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OPTIMIZATION OF LOAD DISPATCHING FOR MINIMIZING FUEL AND ENVIRONMENTAL COSTS AT A VARIABLE-LOAD POWER PLANT FIRING FUEL OIL/GAS

Watcharee Kaewboonsong and Vladimir I. Kuprianov

School of Manufacturing Systems and Mechanical Engineering
Sirindhorn International Institute of Technology, Thammasat University
P.O. Box 22, Thammasat Rangsit Post Office, Pathumthani, 12121, Thailand.

ABSTRACT

This work is focused on the development and application of a cost-based method for optimization of l dispatching for a 1330-MW power plant consisting of three 310-MW units co-firing medium-S fuel oil natural gas and two 200-MW units fired with low-S fuel oil. The objective function for the optimizatio aimed at minimizing the total costs for the entire power plant including “internal” (or fuel) costs as well “external” (or environmental) costs associated with the damage done by the power plant to the environm and humans. Both fuel and environmental costs are predicted using relevant models. A lin programming-based approach was applied for determining the optimum load dispatch for this power plant. optimization of load distribution was carried out with the use of the typical daily load curve (electri demands) for distinct climatic seasons in Thailand. According to the computational results, the optimum l dispatch of the power plant units was strongly affected by the pattern of the daily electricity demand as wel by the fuel option.

Keywords: Utility boilers, Environmental impacts, Unit load, Total cost saving.

1. INTRODUCTION

In the Thai power generation sector, fuel oil/gas-fired power plants are basically involved in covering the changes in the electricity demand which is basically subject to strong seasonal as well as daily random fluctuations. Conventionally, current load of each boiler unit at a power plant is proportional to the total power plant output, thereby diminishing the individual swings of the units [1]. However, this most apparent “objective fuel-based power generation at the minimized fuel consumption.

A cost-based optimization model for load dispatching, including effects of boiler operating conditions and fuel properties on the total “internal” (i.e. fuel) and “external” costs (the latter being associated with the environmental impacts by boiler NO_x, SO_3, SO_2 and CO_2 emissions) for a fuel oil-fired power plant, was proposed in Ref. [4]. This work was aimed at further development of the cost-based computational method for the minimizing of total fuel and environmental costs through optimal distribution of the total load over distinct units of a thermal power plant (co-) firing fuel oil/gas.

2. OPTIMIZATION CONCEPT

The major assumption of this optimization study presumes that the selected power plant consists of two groups of boilers, and all the units of a single group have identical parameters and characteristics at the same time function” does not lead, in effect, to the best economical and environmental benefits for a power plant consisting of boiler units of different capacities fired (or co-fired) with different fuels.

Some strategies and algorithms (models) for environmental-economic load dispatch are reviewed in Refs. [2,3]. Most of the research works were aimed at reducing NO_x and SO_x emissions from the fossil instant. The constraints and limitations related to the boiler units firing fuel oil/gas are discussed in Ref. [4].

For distinct boiler units, the relationship between the minimized parameter, Y (in this work, the total fuel and environmental costs), and unit load, U, is represented by the straight-line regression fit of the form: $Y_m = a_m + b_m U_m$ (m = 1,2). This approach makes it possible to involve a linear programming tool in the optimization procedure.

For a given point in time, or relatively short time period, t_i, the current load demand, $L(t_i)$, can be written as a sum of the individual boiler loads, these are, respectively, $U_1(t_i)$ and $U_2(t_i)$ for the two unit groups, containing n_1 and n_2 boilers:

$$L(t_i) = \sum_{j}^{n1} U_{1j}(t_i) + \sum_{k}^{n2} U_{2k}(t_i). \qquad (1)$$

++Disregarding the non-variable terms in the correlation for Y_m (i.e. a_1 and a_2), a suitable objective function, $J(t_i)$, can then be written as:

$$J(t_i)=Min[b_1\sum_{j}^{n1} U_{1j}(t_i)+ b_2\sum_{k}^{n2} U_{2k}(t_i)]. \qquad (2)$$

Since all the boilers of the first and second groups of the power plant units have supposedly the identical loads during the time period of interest, $G_1(t_i)$ and $G_2(t_i)$, respectively, we can simplify the objective function and represent it by:

$$J[G_1(t_i),G_2(t_i)] =Min[n_1b_1G_1(t_i) + n_2b_2G_2(t_i)]. \qquad (3)$$

Taking into account the load constraint:

$$L(t_i) = n_1G_1(t_i) + n_2G_2(t_i), \qquad (4)$$

The objective function is then rewritten as:

$$J[G_1(t_i)] = Min[n_1(b_1 - b_2)G_1(t_i) + b_2L(t_i)]. \qquad (5)$$

The optimization problem is, thus, reduced to the determining of $G_1(t_i)$ for the time period t_i, for which $J[G_1(t_i)]$ must be minimized. By Eq. (4), one can then find $G_2(t_i)$.

