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REDUCTION OF PHASE INTERACTIONS IN CONTROL PROCESSES OF "ARC STEEL-MAKING FURNACE – POWER SUPPLY SYSTEM" COMPLEX ELECTRICAL TECHNOLOGICAL SYSTEM

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Abstract. In the article system engineering solutions for enhancing the single-phase autonomy of the processes of controlling the coordinates of electrical mode (EM) in an electrical mechanical sub-system of moving the electrodes of an electric arc steel-making furnace by including a cross-link compensator into its structure. The technique of the synthesis of transfer functions of the cross-link compensator in phase control channels are proposed and mathematical models of cross-link compensators for electric arc furnace EAF-3 (ukr. ДСП-3) are obtained.

Key words: electric arc furnace, power supply, compensator of cross links, controller, synthesis, optimazation, dynamics, criterion.

1. Introduction

Electric arc furnaces (EAF) refer to the category of complex three-phase interrelated systems. They are characterized by extremely dynamic, unsteady and phase-asymmetric load, as well as high unit power (from 1.5 to 170 MVA and higher). Taking into account the current trend towards the increase of the production of arc-furnace steel (at present it makes up more than 50% of the total world steel production), scrap melting intensification and the increase of specific power of electric power equipment (1.0–1.3 MVA/t), the task of encreasing the electrotechnical efficiency of making arc-furnace steel in the EAFs is quite important and topical.

2. Analysis of recent achievements

One of the promising directions of improving existing technical means for control over melting phase in the EAF is the development of new efficient, simple and reliable circuitry and algorithmic solutions based on the use of semiconductor power converters and microprocessor technology in the feeding and controlling modes of the system comprising electric arc furnace and power supply (EAF-PS system) [1]. In accordance with that direction the solution described in [2] was developed for optimal control and quality stabilization of electrical mode coordinates. But these solutions do not take into account cross links existing and acting in the system.

3. The aim of the investigation

The aim of the investigation is the development of system engineering solutions to the task of creating single-phase autonomy of mode coordinates control and increasing dynamic accuracy of their stabilization at a preset level.

4. The results of the investigation

For realizing the strategy of multicriterial optimal control over the modes of the EAF-PS system, the structure of a multicircuit high-speed system was developed [2]. It consists of several subsystems, namely, the subsystem cotrolling the position of electrodes (SCPE), the subsystem controlling furnace mode coordinate (SCFMC) and the subsystem controlling power supply mode coordinate (SCPSMC) (Fig. 1).

Functional potential of such a structure is directed towards increasing the dynamic and static accuracy of controlling mode coordinates of electrical arc steel-making, decreasing the level of negative interaction of the EAF and power supply, increasing the electrical efficiency, decreasing energy intensity, increasing furnace productivity, prolonging the life duration of power equipment and increasing the quality of arc-furnace steel. Such solutions have been developed on the basis of an integrated system approach which takes into account modes and functional characteristics of EAF, as well as those of power supply.

Modern trends towards increasing unit tonnage of EAF and specific power of furnace transformers (FT) provide the necessity for obtaining the high-performance circuitry and algorithmic provision of the optimization of electric steel-making phases (modes). Therefore, the authors propose to expand the functional capabilities of the automatic control system (ACS) with the modes of the EAF-PS system which can be achieved by the means of high-speed wide-range adjustment of coordinates and parameters of the arc power supply according to the relevant control modes. On this basis, the efficient multifunctional and multicircuit system for optimal controlling the modes of the EAF-PS system is to be created according to given quality criteria.

As the basis of the approach mentioned above, the concept of priority suppression of disturbances in the source of their occurence is introduced. The multicircuit structure of the coordinate–parametric system for controlling the modes of the EAF-PS system developed according to this approach is shown in Fig. 1. The abbreviations and signals shown in Fig. 1 read as follows:

