ENERĢĒTIKA
UN ELEKTROTEHNIKA
ISSN 1407-7345 2008-23
POWER AND ELECTRICAL
ENGINEERING

SILTUMELEKTROSTACIJU REŽĪMU IEDARBĪBAS NOVĒRTĒJUMS UZ APKĀRTĒJO VIDI

EVALUATION OF THERMAL POWER PLANT MODE INFLUENCE ON THE ENVIRONMENT

Anatoly Mahnitko, *Professor, Dr.Sc.Ing.*
Riga Technical University
Power Engineering Institute
Address: Kronvalda blv., 1, LV-1010, Riga, Latvia
Phone: +371 7089938, fax: +371 7089931
E-mail: mahno@eef.rtu.lv

Alexander Gavrilov, *M.Sc.Ing., PhD student*
Riga Technical University
Power Engineering Institute
Address: Kronvalda blv., 1, LV-1010, Riga, Latvia
Phone: +371 26161738, fax: +371 7089931
E-mail: A.Gavrilovs@inbox.lv

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

Introduction

Generated power effective distribution problem's solution is one of the most important power system functioning aims. In addition, it is necessary to provide system power, working and financial resources high efficiency, safety and steady power supply [1]. Also, all power structures negatively affect the environment, that's why ecological aspects must be taken into account during the optimization. In accordance with normative documentation [2, 3] EU requires to take into account certain requirements on the power generation and transmission levels. In those directives there are strict standards on power generation that minimally influence the environment. Without those documents there are also queue of factors that should be considered. For example, problems of power losses minimization in the network. In common, the optimization problem is very difficult because of power system large scale and also power system elements' technological, economical and mode parameters difference.
In the work electric power system mode optimization algorithm is looked out and its example taking into account power system mode technological constraints and aimed at decreasing the negative effect on the environment and power losses in the network is considered. The method is illustrated applying it on a test system composed of three stations.

1. Power system mode optimization mathematical 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]:

$$\varepsilon_1 = \varepsilon_2 = \ldots = \varepsilon_n = \varepsilon_б \qquad (1)$$

where $\varepsilon_i = \dfrac{\partial B_i}{\partial P_i}$, $i = \overline{1, n}$ – i generator incremental fuel consumption considering balance node (ε_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/h];
c_i – equivalent fuel price, [€/t].
The optimal power system mode as well is searched in the feasible area, which is formed by the technological limitations on power generation:

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

From the majority of models that describes the post setup regime the conventional model of power balance in the node of electric power system is used:

$$\begin{aligned} &\sum_i P_{\varepsilon_i} + \sum_i P_{ij}\left(U_i, U_j, \delta_i, \delta_j\right) - \sum_i P_{n_i} = 0, \qquad i \in n \\ &\sum_i Q_{\varepsilon_i} + \sum_i Q_{ij}\left(U_i, U_j, \delta_i, \delta_j\right) - \sum_i Q_{n_i} = 0, \qquad i \in n \end{aligned} \tag{4}$$

where P_{gi}, Q_{gi} – active and reactive power of generation 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 overflow from i node to j;
U_i, U_j –voltage modules in nodes i and j;
δ_i, δ_j – phase angle nodes i and j;
n – total number of nodes in the network.
To consider losses in the power network its expression as quadratic functions of generator powers will be used. This expression is formed as [6]:

$$\Delta P = \sum_{i=1}^{n_г} \sum_{j=1}^{n_г} P_i B_{ij} P_j \tag{5}$$

where B_{ij} – loss coefficients or B-coefficients, that could be calculated using the expression [1]:

$$B_{ij} = \frac{R_{ij}}{U_i \cdot U_j} \cos \delta_{ij} \tag{6}$$

where δ_{ij} – phase angle offset between voltage vectors U_i and U_j;
R_{ij} – power line active impedance between nodes i and j.
So, transmission losses expression is:

$$\Delta P = \sum_{i=1}^{n_г} \sum_{j=1}^{n_г} \frac{R_{ij} \cdot P_i \cdot P_j}{U_i \cdot U_j} \cos \delta_{ij} \tag{7}$$

Thus, power losses consideration transforms function (2) into expression:

$$\sum^{n} c_i \cdot B_i + c_L \cdot \Delta P \to \min \tag{8}$$

where c_L – power losses cost $c_L = 3630\ EUR/MW$.
Damage from emissions that come in atmosphere can be defined as [6]:

$$Y_i = c_d \cdot M_{\Sigma i} \tag{9}$$

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

c_d – 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 [5]: $c_d = 3.33 \cdot c_i$ [€/t].