For an individual boiler unit (co-) firing fuel oil/gas, the "internal" costs, US\$/s, accounting for the boiler fuel consumption and fuel prices, are found for the time period t_i, to be:

$$K_{int}(t_i) = P_{fo}\,\dot{m}_{fo}(t_i) + P_{ng}\,Q_{ng}(t_i) \qquad (6)$$

where P_{fo}, US\$/kg, and P_{ng}, US\$/m^3, are prices of fuel oil and fuel gas, respectively; $\dot{m}_{fo}(t_i)$, kg/s, and $Q_{ng}(t_i)$, m^3/s, are current fuel oil and fuel gas consumptions by the boiler.

Meanwhile, for the selected boiler unit, the "external" costs US\$/s, including effects of the major gaseous emissions, are determined for the particular time period t_i by:

$$K_{ext}(t_i) = P_{NOx}\,\dot{m}_{NOx}(t_i) + P_{SO2}\,\dot{m}_{SO2}(t_i) + P_{SO3}\,\dot{m}_{SO3}(t_i) + P_{CO2}\,\dot{m}_{CO2}(t_i) \qquad (7)$$

In Eq. (7), the emission rates are predicted based on the boiler operating conditions as well as on the fuel options and properties (see Part 1 of the paper), whereas the specific "external costs", P_{em}, or cost of damage done by the 1 kg pollutant to the environment and humans are selected from Refs. [5,6].

The total costs combining the above "internal" and "external" costs are found to be:

$$K_{total}(t_i) = K_{int}(t_i) + K_{ext}(t_i) \qquad (8)$$

3. CASE STUDY AND ESSENTIAL INPUT

A 1330-MW power plant comprising two 200-MW and three 310-MW boiler units was the focus of this study. All the boiler units of this power plant were operated with variable loads during 24-hours period accompanied with corresponding changes in the key operating variables (excess air ratio, flue gas recirculation, waste gas temperature, feedwater temperature) affecting the cycle thermal efficiency as well as the boiler thermal efficiency and major emissions.

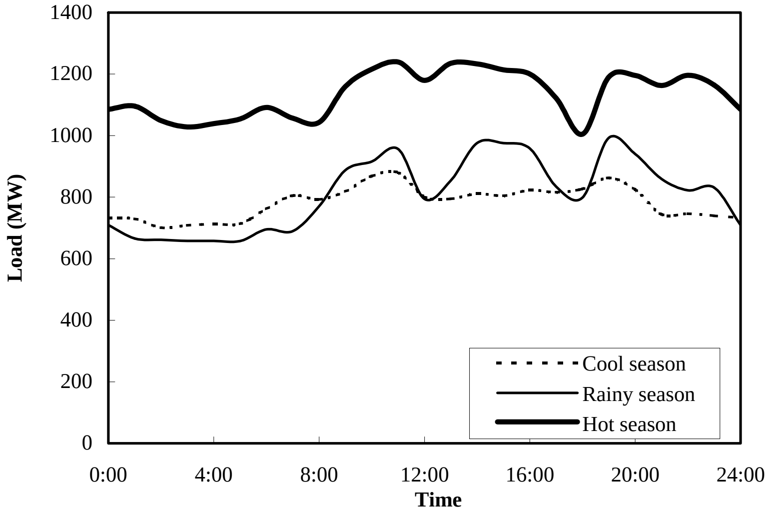
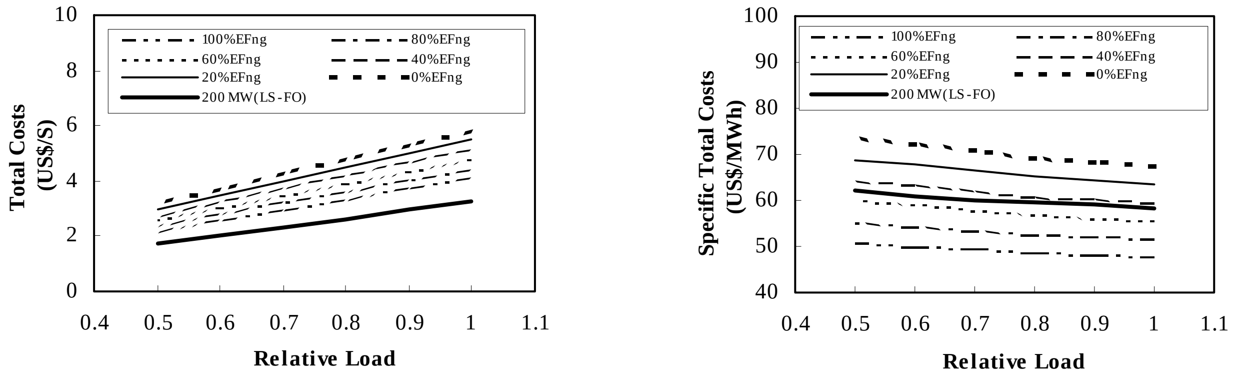