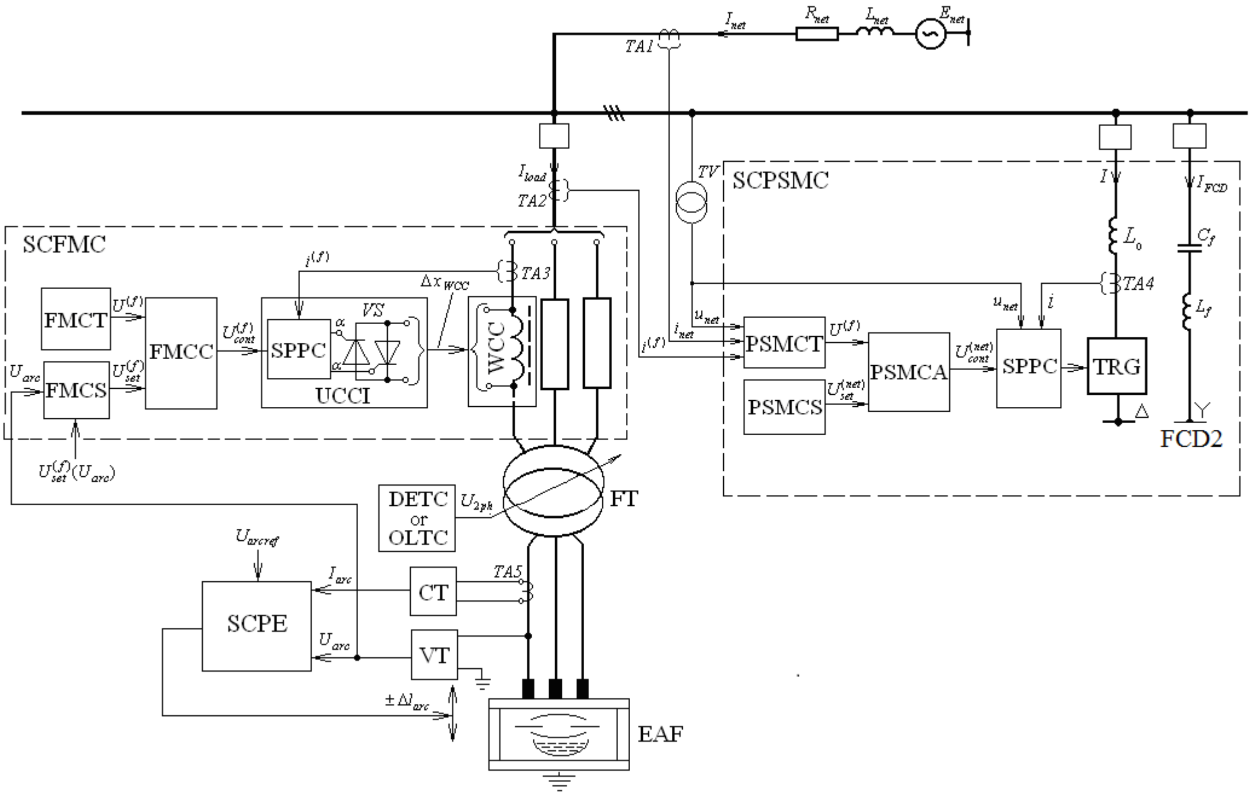

Fig. 1. Functional block diagram of multicircuit SAC for multicriterion mode optimization of the EAF-PS system.

SCPE – subsystem controlling the position of electrodes;
SCFMC – subsystem controlling furnace mode coordinate;
SCPSMC – subsystem controlling power supply mode coordinate;
FMCT – furnace mode coordinate transducer;
FMCS – furnace mode coordinate setter;
FMCC – furnace mode coordinate controller;
SPPC – system of pulse-phase control;
UCCI – unit controlling the coil inductance;
WCC – welding choke coil;
PSMCT – power supply mode coordinate transducer;
PSMCS – power supply mode coordinate setter;
PSMCA – power supply mode coordinate adjuster;
TRG – thyrister-reactor group;
FCD – filter-compensating device;
DETC – de-energized tap changer;
OLTC – on-load tap changer;
CT – current transducer;
VT – voltage transducer;
EAF – electric arc furnace;
FT – furnace transformer;
$U_{set}^{(f)}$ – setting value of furnace voltage;
U_{arc} – running value of arc voltage;
$U^{(f)}$ – furnace voltage;
$U_{cont}^{(f)}$ – controlling value of furnace voltage (signal);
$i^{(f)}$ – instantaneous furnace current;
i – instantaneous reactor current;
I_{load} – load current (effective value);
i_{net} / I_{net} – power network current (instantaneous/ effective);
R_{net} – equivalent inductance of power network;
L_{net} – equivalent resistance of power network;
u_{net} / U_{net} – running value of power network voltage (instantaneous/effective);
E_{net} – electromotive force of power network;
$U_{set}^{(net)}$ – setting value of power network voltage;
$U_{cont}^{(net)}$ – controlling value of power network voltage;
$U_{arc\ ref}$ – reference value of arc voltage;
$U_{set}^{(f)}(U_{arc})$ – setting value of voltage for formation of external furnace characteristic;
U_{2ph} – secondary phase-to-earth voltage of furnace transformer;
I_{FCD} – FCD current;
C_f – filter capacitance;
L_f – filter inductance;
I_{arc} – running value of arc current;
Δl_{arc} – arc length disturbance;
a – thyristor firing angle;
Δx_{WCC} – change in WCC inductance.

The existence of close cross-links between particular phase channels as well as between the control channels of different subsystems of the electric technological system EAF-PS impedes the necessary dynamic and static accuracy of controlling the mode coordinates, so that the autonomic (independent and phase-divided) control and desirable values of the generalized control objective functional chosen for the current melting period or the partial optimality criteria cannot be achieved.