All of three power system optimization criterions (fuel consumption, power losses in the network and emissions in the environment minimization) simultaneous consideration can be observed as the function:

$$\sum^{n} c_i \cdot B_i + \sum^{n} c_d \cdot M_{\Sigma i} + c_L \cdot \Delta P \rightarrow \min \tag{10}$$

2. Power system mode optimization ignoring damage to the environment and power losses

Optimization model is looked up on the power system test scheme that consists of three heat power plants (Fig.1). System total demand is $P_D = 975\ MW$. Line active impedances are $R_{1-4} = 11.7\ \Omega$; $R_{2-4} = 14.5\ \Omega$ and $R_{3-4} = 10.8\ \Omega$. Network voltage is $U_{nom} = 330\ kV$. During calculations reactive power flows are neglected. Black fuel is used oil in all power plants. Black fuel oil price is $c_f = 200$ €/t.

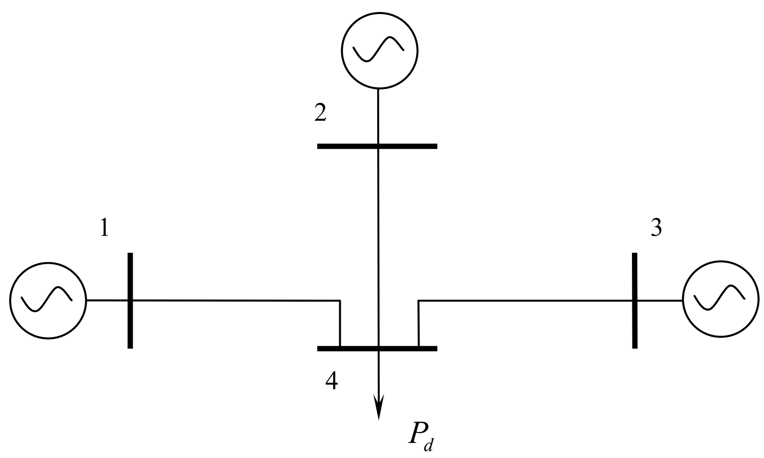


Figure 1. Three plants power system

Power plant fuel consumption characteristics are expressed as second order polynomials:

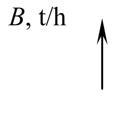
$$\begin{aligned} B_1 &= 500 + 5.3 \cdot P_1 + 0.004 \cdot P_1^2 \quad \text{t/h} \\ B_2 &= 400 + 5.5 \cdot P_2 + 0.006 \cdot P_2^2 \quad \text{t/h} \\ B_3 &= 200 + 5.8 \cdot P_3 + 0.009 \cdot P_3^2 \quad \text{t/h} \end{aligned} \tag{11}$$

Fuel consumption graphic representation is shown in Fig.2.
Technological limitations (2) are:

$$\begin{aligned} 200 \le P_1 \le 450\ MW \\ 150 \le P_2 \le 350\ MW \\ 100 \le P_3 \le 225\ MW \end{aligned} \tag{12}$$

Power balance equation (4) neglecting transmission losses and reactive powers is:

$$\sum^{3} P_i - P_{и} = 0 \tag{13}$$



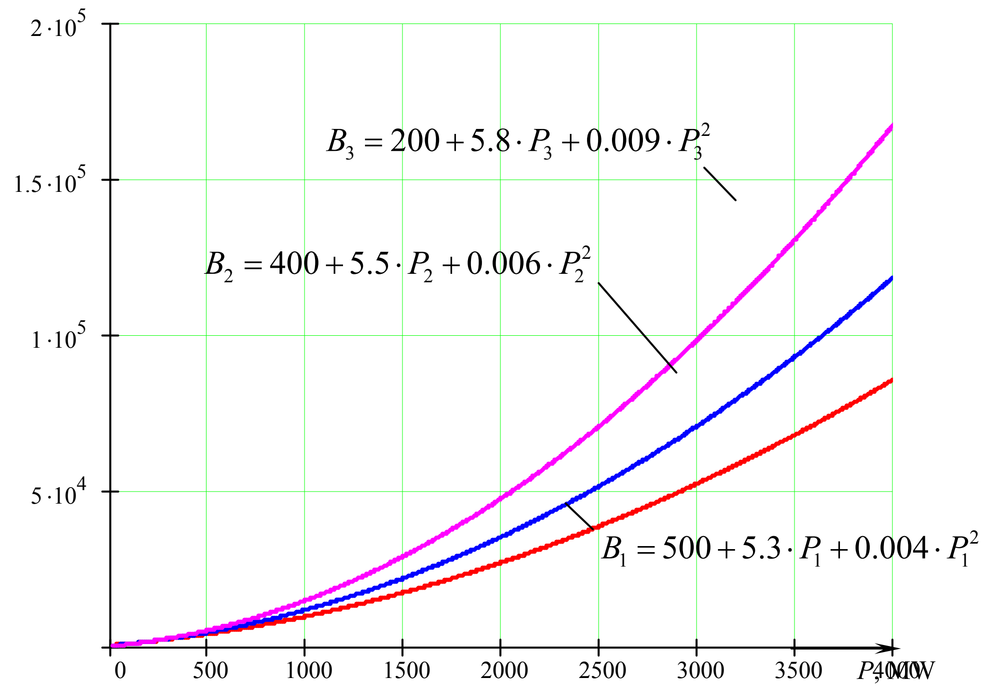


Figure 2. Fuel consumption curves

Solving the optimization problem the optimal active powers in nodes neglecting power losses and emissions in atmosphere are gained:

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

Total power generation costs ignoring power losses and atmosphere emissions:

$$C_\Sigma = \sum_i^3 c_f \cdot B_i = 1.65 \cdot 10^6\ \text{€/h}$$

3. Power system mode optimization including losses

Using losses model (7) we can get expression of transmission losses:

$$\Delta P = 0.000119 P_1^2 + 0.000148 P_2^2 + 0.00011 P_3^2\ \ MW$$

Using the optimization expression (8) power system's (Figure 1) mode optimization is performed. As a result the economic dispatch is gotten:

$$\overset{*}{P}_1 = 450\ MW,\quad \overset{*}{P}_2 = 323.303\ MW,\quad \overset{*}{P}_3 = 201.697\ MW$$

Total production costs including power losses are:

$$C_\Sigma = \sum_i^3 c_f \cdot B_i + c_L \cdot \Delta P = 1.81 \cdot 10^6\ \text{€/h}$$

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

4. Power system mode optimization considering unhealthy emissions

Power system (Fig. 1) mode optimization taking into account unhealthy emissions in atmosphere is performed using the methodology from [8, 9].
Noxious products from black oil fuel combustion in each power plant that come in atmosphere consist of [8, 9]:

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

$$M_P = B_i \cdot A^P \cdot f \cdot (1-\eta_s) \quad (14)$$

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 $f = 0.01$;
η_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]

$$M_{SO_2} = 0.02 \cdot B_i \cdot S^r \cdot \left(1-\eta'_{SO_2}\right) \cdot \left(1-\eta''_{SO_2}\right) \quad (15)$$

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

$$M_{NO_2} = 0.001 \cdot K_{NO_2} \cdot Q_N^p \cdot B_i \cdot (1-\beta) \quad (16)$$

where K_{NO_2} – coefficient that considers nitrogen oxide generation on heat unit. For the black oil fuel $K_{NO_2} = 0.03 \ kg/GJ$;
Q_N^p – fuel combustion low heat, MJ/kg. For the black oil fuel $Q_N^p = 39.85$ MJ/kg;
β – coefficient that considers nitrogen oxide decrease by the complex of technological measures. For the heated by black oil fuel enclosure it is $\beta = 0.8$.
Thus, total emissions of noxious products in atmosphere M_Σ from black fuel oil combustion in each heat power plant are:

$$M_\Sigma = M_P + M_{SO_2} + M_{NO_2} = B_i \cdot A^P \cdot f \cdot (1-\eta_s) +$$
$$+ 0.02 \cdot B_i \cdot S^p \cdot \left(1-\eta'_{SO_2}\right) \cdot \left(1-\eta''_{SO_2}\right) + 0.001 \cdot K_{NO_2} \cdot Q_н^p \cdot B_i \cdot (1-\beta) = B_i \cdot 0.1 \cdot 0.01 \cdot (1-0.4) +$$
$$+ 0.02 \cdot B_i \cdot 1.9 \cdot (1-0.02) \cdot (1-0) + 0.001 \cdot 0.03 \cdot 39.85 \cdot B_i \cdot (1-0.8) = 0.0381 \cdot B_i.$$

The optimal power system mode is achieved when active powers of generation are:

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

Total production costs including emissions in atmosphere:

$$C_\Sigma = \sum_i^3 c_f \cdot B_i + \sum_i^3 c_d \cdot M_{\Sigma i} = 1.86 \cdot 10^6 \text{ €/h}$$

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

5. Power system mode optimization including unhealthy emissions and power losses

Power system (Fig.1) mode optimization taking into account unhealthy emissions and transmission losses was made using optimization condition (10). As a result economic dispatch was gained:

$$\overset{*}{P}_1 = 450 \ MW, \quad \overset{*}{P}_2 = 323.364 \ MW, \quad \overset{*}{P}_3 = 201.636 \ MW$$

Total production cost including power losses and unhealthy emissions in the atmosphere:

$$C_\Sigma = \sum_i^3 c_f \cdot B_i + \sum_i^3 c_d \cdot M_{\Sigma i} + c_L \cdot \Delta P = 2.02 \cdot 10^6 \text{ €/h}$$

Total production costs increased by 21.8% if transmission losses and negative effect on the environment are observed.

6. Extra fuel consumption and damage evaluation

Specific damage from fuel combustion (1 t.) can be calculated using the expression [5]:

$$\Delta c = \alpha_{mP} \cdot A_P \cdot Y_P + \alpha_{mSO_2} \cdot A_{SO_2} \cdot Y_{SO_2} + \alpha_{mNO_2} \cdot A_{NO_2} \cdot Y_{NO_2} \quad (18)$$

where α_{mP}, α_{mSO_2}, α_{mNO_2} – coefficients for ashes, sulphur and nitrogen oxides that consider local factors to determine damage;
A_P, A_{SO_2}, A_{NO_2} – specific emissions of dust, sulphur and nitrogen oxides;
Y_P, Y_{SO_2}, Y_{NO_2} – specific damage from ashes, sulphur and nitrogen oxides emissions.
Then total damage can be defined from the expression [5]:

$$Y = \alpha_{mP} \cdot M_P \cdot Y_P + \alpha_{mSO_2} \cdot M_{SO_2} \cdot Y_{SO_2} + \alpha_{mNO_2} \cdot M_{NO_2} \cdot Y_{NO_2} \quad (19)$$

Local factor coefficient α_m meaning is: in special weather (lull, low clouds, heightened background pollution, smog etc.) damage increases by α_m times. Density of population, industry, agriculture and climatic conditions of power plant area affects on the α_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 [5]:

$$Y_P = Y_{SO_2} = Y_{NO_2} = 3.33 \cdot c_i \quad (20)$$

Local factor estimated values are also assumed equal:

$$\alpha_{mP} = \alpha_{mSO_2} = \alpha_{mNO_2} = \alpha_m \quad (21)$$

During calculations large α_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 was accepted: $S^r = 1.9\,\%$; $A^P = 0.1\%$; ashegrabber efficiency $\eta_s = 0.4$.

