# Thermal Power Plant Emissions Minimization taking into account Losses in Network

Anatoly Mahnitko, Alexander Gavrilov
Riga Technical University, Power Engineering Institute
Kronvalda blv. 1, Riga, Latvia, E-mail: mahno@eef.rtu.lv, a.gavrilovs@inbox.lv

***Abstract*** **-** This paper introduces a multipurpose mode optimization model for power system aimed to minimizing the fuel consumption of the electric power generation process, as well as decreasing the negative effect on the environment and decreasing power losses. During the optimization, technological constraints of the power system mode are taken into account in the form of linear and non-linear equations. The use of the method is illustrated by applying it on a test system composed of three stations. As a result of the optimization, additional expenses needed for compensating ecologically harmful influences on the environment are estimated.

***Keywords*****:** ***electric power system, optimization, cost function, fuel consumption, harmful influence to the environment, losses***

## I. INTRODUCTION

As all power systems are developing it becomes actual to control its mode in normal exploitation conditions – optimal load power distribution between system generators. In addition it is necessary to provide system power, working and financial resources high efficiency, safety and steady power supply. Also, all power structures negatively affect the environment, that's why we must take into account ecological aspects during the optimization. In accordance with [2, 3] EU requires to take into account certain requirements on the power generation and transmission levels. Those requirements are defined in EU instructions form. In the instructions there are strict standards on power generation that minimally influence the environment. Without those directives there are also queue of factors that should be considered. For example, problems and questions of power losses minimization. This problem is very difficult because of power system large scale and its fast development, and also power system elements' technological, economical and mode parameters difference.

Thus it is looked out electric power system mode optimization algorithm and its example taking into account technological constraints of the power system mode and decreasing the negative effect on the environment and power losses are considered. The method is illustrated applying it on a test system composed of three stations.

## II. POWER SYSTEM MODE OPTIMIZATION MODEL

During power system centralized control as dispatching system main criteria was active power optimal dispatch between system generators that provided fuel consumption minimization – incremental fuel consumption increase equality [4]:

$$\varepsilon_1 = \varepsilon_2 = ... = \varepsilon_n = \varepsilon_b, \tag{1}$$

where $\varepsilon_i = \dfrac{\partial B_i}{\partial P_i}$, $i = \overline{1,n}$ – $i$ generator incremental fuel consumption considering balance node ($\varepsilon_b$).

In conventionally regulated market the optimization problem is formed as power generation total cost minimization (in financial terms):

$$\sum^{n} c_i \cdot B_i \to \min, \tag{2}$$

where $B_i$ – equivalent fuel consumption, [t.e.f./h];
$c_i$ – equivalent fuel price, [€/h];

The optimal power system mode is searched in feasible area, which is formed by the inequality constraints that determine minimum and maximum generating limits respectively for plant $i$:

$$P_{i\ \min} \le P_i \le P_{i\ \max}. \tag{3}$$

From the model body that describes power system stationary mode power balance equations in the system's nodes [5] is taken into account:

$$\sum_i P_{g_i} + \sum_i P_{ij}\left(U_i, U_j, \delta_i, \delta_j\right) - \sum_i P_{d_i} = 0, \tag{4}$$

$$\sum_i Q_{g_i} + \sum_i Q_{ij}\left(U_i, U_j, \delta_i, \delta_j\right) - \sum_i Q_{d_i} = 0,$$

where $P_{g\,i}, Q_{g\,i}$ – active and reactive generated power in node $i$ ( $i \in n$ );

$P_{d_i}, Q_{d_i}$ – active and reactive load power in node $i$;

$P_{ij}$, $Q_{ij}$ – active and reactive power flow from node $i$ to $j$;

$U_i$, $U_j$ –voltage modules in nodes $i$ and $j$;

$\delta_i$, $\delta_j$ – phase angle nodes $i$ and $j$;

$n$ – the total number of generating plants.

If it is necessary to optimize the power system mode minimizing fuel expenses and emissions into environment, then optimization condition is:

$$\sum^{n} c_i \cdot B_i + \sum^{n} Y_i \to \min\,, \tag{5}$$

where $\sum^{n} Y_i$ – total damage from emissions that come in atmosphere, [€/t].