In the static mode, the numerical form of linkedness between the inputs and outputs of SAC of electric steel-making process can be calculated with the use of the Bristol matrix:

$$\Lambda = \begin{bmatrix} l_{11} \ldots l_{1m} \\ \ddots \\ l_{m1} \ldots l_{mm} \end{bmatrix},$$

whose elements, in the static mode, are determined as follows:

$$l_{ij} \equiv \frac{(\partial y_i / \partial u_j)_{\text{all subsystem phase loops are open}}}{(\partial y_i / \partial u_j)_{\text{all but } u_j \text{ subsystem phase loops are closed}}},$$

$i, j = \overline{1,m}$, that is, they are equal to the ratio between, on the one hand, the derivative of the steady-state output value y_i of a certain mode coordinate in an open-loop system with respect to the control signal u_j and, on the other hand, the derivative of the same steady-state output value y_i in a closed-loop system with respect to the same control signal u_j.

If the absolute values of off-diagonal elements of this system matrix increase and the absolute values of diagonal elements decrease, the system linkedness (the effectiveness of cross-linking) increases. When off-diagonal elements tend to zero and diagonal elements tend to unity, that is, when Bristol matrix of the system converts into the identity matrix which refers to the system with negligibly small effectiveness of cross-linking, dynamic characteristics of certain phase control channels are similar to characteristics of autonomous (independent) control channels.

So, taking into account such an indicator as the form of the Bristol matrix, let us analyze various approaches to making the modes of the EAF phases autonomous.

As one of the proposed approaches to the above mentioned problem, the structure of SAC of the modes of the EAF-PS system can be supplemented by the compensator of cross links. The functional block diagram of the structure of the autonomous coordinate & parametric SAC of the steel-making mode of the EAF-PS system with the compensator of cross links is shown in Fig. 2, where $\vec{x}$ is a system control vector; $\vec{e}$ is a control error vector; $\vec{z}$ is an output signal vector of one-dimentonal controllers; $\vec{u}$ is an output signal vector of one-dimentonal compensators; $\vec{y}$ is a vector of output (controlled) furnace coordinates; $\vec{f}$ is a vector of disturbances (external influences).

The component signals x_i of the system control vector $\vec{x}$ change rather rarely (it happens more often at the beginning of the technological period) and, as usual, when the furnace is switched off. That is why cross links caused by those changes do not affect the dynamics of mode coordinates in the electric steel-making process. Taking this into account, it is not necessary to develop the model of a separate compensator of the system control vector components for eliminating the cross links caused by the change of the vector $\vec{x}$.

The structure of the dynamic model of the control over the electric steel-maikng can be determined by a following general system matrix transfer function:

$$\mathrm{W}(p) = \begin{bmatrix} W_{11}(p) & W_{12}(p) \ldots W_{1l}(p) \\ W_{21}(p) & W_{22}(p) \ldots W_{2l}(p) \\ \vdots & \vdots \quad \vdots \quad \vdots \\ W_{l1}(p) & W_{l2}(p) \ldots W_{ll}(p) \end{bmatrix}, \qquad (1)$$

where $W_{ii}(p)$ are transfer functions characterizing signal transfer from the input of a single phase channel controlling a particular subsystem to its output; $W_{ij}(p)$ are transfer functions describing signal transfer from the input of a single phase channel controlling a particular subsystem to the output of a different phase channel of the same subsystem or to the output of a phase channel controlling a different subsystem.

Transfer functions $\mathrm{W}_{ii}(p)$ and $\mathrm{W}_{ij}(p)$ are determined by the results of full-scale experiments during the process of steel-making or with the use of a digital simulator.

In a multidimentional ACS of the modes of the EAF-PS system, the elimination of the dynamic and static cross links or their decrease to the negligibly small levels transforms the matrix transfer function (1) of the closed-loop system into the diagonal one, under the condition that the number of the controlling inputs of the system is equal to the number of the observational mode coordinates ($m = l$) of the electric steel-making process and the transfer matrix $\mathbf{W}_p(p)$ of the controllers of the mode coordinates is diagonal:

$$\mathrm{W}(p) = \begin{bmatrix} W_{11}(p) & 0 & \ldots & 0 \\ \vdots & W_{22}(p) & \ldots & 0 \\ \vdots & 0 & \vdots & 0 \\ 0 & 0 & \ldots & W_{ll}(p) \end{bmatrix},$$

and each of its phase circuits can be adjusted independently, that is, it can be considered as autonomous while being adjusted with the use of any methods of classical control theory.