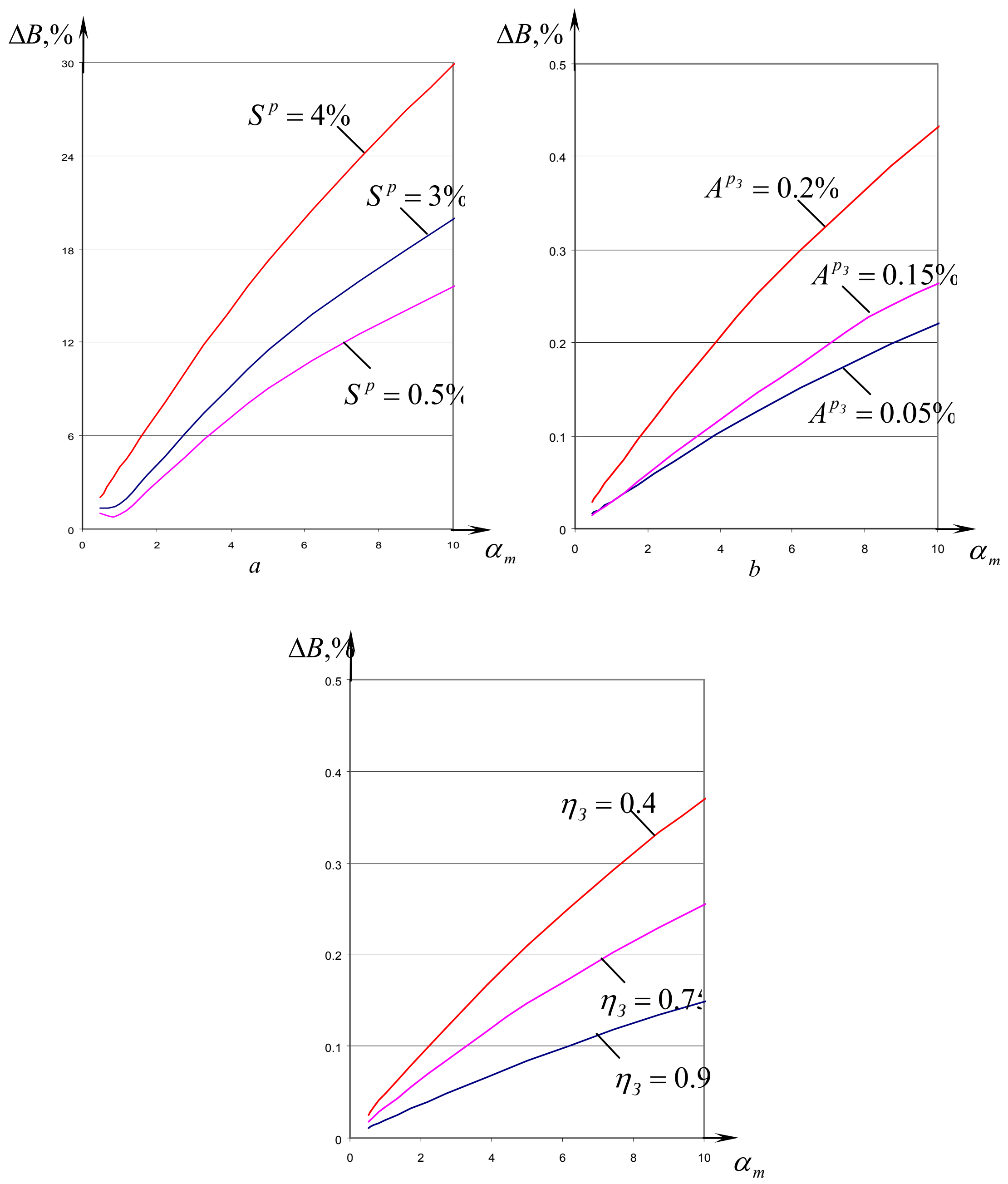


Figure 3. Extra fuel consumption needed for compensating ecologically harmful influences on the environment depending on local factor coefficient α_m, changing:

a – sulphar part in fuel; *b* – ashes part in fuel; *c* – ashegrabber efficiency

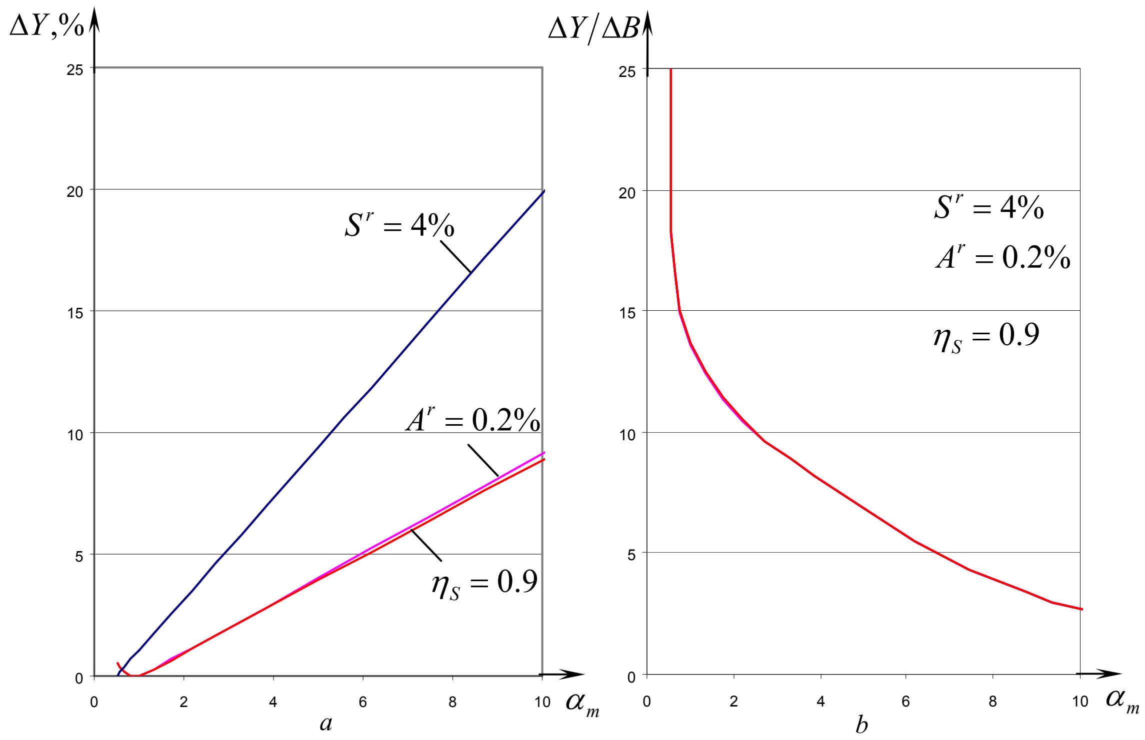


Figure 4. Damage alternation (*a*) and its comparison with extra fuel consumption (*b*) depending on local factor coefficient α_m

Results of the calculations are shown in Fig.3. Fuel consumption curve depending on coefficient α_m 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. As we can see from graphics in Fig.4 all of three variable parameters' (ashes and sulphur part in fuel on operating mass) influence is different, but curves' character has been saved. Nevertheless sulphur part in fuel influence on fuel extra consumption to compensate noxious emissions is greater.

There is shown damage alternation depending on factor coefficient α_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 α_m.

7. Power system mode optimization by criteria importance

In this work power system mode optimization was made taking into account three factors:

- fuel consumption minimization on power plants;
- power loses minimization in the network;
- unhealthy emissions minimization during power generation.

All criteria were equivalent. Let us look out every factor influence degree on the result of optimization. For this, in the expression (12) weight coefficients should be included:

$$\sum^{n} x \cdot c_f \cdot B_i + \sum^{n} y \cdot c_d \cdot M_{\Sigma i} + z \cdot c_L \cdot \Delta P \rightarrow \min \qquad (17)$$

where *x*, *y*, *z* – weight coefficients that consider minimization of fuel consumption, minimization of unhealthy emissions in atmosphere, minimization of power losses, accordingly. At that, $x + y + z = 1$.

As a base mode there was chosen power system mode when all weight coefficients were equal (all factors are equal – $x = y = z = 1/3$). In that case total production costs are: $C_{\Sigma} = 6.715 \cdot 10^5$ €/h.

Changing one weight coefficient from 1 (only this factor consideration) to 0 (that criteria is not considered), while all other coefficients are equal (they could be calculated using the expression $y = z = (1 - x)/2$), characteristics of selected factors observation during the optimization were gotten (Figure 5).

