Features of using linear graphs in developing mathematical model of metal melting process in induction crucible furnace

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Abstract. The use of linear graphs in the development of a mathematical model of metal melting in an induction crucible furnace allows to determine the metal melting temperature and control the excess temperature in the main parts of the furnace. In addition, if it is necessary to optimize the thermal mode of operation of the furnace according to the presented graph conversion method, a graph model of any part of the furnace with the desired thermal parameters can be obtained.

Modern induction heating plants are complex high-performance, energy-intensive units with a capacity of tens of megawatts. High efficiency of the heating process is equivalent to energy saving and automatically leads to economical technology. In turn, the development and creation of efficient control systems for induction heating plants with high technical and economic indicators and high efficiency is one of the most pressing tasks in induction heating technology.[1]

Due to the difficulty of calculating the process of heating the molten metal and the main structural parts of induction crucible furnaces from the point of view of engineering practice, it is of great interest to develop a mathematical model based on linear graphs used in the analysis of linear electric circuits.[4]

The induction crucible furnace can be represented as a thermal circuit consisting of four interconnected thermal bodies.[1] The system of thermal balance equations for the steady state of such a scheme is as follows:

$$\left.\begin{aligned} \Lambda_{11}\Theta_1 - \Lambda_{12}\Theta_2 - \Lambda_{13}\Theta_3 = P_1, \\ -\Lambda_{21}\Theta_1 + \Lambda_{22}\Theta_2 - \Lambda_{23}\Theta_3 - \Lambda_{24}\Theta_4 = P_2, \\ -\Lambda_{31}\Theta_1 - \Lambda_{32}\Theta_2 + \Lambda_{33}\Theta_3 - \Lambda_{34}\Theta_4 = P_3, \\ -\Lambda_{42}\Theta_2 - \Lambda_{43}\Theta_3 + \Lambda_{44}\Theta_4 = P_4 \end{aligned}\right\}, \quad (1)$$

where Θ_1, Θ_2, Θ_3, Θ_4 – excess temperature of molten metal, inductor, lining and crucible induction furnace housing, ^{0}C; P_1, P_2, P_3, P_4 – power loss of corresponding parts of crucible induction furnace, kW; $\Lambda_{12} = \Lambda_{21}$, $\Lambda_{13} = \Lambda_{31}$, $\Lambda_{23} = \Lambda_{32}$, $\Lambda_{24} = \Lambda_{42}$, $\Lambda_{34} = \Lambda_{43}$ – thermal conductivity between the parts of the crucible induction furnace under consideration; Λ_1 – heat dissipation of molten metal through open arch of crucible; Λ_4 – heat transfer of furnace housing; $\Lambda_{11} = \Lambda_{12} + \Lambda_{13} + \Lambda_1$ – total thermal conductivity of the molten metal; $\Lambda_{22} = \Lambda_{21} + \Lambda_{23} + \Lambda_{24}$ – total thermal conductivity of inductor; $\Lambda_{33} = \Lambda_{31} + \Lambda_{32} + \Lambda_{34}$ – total thermal conductivity of lining; $\Lambda_{44} = \Lambda_{22} + \Lambda_{43} + \Lambda_4$ – total thermal conductivity of the housing.

The system of thermal balance equations (1) can be represented as directional graphs according to the methodology presented in [2, 3]:

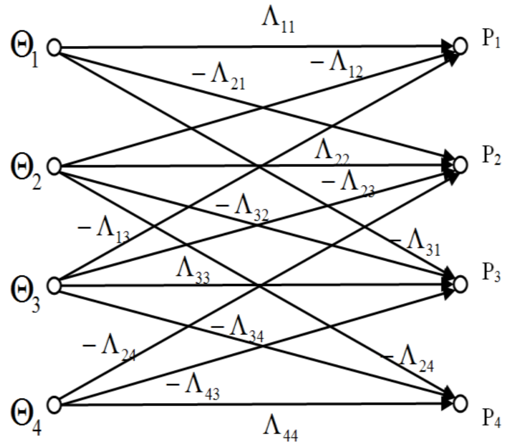


Fig.1. System of thermal balance equations (1) in the form of directed graphs

Inverse the graph shown in Fig.1 (Fig. 2).