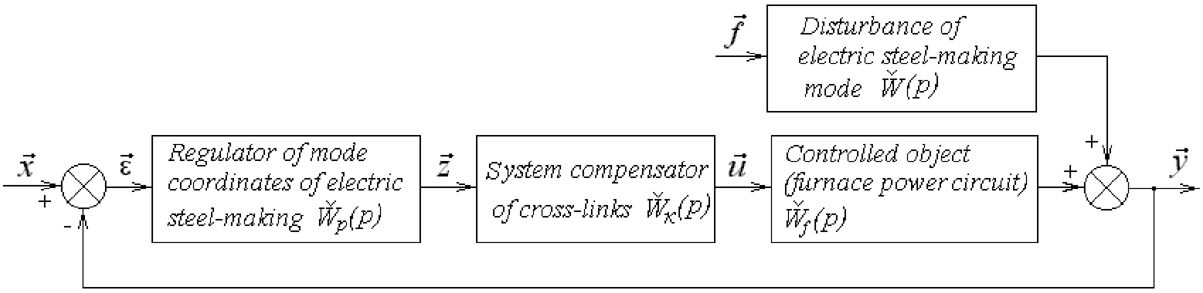

Fig. 2. Functional block diagram of multidimentional autonomous SAC of modes of the EAF-PS system.

The model of a one-dimensional mode coordinates controller is introduced by the diagonal transfer matrix:

$$\mathbf{W}_p(p)=\begin{bmatrix} W_{11p}(p) & 0 & \ldots & 0\\ \vdots & W_{22p}(p) & \ldots & 0\\ \vdots & 0 & \vdots & 0\\ 0 & 0 & \ldots & W_{llp}(p)\end{bmatrix}.$$

Therefore, taking into account the transfer matrix of the compensator $\mathrm{W}_\kappa(p)$, the transfer matrix of closed-loop SAC of the modes of EAF-PS system can be described by the following expression:

$$\begin{aligned}\vec{y}(p)&=(\mathrm{I}+\mathrm{W}(p)\cdot\mathrm{W}_\kappa(p)\cdot\mathrm{W}_p(p))^{-1}\times\\ &\times(\mathrm{W}(p)\cdot\mathrm{W}_\kappa(p)\cdot\mathrm{W}_p(p)\cdot\vec{x}(p)+\mathrm{W}_f(p)\cdot\vec{f}(p)),\end{aligned}$$

or

$$\vec{y}(p)=\mathrm{G}(p)\cdot\vec{x}(p)+\mathrm{G}_f(p)\cdot\vec{f}(p)),$$

where $\mathrm{G}(p)$ and $\mathrm{G}_f(p)$ are matrix transfer functions with respect to control vector and disturbances vector, accordingly.

The compensator $\mathrm{W}_\kappa(p)$ is intended for eliminating or reducing the effects of cross links. As it is mentioned above, theoretically it should provide the diagonal state of the matrix $\mathrm{G}(p)$

$$\begin{aligned}\mathrm{G}(p)&=(\mathrm{I}+\mathrm{W}(p)\cdot\mathrm{W}_\kappa(p)\cdot\mathrm{W}_p(p))^{-1}\times\\ &\times\mathrm{W}(p)\cdot\mathrm{W}_\kappa(p)\cdot\mathrm{W}_p(p)\end{aligned}\tag{2}$$

at any instant, or the approximation $\mathrm{G}(p)$ to the identity matrix I in the static state while $t\to\infty$ ($p\to 0$) and appropriate adjustment of variable parameters of one-dimentional controllers $w_{ii_p}(p)$.

Taking into account the fact that transfer matrix $\mathrm{W}_p(p)$ is diagonal, it can be stated that the necessary condition for matrix $\mathrm{G}(p)$ to be diagonal, as well as for obtaining the boundary relation $\mathrm{G}(p)\to\mathrm{I}$ under the increase of amplification factors, the following equation should be satisfied:

$$\mathrm{W}(p)\cdot\mathrm{W}_\kappa(p)=diag\mathrm{W}(p).$$

From this expression the transfer function of the dynamic compensator of cross links is obtained:

$$\mathrm{W}_\kappa(p)=\mathrm{W}(p)^{-1}\cdot diag\mathrm{W}(p),\tag{3}$$

where $diag\mathrm{W}(p)$ is a diagonal matrix obtained from $\mathrm{W}(p)$ by replacing its off-diagonal elements with zeroes.