Total damage can be defined as [6]:

$$Y_i = c_k \cdot M_{\sum i}\,, \tag{6}$$

where $M_{\sum i}$ – noxious products that are emitted in atmosphere, [t/h];

$c_k$ – specific damage from ashes, sulphur oxide and nitrogen oxides, [€/t]. It was accepted that the specific damage from all three parameters is approximately identical and makes 3.33 of fuel price: $c_k = 3.33 \cdot c_i$ [€/t].

That is why optimization condition can be expressed as:

$$\sum^{n} c_i \cdot B_i + \sum^{n} c_k \cdot M_{\sum i} \to \min\,. \tag{7}$$

When transmission distances are very small and load density is very high, transmission losses may be neglected and the optimal dispatch of generation is achieved with all plants operating at equal incremental production cost. However, in a large interconnected network where power is transmitted over long distances with low load density areas, transmission losses are a major factor and affect the optimum dispatch of generation. One common practice for including the effect of transmission losses is to express the total transmission loss as a quadratic function of the generator power outputs. The simplest quadratic form is [7]:

$$P_L = \sum_{i=1}^{n_g} \sum_{j=1}^{n_g} P_i B_{ij} P_j\,, \tag{8}$$

where $B_{ij}$ – loss coefficients or $B$-coefficients.

Loss coefficients could be calculated from the expression [8]:

$$B_{ij} = \frac{R_{ij}}{U^2 \cdot \cos^2 \varphi_G}\,, \tag{9}$$

where $\cos\varphi_g$ – generator power factor.

So, transmission losses expression is:

$$P_L = \sum_{i=1}^{n_g} \sum_{j=1}^{n_g} \frac{R_{ij} \cdot P_i \cdot P_j}{U^2 \cdot \cos^2 \varphi_G}\,. \tag{10}$$

Optimization expression including losses is:

$$\sum^{n} c_i \cdot B_i + c_L \cdot P_L \to \min\,. \tag{11}$$

where $c_L$ – power losses cost $c_L = 3630\ EUR/MW$ .

Optimization condition including emissions into environment and transmission losses is:

$$\sum^{n} c_i \cdot B_i + \sum^{n} c_k \cdot M_{\sum i} + c_L \cdot P_L \to \min\,. \tag{12}$$

## III. POWER SYSTEM MODE OPTIMIZATION IGNORING UNHEALTHY EMISSIONS

The simpliest economic dispatch problem is the case when transmission losses are neglected. In essence, the model assumes that the system is only one bus with all generation and loads connected to it. It is necessary to determine optimal total demand $P_D$ distribution between three heat power plants (Fig. 1), that requires minimum fuel costs according to (2). Reactive power flows are neglected. System total demand is $P_D = 975\ MW$ .

Black fuel is used oil in all power plants. Black fuel oil expenses are $c_m = 200$ €/t. Power plant fuel consumption is:

$$\begin{aligned} B_1 &= 500 + 5.3 \cdot P_1 + 0.004 \cdot P_1^2 \ \ t/h; \\ B_2 &= 400 + 5.5 \cdot P_2 + 0.006 \cdot P_2^2 \ \ t/h; \\ B_3 &= 200 + 5.8 \cdot P_3 + 0.009 \cdot P_3^2 \ \ t/h. \end{aligned} \tag{13}$$

Fuel consumption graphic representation is shown in Fig.2.

The problem is to minimize cost function

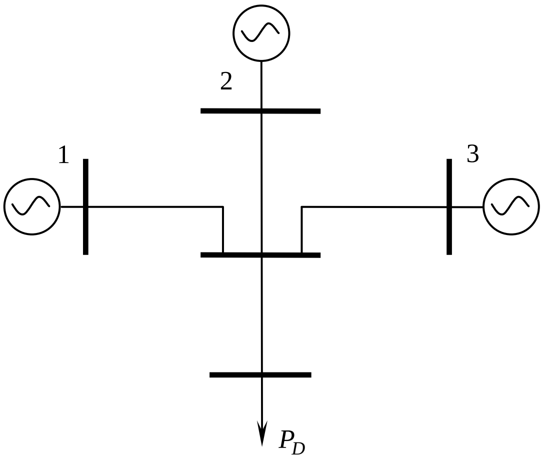


Fig.1 Three plants power system

$$F(P) = 500 + 5.3 \cdot P_1 + 0.004 \cdot P_1^2 + 400 +$$
$$+ 5.5 \cdot P_2 + 0.006 \cdot P_2^2 + 200 + 5.8 \cdot P_3 + 0.009 \cdot P_3^2,$$