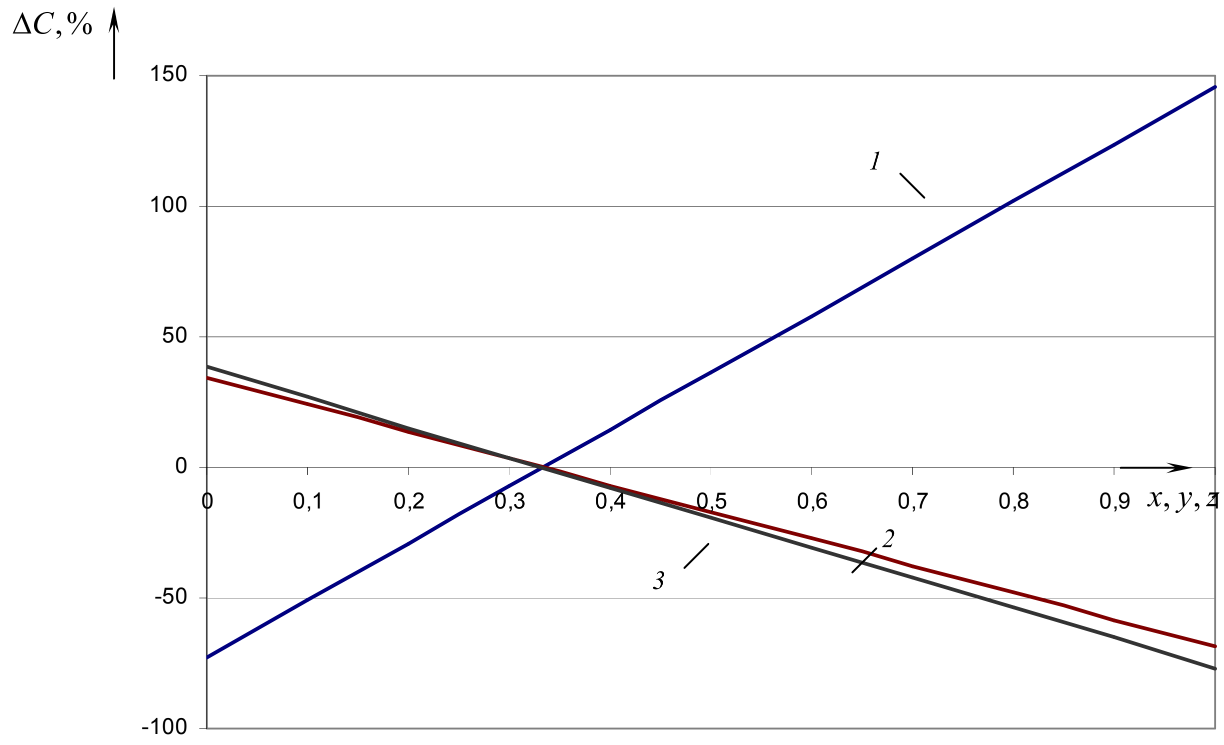


Figure 5. Selected criteria influence on total system expenses:
1 – *x* weight variation (*y* = *z*); *2* – *y* weight variation (*x* = *z*); *3* – *z* weight variation (*x* = *y*).

Let us analyze gotten results. How it could be seen in Fig.5 the base variant confirms with the curves' crossing point of X-axis, where all considered factors are equal ($x = y = z = 1/3$). By increasing fuel consumption criteria importance (all other criteria weight decreases) it could be observed increase of total expenses (curve *1*). It could be explained by fuel cost major influence on the total expenses. That's why considering only fuel consumption ($x = 1$) other two optimization factors' weights decrease to 0 ($y = z = 0$) and, due to fuel cost major effect, total costs increase by almost 50%. Lines *2* and *3* in Fig.5 have dropping character that is entailed with emissions in atmosphere and power losses less influence on total expenses (in comparison with fuel costs). In additional, it is observed almost similar lines *2* and *3* slant that shows on similar sensitivity of ecological effect and power losses consideration on total system expenses.

8. Conclusions

1. Power system optimization algorithm taking into account transmission losses and damage to the environment was considered.
2. The use of the algorithm was checked applying it on a test system. Results show that ecological effect and power losses consideration increased total production costs.
3. There were gained characteristics that show damage alternation depending on local factor coefficient. It was obtained power system extra fuel consumption to reduce harmful influence on the environment changing fuel parameters.
4. It was looked out each of selected criterions (minimization of fuel expenses; power losses minimization; minimization of unhealthy emissions during power generation) on results of optimization.

