trial values of decision variables for contribution of levels in the traditional Taguchi Method. The mathematical form is shown below.

$$L^{new} = L^{old} + V_{mov} \quad (9)$$

$$V_{mov} = c_1 \times (J_b - L^{old}) + c_2 \times (T_b - L^{old}) \quad (10)$$

where L^{old} the last contracted capacity in the iteration;
L^{new} the new contracted capacity;
V_{mov} the size of movement;
J_b the lowest-cost combination of contracted capacity in this iteration;
T_b the lowest-cost combination of contracted capacity so far;
c_1, c_2 the random numbers between 0 and 1.

Each iteration of the optimization would have a combination of contracted capacity with a calculated total power expenses. It is noted that contribution of each level is the summation of expenses of the same level number. The contribution of levels has six kinds of level combinations as shown below [7, 8]:

1. $V_{j,k}^{(1)} > V_{j,k}^{(2)} > V_{j,k}^{(3)}$
2. $V_{j,k}^{(3)} > V_{j,k}^{(2)} > V_{j,k}^{(1)}$
3. $V_{j,k}^{(1)} > V_{j,k}^{(3)} > V_{j,k}^{(2)}$
4. $V_{j,k}^{(3)} > V_{j,k}^{(1)} > V_{j,k}^{(2)}$
5. $V_{j,k}^{(2)} > V_{j,k}^{(1)} > V_{j,k}^{(3)}$
6. $V_{j,k}^{(2)} > V_{j,k}^{(3)} > V_{j,k}^{(1)}$

Table 3. The example orthogonal matrix $L_{81}(3^{21})$

Experiment	Test factor (capacity contracts of each month)					cost
	$Y_{1,1}$	…	$Y_{4,2}$	…	$Y_{7,3}$	
1	1	…	1	…	2	J_1
2	1	…	2	…	3	J_2
3	1	…	3	…	1	J_3
⋮	⋮	⋮	⋮	⋮	⋮	
79	3	…	2	…	1	J_{79}
80	3	…	3	…	2	J_{80}
81	3	…	1	…	3	J_{81}
Contribution of Level 1	$Y_{1,1}^{(1)}$	…	$Y_{4,2}^{(1)}$	…	$Y_{7,3}^{(1)}$	
Contribution of Level 2	$Y_{1,1}^{(2)}$	…	$Y_{4,2}^{(2)}$	…	$Y_{7,3}^{(2)}$	
Contribution of Level 3	$Y_{1,1}^{(3)}$	…	$Y_{4,2}^{(3)}$	…	$Y_{7,3}^{(3)}$	

In a new iteration, values of contracted capacities can be created through Eqs. (9) and (10), and contribution combinations of levels above. On the other hand, two different columns are exchanged to generate different orthogonal matrix. The purpose is to decrease the probability of trapping into local optimization. The search algorithm would terminate if either of the two stopping rules is satisfied.

1. Maximum of 1000 iteration;
2. No significant change occurs for a total 100 iterations.

4 Numerical Results

To verify the effectiveness of the proposed method, this paper employed the real data collected from an optoelectronics factory with self-owned generating units in September, 2004 to March, 2005. The data include the operation costs of the self-owned generating units, the predicted power load demands, and the purchase cost of power from utilities. The results obtained from the proposed method are compared with that currently adopted by the factory for the power dispatching and contracted capacity setting. The studies consist of the following steps for performance comparison of the proposed and the existing methods:

Table 4. The power consumption and expenses by the improved Taguchi method

Items \ Month		April	May	June	July	August	September	October
Contracted capacity (kw)	Peak contracts	17,110	34,902	35,607	38,025	39,889	35,506	34,302
	Half-peak contract	14,846	10,009	14,163	14,966	14,779	15,979	12,506
	Off-peak contract	23,544	12,298	12,430	11,209	11,532	16,715	19,232
Power consumption from TPC (kWh)	Power consumption	14,402,225	36,514,260	26,386,307	29,165,754	30,344,177	28,797,368	30,419,752
	Reactive power consumption	5,227,310	13,252,907	9,576,951	10,585,755	11,013,466	10,452,049	11,040,896
Power consumption from generating units (kWh)	Power consumption	20,495,682	419,817	9,739,175	14,159,856	12,152,706	14,910,261	7,032,199
	Reactive power consumption	15,371,762	314,863	7,304,381	10,619,892	9,114,230	11,182,696	5,274,149
Expenses for TPC ($)		27,799,580	30,016,796	45,845,241	52,769,086	52,808,453	49,752,023	31,614,066
Expenses for generating units ($)		18,879,867	7,560,714	17,828,309	22,602,644	20,434,922	23,413,082	11,275,414
Total expenses ($)		46,679,447	37,577,510	63,673,550	75,371,730	73,243,375	73,165,105	42,889,480