subject to the inequality constraints (3):

$$200 \le P_1 \le 450\,MW;$$
$$150 \le P_2 \le 350\,MW; \qquad (14)$$
$$100 \le P_3 \le 225\,MW;$$

and power balance equation (4) neglecting transmission losses and reactive power:

$$\sum^{3} P_i - P_D = 0. \qquad (15)$$

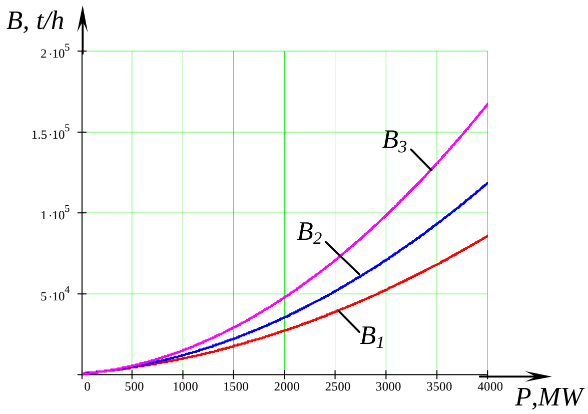


Fig.2 Fuel consumption curves

Solving the optimization problem the optimal active powers in nodes is gained:

$$\overset{*}{P}_1 = 450\ MW,\ \overset{*}{P}_2 = 325\ MW,\ \overset{*}{P}_3 = 200\ MW.$$

Now it is possible to determine the optimal fuel costs:

$$C_k = \sum_{i}^{3} c_m \cdot B_i = 1.65 \cdot 10^6\ EUR/h.$$

## IV. POWER SYSTEM MODE OPTIMIZATION TAKING INTO ACCOUNT UNHEALTHY EMISSIONS

Power system mode optimization taking into account unhealthy emissions in atmosphere is shown using the same power system test scheme (Fig. 1). It is necessary to determine optimal load power $P_D$ distribution between three heat power plants that asks minimum fuel costs and minimum damage to the environment according to optimization condition (7).

Noxious products from black oil fuel combustion in each power plant that come in atmosphere consist of [9, 10]:

- volatile ashes and unburn fuel emissions in atmosphere [t/h]

$$M_P = B_i \cdot A^P \cdot f \cdot (1 - \eta_s), \qquad (16)$$

where $A^P$ – ashes part in fuel on operating mass, %. For black oil fuel this value is $A^P = 0.1\%$;
$f$ – coefficient, which value for the heated by black oil fuel enclosure is $f = 0.01$;
$\eta_s$ – hard particle part that is caught in ashegrabber. In the practical calculations it can be accepted as $\eta_s = 0.4$;

- sulphur oxide emissions [t/h]

$$M_{SO_2} = 0.02 \cdot B_i \cdot S^r \cdot (1 - \eta'_{SO_2}) \cdot (1 - \eta''_{SO_2}), \qquad (17)$$

where $S^r$ – sulphur part in fuel on operating mass, %. For the black oil fuel $S^r = 1.9\ \%$;
$\eta'_{SO_2}$ – sulphur oxide part that is knot together by ashes. For the black oil fuel $\eta'_{SO_2} = 0.02$;
$\eta''_{SO_2}$ – sulphur oxide part that is caught in ashegrabber. For the dry ashegrabber this value is $\eta''_{SO_2} = 0$;

- nitrogen oxide emissions [t/h]

$$M_{NO_2} = 0.001 \cdot K_{NO_2} \cdot Q_N^p \cdot B_i \cdot (1 - \beta), \qquad (18)$$

where $K_{NO_2}$ – coefficient that considers nitrogen oxide generation on heat unit. For the black oil fuel $K_{NO_2} = 0.03\ kg/GDz$;

$Q_N^p$ – fuel combustion low heat, MJ/kg. For the black oil fuel $Q_N^p = 39.85$ MDz/kg ;

$\beta$ – coefficient that considers nitrogen oxide decrease by the complex of technological measures. For the heated by black oil fuel enclosure it is $\beta = 0.8$ .