If it provides for full compensation, the transform matrix of the close-loop system controlling the steel-making process is to be written down as follows:

$$\begin{aligned}\vec{y}(p)&=(\mathbf{I}+diag\mathbf{W}(p)\cdot\mathbf{W}_p(p))^{-1}\cdot(diag\mathbf{W}(p)\times\\ &\times\mathbf{W}_p(p)\cdot\vec{x}(p)+\mathbf{W}_f(p)\cdot\vec{f}(p)),\end{aligned}\tag{4}$$

or

$$\begin{aligned}y_i(p)&=\frac{W_{ii_p}(p)\cdot W_{ii}(p)}{1+W_{ii_p}(p)\cdot W_{ii}(p)}\cdot x_i(p)+\\ &+\frac{1}{1+W_{ii_p}(p)\cdot W_{ii}(p)}\cdot\sum_{j=1}^{k}W_{ij\,f}(p)\cdot f_i(p),\end{aligned}\tag{5}$$

where $i=1,2,\ldots,l$.

It is necessary to mention here, that the obtained model of the compensator (3) guarantees the absolute autonomy with respect to control vector components. Also, in spite of the fact that each parametric or coordinate system disturbance can affect all outputs or the majority of them, the effect of the mode disturbances on any output can be compensated by a single one-dimentional controller $W_{ii_p}(p)$.

The requirements for the compensation of cross links of each local subsystem are different in the static or dynamic state. Undoubtedly, the full compensation of cross links in the system would be the best solution, but it is rather difficult to be implemented in practice. This difficulty is caused by the considerable order of the matrix transfer function (1) of the system and the complexity of its particular elements $W_{ii}(p)$ and $W_{ij}(p)$. It is possible to somewhat simplify its implementation. After analyzing the operation peculiarities, requirements and characteristics, the conditions of compensating cross links in different subsystems should be set apart from each other, since each subsystem can contain some excessive functional possibilities concerning the compensation of cross links. In addition, not all cross linksshould be compensated, for example, some additionally embedded, functionally necessary links between the outputs of SRLE and the inputs of SRFMC. So, it is reasonable to develop the compensators (with the use of the technique (3)–(5)) for single local subsystems which would eliminate or significantly reduce the cross links occurring in the phase channels controlling the coordinates of the local subsystems.

For example, for electromechanical SCPE the frequency range which can be handled by the subsystem with tolerable accuracy is considerably narrower than the frequency range of the spectrum of coordinate disturbances. The main mode of this subsistem is the dynamic mode of handling the disturbances accompanied by considerable continuous dynamic error of their control. Static modes (in deterministic sense) of this subsystem do not exist. Therefore, for the reduction of the root-mean-square error of SCPE control it is reasonable to synthesize the compensator of cross links according to above mentioned model of full dynamic compensation (3)–(5) providing for the elimination of the effects of static and dynamic cross links.

Let us obtain the transfer function of the compensator $W_k(p)$ for the electromechanical SCPE as the subsystem with intensive cross links occurring because of using the three-wire system of arc feeding and forming the control signal of this system according to derivative action.

In Fig. 3 the time dependencies of step responses $U_{arcA}(t)$, $U_{arcB}(t)$, and $U_{arcC}(t)$ at each SCPE output of ASF-3 (ukr. ДСП-3) furnace are shown. They are caused by unit-step arc length disturbance in *C*-phase while the automatic control system has been adjusted for handling a transient process without its overregulation as appropriate for the minimization of the variance of the EAF coordinates.

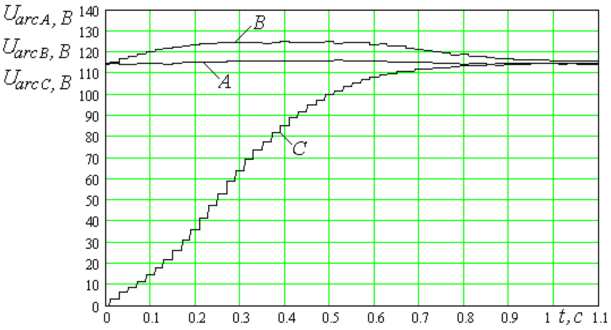

Fig. 3. Time dependencies of the SCPE output responses caused by unit-step arc length disturbance in C-phase while adjusting the arc length according to the derivative control mode.

The analysis of these step responses, as well as the characteristics obtained under the unit-step disturbances in phases *A* and *B*, shows that the magnitude of the response on the output of lagging phase is relatively the least and non-significant, so, it can be neglected. Taking this into account and on the basis of the step responses obtained in practice, the matrix transfer function of the electromechanical subsystem controlling the position of electrodes has been determined as follows:

$$W_1(p)=\begin{bmatrix}\dfrac{115.1}{0.258p+1} & \dfrac{8.12p}{0.0921p^2+0.53p+1} & 0\\ 0 & \dfrac{113.8}{0.262p+1} & \dfrac{8.96p}{0.098p^2+0.61p+1}\\ \dfrac{7.838p}{0.0877p^2+0.491p+1} & 0 & \dfrac{114.2}{0.252p+1}\end{bmatrix}$$