Fig 1. Representative daily load curves for a 1330-MW power plant for three climatic seasons in Thailand [4].



(a)

(b)

Fig 2. Absolute (*a*) and specific (*b*) total costs versus relative unit load for the 310-MW boiler co-firing medium-S fuel oil with fuel gas at different EF_{ng} as well as for the 200-MW boiler firing low-S fuel oil.

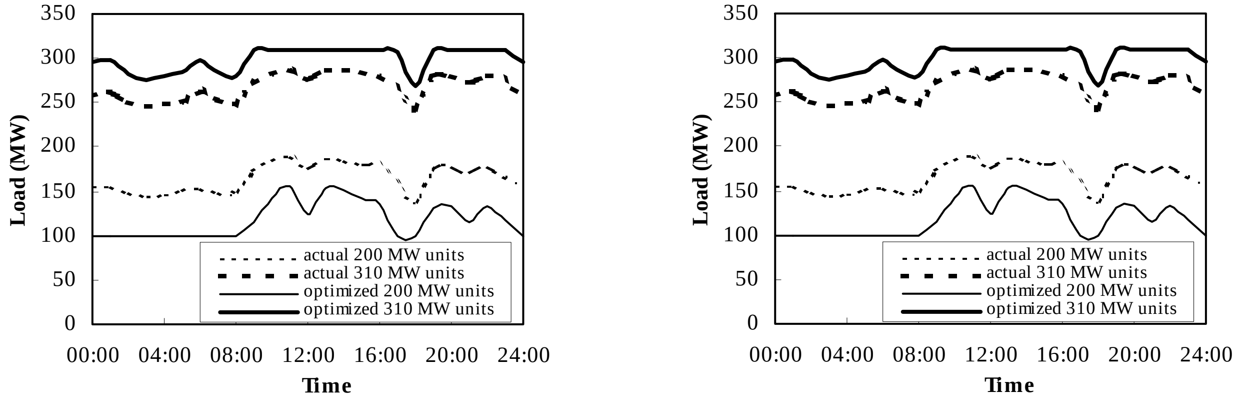
The representative daily load curves for this power plant are shown in Fig. 1 for different climatic seasons in Thailand [4]. The curves, plotted with the use of the averaged (over each 1-hr period of a day) load values, were obtained from the statistical data treatment. Standard deviations for the trend curves shown in Fig. 1 did not excess 126 MW, i.e. about 10% installed power plant capacity.

The load unit optimization was carried out for each climatic season taking into consideration the basic fuel option currently employed at this power plant: firing the 200-MW boiler units with low-S fuel oil only and co-firing the 310-MW boiler units with medium-S fuel oil and natural gas. The prices for the applied fuels were assumed to be: 0.15 US$/kg for low-S fuel oil, 0.125 US$/kg for medium-S fuel oil and 0.1 US$/m^3 for natural gas.