Solving the optimization problem the optimal active powers in nodes is gained:

$$\overset{*}{P}_1 = 450\ MW,\quad \overset{*}{P}_2 = 324.98\ MW,\ \overset{*}{P}_3 = 200.02\ MW.$$

The optimal fuel costs taking into account the negative effect on the environment:

$$C_\Sigma = \sum_i^3 c_m \cdot B_i + \sum_1^3 c_k \cdot M_{\Sigma i} = 1.86 \cdot 10^6\ EUR/h.$$

As we can see from the results total costs increased by 12.7% if emissions in atmosphere are observed.

## V. POWER SYSTEM MODE OPTIMIZATION INCLUDING LOSSES

Test system (Fig.1) technical parameters are: line active impedances $R_{1-4} = 11.7\ \Omega$ ; $R_{2-4} = 14.5\ \Omega$ and $R_{3-4} = 10.8\ \Omega$ . Generators power factor is $\cos\varphi_G = 0.95$ . Network voltage is $U_{nom} = 330\ kV$ .

Using losses model (10) transmission losses expression is:

$$P_L = 0.000119 P_1^2 + 0.000148 P_2^2 + 0.00011 P_3^2\ MW.$$

Using optimization expression (10) power system mode optimization is performed. As a result the economic dispatch is gotten:

$$\overset{*}{P}_1 = 450\ MW,\quad \overset{*}{P}_2 = 323.3\ MW,\ \overset{*}{P}_3 = 201.7\ MW.$$

Total production cost including power losses is:

$$C_\Sigma = \sum_i^3 c_m \cdot B_i + c_L \cdot P_L = 1.81 \cdot 10^6\ EUR/h.$$

Total production costs increased by 9.7% if transmission losses are observed.

## VI. POWER SYSTEM MODE OPTIMIZATION INCLUDING UNHEALTHY EMISSIONS AND LOSSES

Power system (Fig.1) mode optimization taking into account unhealthy emissions and transmission losses was made using optimization condition (12). As a result economic dispatch was gained:

$$\overset{*}{P}_1 = 450\ MW,\quad \overset{*}{P}_2 = 323.36\ MW,\ \overset{*}{P}_3 = 201.64\ MW.$$

Total production cost including power losses and atmosphere emissions:

$$C_\Sigma = \sum_i^3 c_m \cdot B_i + \sum_i^3 c_k \cdot M_{\Sigma i} + c_L \cdot P_L = 2.02 \cdot 10^6\ EUR/h.$$

Total production costs increased by 22.4% if transmission losses and unhealthy emissions in atmosphere are observed.

## VII. FUEL EXTRA CONSUMPTION AND DAMAGE VALUATION

Total damage from fuel combustion can be calculated using the expression [6]:

$$Y = \alpha_{mP} \cdot M_P \cdot Y_P + \alpha_{mS} \cdot M_{SO_2} \cdot Y_{SO_2} + \alpha_{mN} \cdot M_{NO_2} \cdot Y_{NO_2}\ .$$

where $\alpha_{mP}, \alpha_{mS}, \alpha_{mN}$ – coefficients for ashes, sulphur and nitrogen oxides that consider local factors to determine damage;

$Y_P, Y_{SO_2}, Y_{NO_2}$ – specific damage from ashes, sulphur and nitrogen oxides emissions.

Local factor coefficient $\alpha_m$ meaning is: in special weather (lull, low clouds, heightened background pollution, smog etc.) damage increases by $\alpha_m$ times. Density of population, industry, agriculture and climatic conditions of power plant area affects on the $\alpha_m$ value.