Now in accordance to expression (3) the matrix transfer function of the compensator of cross links for the subsystem controlling the position of electrodes is obtained as follows:

$$W_{1k}(p)=W_1(p)^{-1}\cdot diag W_1(p)=\begin{bmatrix}W_{AA_k}(p) & W_{AB_k}(p) & W_{AC_k}(p)\\ W_{BA_k}(p) & W_{BB_k}(p) & W_{BC_k}(p)\\ W_{CA_k}(p) & W_{CB_k}(p) & W_{CC_k}(p)\end{bmatrix}, \qquad (6)$$

where

$$W_{AA_k}(p)=\frac{1184p^6+20810p^5+0.16\cdot10^6p^4+0.6884\cdot10^6p^3+0.1736\cdot10^7p^2+0.244\cdot10^7p+0.1496\cdot10^7}{1194p^6+20930p^5+0.16\cdot10^6p^4+0.6889\cdot10^6p^3+0.1736\cdot10^7p^2+0.244\cdot10^7p+0.1496\cdot10^7};$$

$$W_{BA_k}(p)=\frac{1.243p^7+21.64p^6+153.2p^5+554.4p^4+1031p^3+722.2p^2}{30.18p^7+646.1p^6+6114p^5+33170p^4+0.1114\cdot10^6p^3+0.232\cdot10^6p^2+0.277\cdot10^6p+0.147\cdot10^6};$$

$$W_{CA_k}(p)=\frac{-60.25p^7-1194p^6-0.1\cdot10^5p^5-45590p^4-0.1191\cdot10^6p^3-0.1694\cdot10^6p^2-0.1027\cdot10^6p}{308p^7+6593p^6+62390p^5+0.3394\cdot10^6p^4+0.114\cdot10^7p^3+0.237\cdot10^7p^2+0.283\cdot10^7p+0.15\cdot10^7};$$

$$W_{AB_k}(p)=\frac{-234p^6-3674p^5-23930p^4-81180p^3-0.1434\cdot10^6p^2-0.1055\cdot10^6p}{1194p^6+20930p^5+0.161\cdot10^6p^4+0.689\cdot10^6p^3+0.174\cdot10^7p^2+0.244\cdot10^7p+0.15\cdot10^7};$$

$$W_{BB_k}(p)=\frac{1184p^6+20810p^5+0.1603\cdot 10^6p^4+0.69\cdot 10^6p^3+0.1736\cdot 10^7p^2+0.244\cdot 10^7p+0.15\cdot 10^7}{1194p^6+20930p^5+0.161\cdot 10^6p^4+0.689\cdot 10^6p^3+0.1736\cdot 10^7p^2+0.244\cdot 10^7p+0.15\cdot 10^7};$$

$$W_{CB_k}(p)=\frac{46.15p^6+649.2p^5+3434p^4+8112p^3+7243p^2}{1194p^6+20930p^5+0.161\cdot 10^6p^4+0.69\cdot 10^6p^3+0.1736\cdot 10^7p^2+0.244\cdot 10^7p+0.15\cdot 10^7};$$

$$W_{AC_k}(p)=\frac{49.26p^6+654.7p^5+3412p^4+8400p^3+8309p^2}{1194p^6+20930p^5+0.161\cdot 10^6p^4+0.69\cdot 10^6p^3+0.174\cdot 10^7p^2+0.244\cdot 10^7p+0.156\cdot 10^7};$$

$$W_{BC_k}(p)=\frac{-62.81p^7-1202p^6-9924p^5-45380p^4-0.1214\cdot 10^6p^3-0.1808\cdot 10^6p^2-0.1178\cdot 10^6p}{300.8p^7+6467p^6+61420p^5+0.334\cdot 10^6p^4+0.113\cdot 10^7p^3+0.235\cdot 10^7p^2+0.282\cdot 10^7p+0.156\cdot 10^7};$$

$$W_{CC_k}(p)=\frac{1184p^6+20810p^5+0.1603\cdot 10^6p^4+0.6884\cdot 10^6p^3+0.1736\cdot 10^7p^2+0.244\cdot 10^7p+0.15\cdot 10^7}{1194p^6+20930p^5+0.1607\cdot 10^6p^4+0.69\cdot 10^6p^3+0.1736\cdot 10^7p^2+0.244\cdot 10^7p+0.15\cdot 10^7}.$$

The dynamic characteristics of the components of the compensator of crosslinks are shown in Fig. 4.