4. RESULTS AND DISCUSSION

Figure 2*a* depicts the time rate of the total fuel and environmental costs for the boiler units

Despite the non-linear effects of some load-dependent operating variables (e.g. excess air and "effective" temperature in the burner zone of a furnace) on the emission characteristics [4], the dependencies of the total operational costs on the boiler relative load could be adequately represented by the straight-line regression fits. For instance, for the 200-MW unit fired with low-sulfur fuel oil, the corresponding coefficients for the fitting curve were found to be: a_1 = 3.0502 and b_1 = 0.1998 (squared correlation R^2 = 0.9998); and for the 310-MW unit co-firing medium sulfur fuel oil with fuel gas at EF_{ng}= 80%, the coefficients were: and a_2 = 2.2307 and b_2 = 0.2382 (squared correlation R^2 = 0.9995), etc. Figure 2*b* shows the specific (i.e. related to 1 MWh of the electricity produced) total costs for the studied boiler units and fuel options. In the whole range of the unit loads (of 50–100%), the 310-MW boiler units co-firing fuel oil/gas at 80% and 100% EF_{ng} turned out to be more beneficial in the electricity generation than the 200-MW units.



(a)

(b)

Fig 3. Actual and optimized daily loads (*a*) and current cost savings (*b*) of the boiler units for the rainy season for 310-MW units co-fired at EF_{ng} = 80% and 200-MW boilers fired with pure fuel oil.

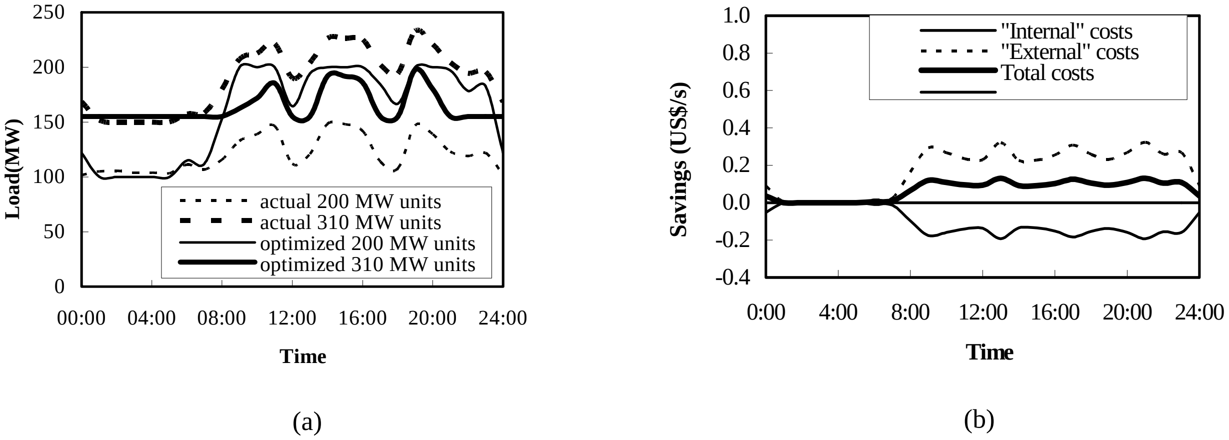


Fig 4. Actual and optimized daily loads (*a*) and current cost savings (*b*) of the boiler units for the rainy season for 310-MW units co-fired at EF_{ng} = 20% and 200-MW boilers fired with pure low-S fuel oil

However, as seen in Fig. 2*b*, at low values of EF_{ng} (up to 30%), the operation of the 310-MW units was accompanied by higher total costs (in the production of 1 MWh electricity) than those for the 200-MW units. For the cases when the specific total costs of the two boiler units were much different, the unit load optimization could apparently lead to the total cost savings.

For EF_{ng}= 40–60%, the specific total costs for the 310-MW unit were found to be comparable with those for the 200-MW unit. For this case, there is no sense in the load optimization; the unit loads might be in the proportional correlation with the current total load (electricity demand) of the power plant.

According to the work objectives, the unit load optimizations were carried out for different climatic seasons in Thailand. As an illustration, Fig. 3*a* compares the optimized and actual unit loads for the fuel option of the co-firing 310-MW units with the medium-S fuel oil and natural gas at EF_{ng} = 80% and firing 200-MW boilers with pure low-S fuel oil, for the hot season. As seen in Fig. 3*a*, the optimized loading for the 310-MW units was suggested to be greater than the actual power output (for almost all the time during a day), whereas the 200-MW units had to operate at the minimum load. These results comply with data in Fig. 2b indicating "cheaper" power generation by the 310-MW units co-fired at EF_{ng} = 80%.