As damage depends on great number of factors than some reasoned value usage is inconvenient. More important is to establish limits of parameter changes. That's why it was accepted that specific damage from all of three parameters is approximately equal and makes 3.33 from fuel costs [6]:

$$Y_P = Y_{SO_2} = Y_{NO_2} = 3.33 \cdot c_i\ . \qquad (19)$$

Local factor estimated values are also assumed equal:

$$\alpha_{mP} = \alpha_{mS} = \alpha_{mN} = \alpha_m\ . \qquad (20)$$

During calculations large $\alpha_m$ coefficient variations were used (from 0 (without damage) to 10). This range is larger than the real one. Fuel quality was also changed in wide ranges. Thus there were changed such fuel parameters as: ashes part in fuel 0.05, 0.15 and 0.2%; sulphur part in fuel 0.5, 3 and 4%. This gave opportunity to evaluate each factor influence. It was assumed that fuel parameters adjustment doesn't change aggregate electrical characteristics. To compare the results base variant from the section 4 was taken: $S^r = 1.9\,\%$ ; $A^P = 0.1\%$ ; ashegrabber efficiency $\eta_s = 0.4$ .

Results of the calculations are shown in Fig.3. Fuel consumption curve depending on coefficient $\alpha_m$ has *U*-kind character. This function minimum is achieved when there is no extra fuel consumption. Dropping curve's part is so called good ecological power system mode. Rising curve's part is adverse ecological power system mode.

There is shown damage alternation depending on factor coefficient $\alpha_m$ in Fig.4 *a*. In Fig.4 *b* there are compared damage changes with extra fuel consumption – it is emission reduction on fuel consumption increasing by 1% $\Delta Y/\Delta B$ – depending on local factor coefficient $\alpha_m$ .

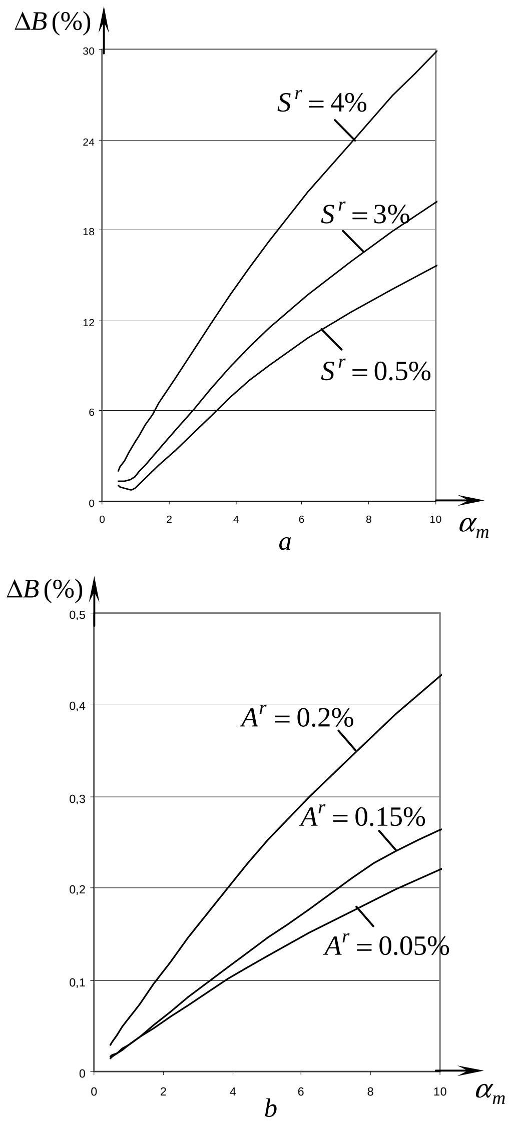


Fig.3 Extra fuel consumption needed for compensating ecologically harmful influences on the environment depending on local factor coefficient $\alpha_m$ , changing:
*a* – sulphar part; *b* – ashes part