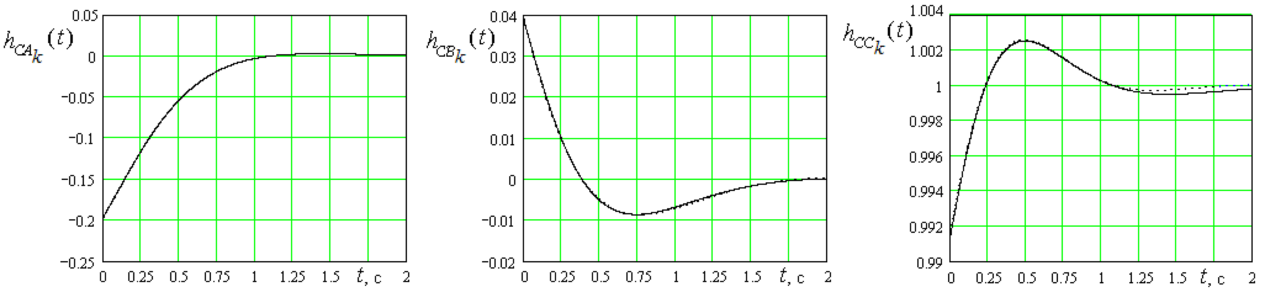

Fig. 4. Step responses $h_{CA_k}(t)$, $h_{CB_k}(t)$, $h_{CC_k}(t)$ *of the respective components* $W_{CA_k}(p)$, $W_{CB_k}(p)$, $W_{CC_k}(p)$ *of the developed compensator of cross links* $\mathrm{W}_{1k}(p)$ *are shown by unbroken line (-) and those of the reduced order compensator are shown by broken line (...........).*

The analysis of the step responses of the components $W_{i\,j_k}(p)$ $(i, j = A, B, C)$ of the compensator demonstrates that, in spite of the high order of $W_{i\,j_k}(p)$, they are not very intricate, and their characteristics do not significantly differ from the step responses of elementary dynamic units, in particular, those of the second order. Therefore, for simplifying the circuitry design of the SRLE compensator $\mathrm{W}_{1k}(p)$ the order of its components is reduced with the use of well-known techniques. As a result, the matrix transfer function $\mathbf{W}_{1k}^{(r)}(p)$ of the compensator with the reduced order is obtained:

$$\mathrm{W}_{1k}^{(r)}(p)=\begin{bmatrix} \dfrac{0.4992p^2+2.5874p+10.16}{0.5034p^2+2.5845p+10.16} & \dfrac{-0.0184p^2-0.0705p}{0.094p^2+0.531p+1} & \dfrac{0.0053p^2}{0.1272p^2+0.5668p+1} \\ \dfrac{0.0051p^2}{0.122p^2+0.5231p+1} & \dfrac{0.4992p^2+2.5874p+10.16}{0.5034p^2+2.5845p+10.16} & \dfrac{-0.1769p^2-0.0738p}{0.8396p^2+2.4916p+1} \\ \dfrac{-0.0175p^2-0.0686p}{0.0895p^2+0.492p+1} & \dfrac{0.0045p^2}{0.115p^2+0.4524p+1} & \dfrac{0.4992p^2+2.5874p+10.16}{0.5034p^2+2.5845p+10.16} \end{bmatrix}$$

For the comparison, in Fig. 3 there are point charts of step responses of transfer functions $W_{CA_k}^{(r)}(p)$, $W_{CB_k}^{(r)}(p)$, $W_{CC_k}^{(r)}(p)$ of the developed reduced order compensator $\mathbf{W}_{1k}^{(r)}(p)$. As it can be seen, under such simplifycation of $\mathrm{W}_{1k}(p)$ the accuracy of reconstructing the step responses $h_{i\,j_k}(t)$ is sustained and, respectively, the proper accuracy of the compensation of the cross links is achieved.

The effectiveness of the application of the compensator of cross links for electromechanical ACS has been investigated in furnaces № 1 and № 2 of the ASF-3 (ДСП-3) type at the “Novovolynsk steel-making plant” public corporation. The obtained results have shown that its application causes the amplitude decrease of arc voltage, current and power oscillations and, consequently, specific power consumption decreases by 3–5 %, time of basic melting decreases by 4–5 % and oscillations of power supply voltage are also reduced.

The authors also propose the other solution to the problem of transforming SRLE from V-canonical structure into P-canonical structure. The arc current should be eliminated from the process of forming the control signal for this subsystem, that is, the derivative control mode in the existing arc power controllers should be replaced by the adjustment of the electrodes position in the arcing modes by the control mode ruled by the deviation of arc voltage U_{arc} from its reference value $U_{arc\,ref}$.

With the use of this approach the processes of controlling the electrodes position (arc voltages), which are autonomous with respect to the phase channels, are obtained. It means that they are invariant to arc current fluctuations caused by the action of coordinate disturbances as well as paramentric ones. In the cases of arc extinction, short circuits or similar situations for fail-safe arc initiation, it is proposed to form the signal controlling the electrodes position according to the derivative action.