Figure 3*b* shows the time-domain potential savings of the "internal", "external" and total costs, resulted from switching the boiler units to the optimized loading for the above conditions. The saving profiles were apparently affected by the time-domain pattern of the electricity demand for the selected season (see Fig. 1).

The most significant effects of the load switching was observed for the day time when the rates of the proposed load change (from actual to optimized) by the units were at the highest values. As may be seen in Fig. 3*b*, both "internal" and "external" costs contributed to the total cost savings in this particular case. Similar result was obtained for the fuel option with EF_{ng} = 100%.

On the contrary, for the fuel option of co-firing 310-MW boiler units at EF_{ng} = 0–20% and firing 200-MW units with pure low-S fuel oil, the optimized time-domain loading for the 200-MW units turned out to be greater than the actual power output of these units; accordingly, the optimized loading for the 310-MW units was found to be lower than the actual loads for these units.

Figure 4*a* depicts the optimized and actual unit loading for the studied power plant for the rainy season for the fuel options when the 310-MW unit were co-fired with the medium-sulfur fuel oil and natural gas at EF_{ng} = 0-20% and the 200 MW units were fired with low-sulfur fuel oil. For this fuel option, the optimized time-domain loading for the 200-MW units turned out to be greater than the actual power output. Again, as in Fig. 3*a*, the most significant differences between the optimized and actual patterns were found for the day time.

However, in order to achieve the savings of the total operational costs for the fuel options in Fig. 4*a*, the power plant should take some extra fuel expense. Despite the losses in the "internal" costs (mostly, during the day time), occurring when the boiler units are switched to the operation at the optimized loads, the significant reduction in the "external" costs covers the above "internal" cost losses leading to the saving of the total costs.

As an illustration, Fig.4b shows the potential time-domain losses of the "internal" costs as well as the saving of the "external" and total costs, resulted from switching the boiler units to the optimized loading for the rainy season for the fuel option of co-firing of the 310-MW units with the medium-sulfur fuel oil and natural gas EF_{ng} = 20% and firing of the 200-MW boilers with low-sulfur fuel oil.

As see from Table 1, the maximum benefit of about 1.12 to 1.75% of total cost savings could be achieved for the hot season if all the boiler units were operated at the optimized loads instead of actual loads, and besides, the 310-MW units were co-fired with fuel oil/gas at high values of 80 and 100%, respectively. Meanwhile, for the same fuel options, the least total cost savings, of about 0.38 to 0.59%, respectively, could be achieved in the cool season.

Table 1: Cost saving/losses for the 1330-MW power plant result from switching the boiler units to operation at the optimized loads for distinct seasons in Thailand

The potential savings/ losses, % per day (200-MW units firing low-S fuel oil and 310-MW units co-firing medium-S fuel oil and fuel gas at different EF_{ng})									
	“Internal” Costs			**“External” Costs**			**Total Costs**		
	Cool Season	**Hot Season**	**Rainy Season**	**Cool Season**	**Hot Season**	**Rainy Season**	**Cool Season**	**Hot Season**	**Rainy Season**
EF_{ng}= 100%	0.455	1.360	0.689	0.773	2.287	1.166	0.587	1.749	0.889
EF_{ng}= 80%	0.450	1.348	0.683	0.281	0.834	0.425	0.375	1.118	0.568
EF_{ng}= 60%	0.446	1.335	0.676	-0.106	-0.320	-0.163	0.184	0.550	0.279
EF_{ng}= 40%	0.441	1.323	0.669	-0.421	-1.262	-0.651	0.013	0.037	0.014
EF_{ng}= 20%	-1.713	-0.963	-1.371	5.675	1.500	2.147	0.560	0.314	0.448
EF_{ng}= 0%	-1.695	-0.954	-1.444	3.530	1.983	2.606	1.114	0.626	0.730

5. CONCLUSIONS

A linear programming tool was successfully applied for the optimization of current loading of the fuel oil/gas-fired boiler units of a power plant operated at different fuel options (including co-firing) with the aim of minimizing the total fuel and environmental costs for the entire power plant.

For the 1330-MW power plant consisting of two 200 MW units firing low-S fuel oil and three 310 MW units co-firing medium-S fuel with natural gas, the optimum load dispatching was strongly affected by the pattern of daily electricity demand as well as by the fuel option.

Application of the load optimization led to the reduction of the total costs for this power plant, and the total cost savings were dependent upon the daily load patterns, fuel option, fuel oil/gas prices as well as on the specific “external” costs.

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