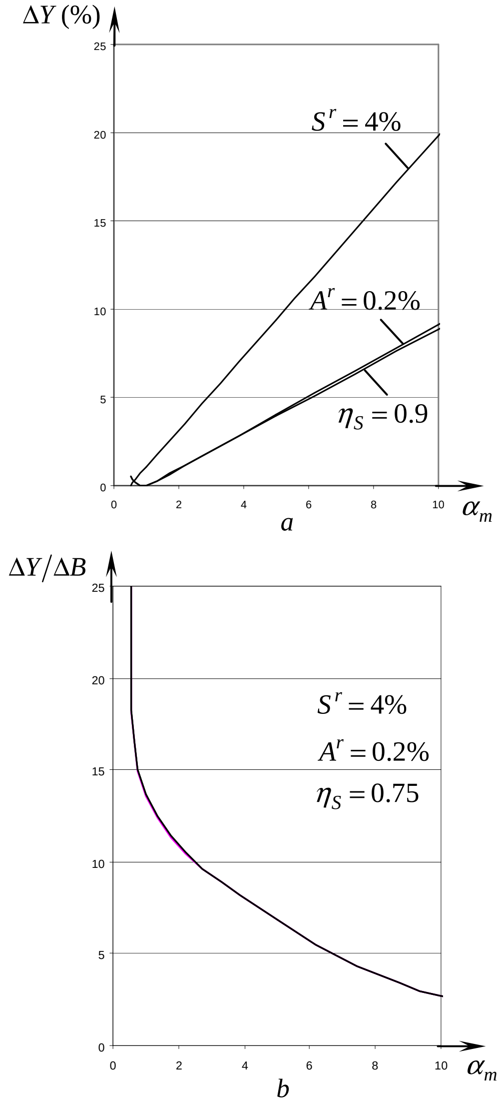


Fig.4 Damage alternation (*a*) and its comparison with extra fuel consumption (*b*) depending on local factor coefficient $\alpha_m$

VIII. CONCLUSIONS

1. Power system optimization algorithm taking into account transmission losses and damage to the environment was considered.
2. The use of the algorithm is checked applying it on a test system. Results show that ecological effect and losses consideration increased total production costs.
3. There were gained characteristics that show damage alternation depending on local factor coefficient. It is obtained power system extra fuel consumption to reduce harmful influence on the environment changing fuel parameters.

ACKNOWLEDGEMENT

This work has been partly supported by the European Social Fund within the National Programme "Support

for the carrying out doctoral study programm's and post-doctoral studies at Riga Technical University".

## REFERENCES

[1] Gerhards J., Mahnitko A. Power System Mode Optimization, Riga, RTU, 2005. 249 p. (in Latvian)

[2] Directive 2001/80/EC of the European Parliament and of the Council on the limitation of emissions of certain pollutions into the air from large combustion plants // Official Journal of the European Communities, 2001. 21 p.

[3] Directive 2001/80/EC of the European Parliament and of the Council of 13 October 2003 establishing a scheme for greenhouse gas emission allowance trading within the Community and amending Council Directive 96/61/EC // Official Journal of the European Communities, 2003. 15 p.

[4] Erohin P. Exercises and Technologies of Power System Mode Control in Power Market Conditions of Russia //Authors summary. – Yekaterinburg: USTU, 2005. 48 p. (in Russian)

[5] Vaskovskaya T. Nodal Prices Difference Indicators in Power Energy Market // Electricity, 2007, Nr.2, pp. 23 – 27. (in Russian)

[6] Baranisova G., Burlaku M., Zhuravlev V. Economical Effect Valuation during Power Dispatching taking into account Ecology Aspects // Electricity, 1982, Nr.9, pp. 62 – 65. (in Russian)

[7] Saadat H. Power System Analysis. – New York: WCB/McGraw-Hill Book Company, 1999. 700 p.

[8] Lukman D., Walshe K., Blackburn T. Loss Minimization in Industrial Power System Operation // Journal of Electrical Systems, 2007, vol. 3, pp. 13 – 25.

[9] Derzsky V., Kaplin N. Power System Mode Multipurpose Optimization, Kiev, 1990. pp. 69 – 80. (in Russian)

[10] Flyagin A., Volodarsky N., Kondratenko A. Teaching Aids for Unhealthy Emissions Calculation during Fuel Combustion, Moscow: Stroyizdat, 1985. 20 p. (in Russian)