1. Determine contracted capacities without using the self-owned generating units;
2. Using the translation method to determine best contracted capacities with the utilities and to dispatch the power output of the self-owned generating units;
3. Using genetic algorithm [12] to determine best contracted capacities and to dispatch the power output of the self-owned generating units;
4. Using the traditional Taguchi method to determine best contracted capacities and to dispatch the power output of the self-owned generating units;
5. Using the proposed improved Taguchi method to determine best capacity contracts with utilities and to dispatch the power output of the self-owned generating units;

Table 4 shows the contracted capacities, the amounts of power consumption from utilities, and electrical power expenses using the proposed method. Table 5 shows the comparisons of electrical power expenses through different methods, including heuristic translation method, genetic algorithm, traditional Taguchi method, and the proposed improved Taguchi method. As shown in this table, results reveal that NT$61,374,887 of electrical power expenses in seven months or about 12.95% of electrical power expenses per month in average (compared to the heuristic translation method) can be saved through the proposed method.
It also shows in the table the ratios of power consumption from self-owned generating units to total amount of power consumption in different methods. The self-owned generating units are

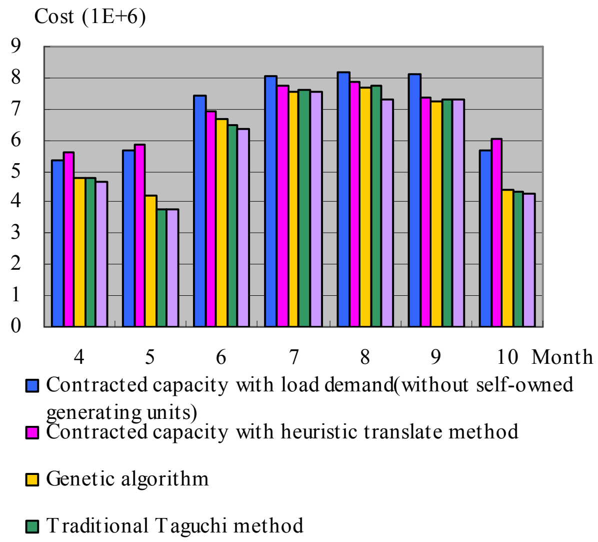

Fig. 3. Power expenses per month obtained from different methods

utilized to a different degrees in the optimal solutions obtained by diverse methods.

Fig. 3 depicts comparisons of electrical power expenses per month obtained from different methods. It is noted that the electrical power expenses of non summer time can be decreased obviously through the proposed method.

5 Conclusion

An improved Taguchi method for contracted capacity optimization based on the integrated Taguchi method and PSO has been presented in this paper. New solutions to be evaluated in the

Table 5. Comparisons of the power expenses in each month for different contracted capacities

Month & Item \ method	Contracted capacities without self-owned generators	Heuristic translation method	Genetic algorithm	Traditional Taguchi method	Proposed improved Taguchi method
April	536,39,560	55,945,047	47,640,905	47,672,861	46,679,447
May	56,389,700	58,333,805	42,155,661	37,827,517	37,577,510
June	74,202,988	69,502,493	66,574,506	64,530,623	63,673,550
July	80,253,377	77,403,594	75,836,955	76,086,997	75,371,730
August	82,109,988	78,661,034	76,487,724	77,576,268	73,243,375
September	81,023,984	73,946,818	72,477,012	73,098,675	73,165,105
October	56,608,304	60,182,293	44,130,695	43,298,175	42,889,480
Total expenses (NT$)	484,227,901	473,975,084	425,303,458	420,091,116	412,600,197
Improvement (%)	-2.16%	0%	10.27%	11.37%	12.95%
Load demand (kWh)	276,939,539	276,939,539	276,939,539	276,939,539	276,939,539
Power consumption from generators (kWh)	0	28,870,409	23,051,099	99,917,921	78,909,696
Ratio (%)	0	10.42	8.32	36.08	28.49

orthogonal matrix in the Taguchi method were created by the PSO scheme. The searching efficiency of the existing Taguchi method is therefore enhanced. To verify the effectiveness of the proposed method, results obtained from the real data of an optoelectronics factory in Taiwan with self-owned generator was used in this paper. Comparisons with other traditional methods have proved that the total electrical power expenses can be saved NT$8,767,841 dollars per month through the proposed method.

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