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. Energosistēmu režīmu optimizācija. – Rīga, RTU, 2005. – 249 lpp.

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. Ерохин П.М. Задачи и технологии оперативно-диспетчерского управления режимами ЕЭС в конкурентно-рыночной энергетике России // Автореферат диссертации на соискание учёной степени доктора технических наук. – Екатеринбург: УГТУ – УПИ, 2005. – 48 с.

5. Барамысова Г.А., Бурлаку М.И., Журавлёв В.Г. Оценка экономического эффекта при распределении нагрузки с учётом экологических факторов // Электричество, 1982, №9, с. 62 – 65

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

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

8. Финягин А.П., Володарский Н.Х., Кондратенко А.П. и др. Методические указания по расчёту выбросов загрязняющих веществ при сжигании топлива в котлах. – М.: Стройиздат, 1985. – 20 с.

9. Дерзский В.Г., Каплин Н.И. Многоцелевая оптимизация режимов электрических сетей энергосистем. – Киев, 1990. с. 69 – 80

Gavrilovs A., Mahņitko A. Siltumelektrostaciju režīmu iedarbības uz apkārtējo vidi novērtējums

Elektroenerģētikas centralizētas pārvaldes apstākļos elektroenerģētiskās sistēmas (EES) režīma optimizācijas galvenais uzdevums bija samazināt summārā kurināmā patēriņu. Nekādi kurināmā piegādes apjomu ierobežojumi netika ņemti vērā.

Brīvā tirgus apstākļos starp enerģētikas subjektiem EES režīma optimizācijas galvenais uzdevums ir samazināt izmaksas naudas izteiksmē. Turklāt katrs elektroenerģijas tirgus dalībnieks cenšas iegūt maksimālo peļņu no savas darbības. Norādītie mērķi ir jāsasniedz, ņemot vērā dažādus ierobežojumus: resursu, tehnoloģiskos, ekoloģiskos u.tml.

Darbā ir apskatīts EES režīma optimizācijas algoritms, ņemot vērā kaitējumu apkārtējai videi. EES testshēmas aprēķins parādīja tās darbspēju un praktiskā izmantojuma iespēju konkrētās EES apstākļos. Ir apskatīta saskaņā ar ekspertu viedokli izvēlēto kritēriju ietekmes pakāpe uz sistēmas kopējiem izdevumiem energosistēmas režīma optimizācijas uzdevumā.

Gavrilovs A., Mahņitko A. Evaluation of thermal power plant mode influence on the environment

In the conditions of the power system centralized management the main task of electric power system (EPS) mode optimization was fuel consumption minimization. No limits on the fuel supply amount were foreseen.

In liberalized electricity market of relations between energy subjects the basic task of the EPS mode optimization is minimization of all expenses. Thus every electric power market participant tends to get maximal income from the activity. But indicated aims must be achieved taking into account different constraints like fuel constraints, technological constraints, emission constraints and other.

This paper introduces EPS mode optimization algorithm aimed at decreasing the negative effect on the environment. The calculations of test EPS show possibility of practical application in the conditions of concrete EPS. It is looked out by expert position selected criteria influence degree on total system expenses during power system mode optimization.

Гаврилов А., Махнитко А. Оценка воздействия режима тепловых станций на окружающую среду

В условиях планового централизованного управления электроэнергетикой главной задачей оптимизации режима электроэнергетической системы (ЭЭС) являлось минимизация суммарного расхода топлива. Никакие ограничения на объемы его поставок не рассматривались и не учитывались.

В условиях рыночных отношений между субъектами энергетики основной задачей оптимизации режима ЭЭС является минимизация затрат в денежном выражении. При этом каждый участник рынка электроэнергии стремится к получению максимальной прибыли от своей деятельности. Указанные цели при этом должны быть достигнуты при соблюдении различного вида ограничений: ресурсных, режимных, экологических и т.п.

В работе рассмотрен алгоритм оптимизации режима ЭЭС с учётом влияния на окружающую среду и минимизации потерь мощности на примере тестовой схемы ЭЭС. Исследована зависимость влияния по степени важности учитываемых критериев, определённых экспертным путём, на общесистемные затраты в задаче оптимизации режима работы ЭЭС.