Switching the control modes is performed in the zone of significant deviations of the furnace operating point from its preset value, where the output signal of the unit of forming the control signal (UFCS) of the SCPE takes on maximum values under the conditions of both control modes (saturation zone of the input/output characteristic of the UFCS) which does not affect the dynamics of the process of controlling the extremal disturbances. The dynamics of changing arc voltages while handling the arc length disturbance in *C*-phase by adjusting the arc voltage deviation is shown in Fig. 5.

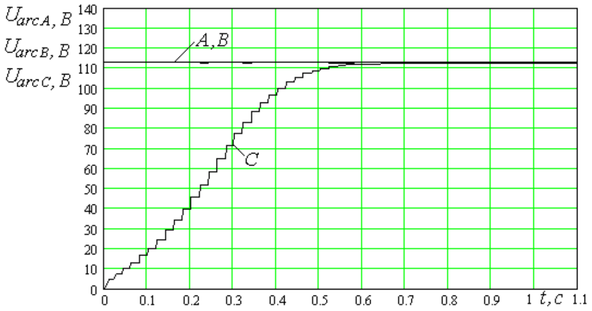

Fig. 5. Change in arc voltages $U_{arcA}(t)$, $U_{arcB}(t)$, $U_{arcC}(t)$ while handling the arc length disturbances in C-phase by adjusting the arc voltage deviation.

Let us mention, that the elements $W_{ij_k}^{(r)}(p)$ of the obtained SCPE compensator $\mathbf{W}_{1k}^{(r)}(p)$, due to the nonlinearity of furnace external characteristic, depends (though insignificantly) on the coordinates of furnace operating point, in particular, on the reference value $U_{arc\,ref}$ of arc voltage. Therefore, a change in the reference value $U_{arc\,ref}$ requires correcting the coefficients of transfer functions $\mathrm{W}_{i\,j_k}^{n}(p)$ of the compensator $\mathbf{W}_{1k}^{(r)}(p)$. However, the application of the control mode ruled by the deviation of arc voltage does not require instantaneous correction, but it causes some complication of the UFCS circuit. The choice of one out of two proposed solutions (the compensator or control mode ruled by the arc voltage deviation) for the elimination of cross-linking is made for each particular EAF taking into account the complexity of its construction, since the accuracy of the dynamic compensation of cross-linking is approximately similar for both cases. Their implementation enables obtaining the nearly autonomous processes of arc length control in the SCPE (Fig. 3, Fig. 5).

If these solutions are used, in the general case, only functionally necessary links between the voltage output of the electromechanical SCPE (arc voltage) and the driving input of the controller of furnace mode coordinate (SCFMC) in appropriate phase channels remain working out of the links existing in the ACS and the arc furnace power circuit. The remaining links are necessary for the formation of desired artificial external characteristic in the zone of average-length and short-length arcs.

But the interactions between current outputs of phase channels in a high-speed SCFMC existing due to a functional link between linear currents in power supply control system of the three-phase arc system are yet not eliminated. Phase channels controlling that subsystem are intended for handling the disturbances of different origin causing the deviation of instantaneous values of the controlled furnace mode coordinate from its preset values $U_{set}^{(f)}(U_{arc})$. Apart from arc length fluctuations, these are deviations of arc voltage gradient, changes of resistance and reactance of furnace elements (caused by different conditions) including those occurring due to the magnetic coupling between the elements of short circuit of the furnace.

The developed solutions enable obtaining the structures of local subsystems of the layered architecture systems controlling the modes of the EAF-PS complex technological system, that belong, according to their dynamical and static features, to the *P*-canonical structures. Their application increases the autonomy of handling the coordinate and paramentrical disturbances in each phase channel and provides independent phase-by-phase adjustment of control vector components in every local subsystem.

5. Conclusions

The system engineering solutions for the elimination or significant reducing the cross-linking effects between the phase channels of the local subsystems are proposed. Their application to practice enables obtaining the autonomous phase-by-phase contol of mode coordinates in the process of electric steel-making.

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ПОФАЗНА АВТОНОМІЗАЦІЯ РЕЖИМІВ У ЕЛЕКТРОТЕХНОЛОГІЧНОМУ КОМПЛЕКСІ “ДУГОВА СТАЛЕПЛАВИЛЬНА ПІЧ – ЕЛЕКТРОПОСТАЧАЛЬНА МЕРЕЖА”

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Запропоновано системотехнічні рішення для підвищенні пофазної автономності процесів регулювання координат електричного режиму в електромеханічній підсистемі переміщення електродів дугової сталеплавильної печі за допомогою під’єднана до її структури компенсатора перерехресних зв’язків. Запропоновано методику синтезу передавальних функцій компенсаторів перехресних зв’язків у фазних каналах регулювання та на основі результатів експерементальних досліджень отримано математичні моделі компенсаторів перехресних зв’язків для дугової печі типу ДСП-3.

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