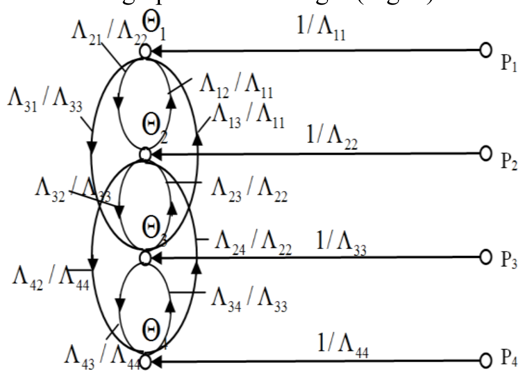
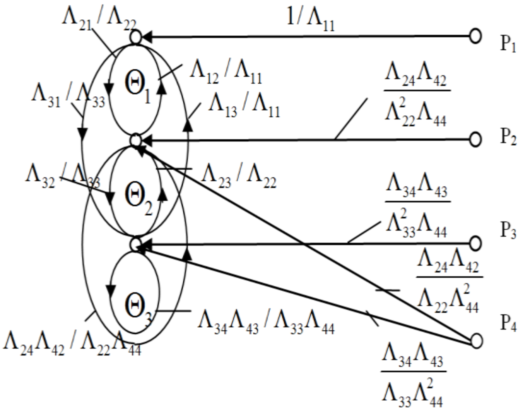


Fig.2. The inversion of the graph shown in Fig.1

We exclude the node Θ_4 from the graph presented in Fig.2 and get two loops with the following transmissions $\Lambda_{34}\Lambda_{43}/\Lambda_{33}\Lambda_{44}$ and $\Lambda_{24}\Lambda_{42}/\Lambda_{22}\Lambda_{44}$ (Fig.3).



$$1-\frac{\Lambda_{34}\Lambda_{43}}{\Lambda_{33}\Lambda_{44}}=\frac{\Lambda_{33}\Lambda_{44}-\Lambda_{34}\Lambda_{43}}{\Lambda_{33}\Lambda_{44}};$$
$$1-\frac{\Lambda_{24}\Lambda_{42}}{\Lambda_{22}\Lambda_{44}}=\frac{\Lambda_{22}\Lambda_{44}-\Lambda_{24}\Lambda_{42}}{\Lambda_{22}\Lambda_{44}}.$$

Fig.3. After being excluded Θ_4 from the graph

Further, from the graph shown in Fig.3, we exclude the loop with transmissions $\Lambda_{34}\Lambda_{43}/\Lambda_{33}\Lambda_{44}$ and $\Lambda_{24}\Lambda_{42}/\Lambda_{22}\Lambda_{44}$ (Fig.4).

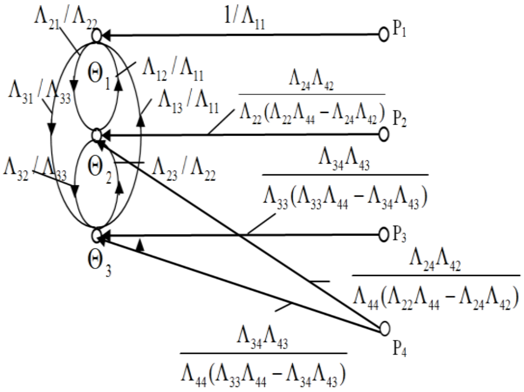


Fig. 4. After being excluded of transmissions $\Lambda_{34}\Lambda_{43}/\Lambda_{33}\Lambda_{44}$ and $\Lambda_{24}\Lambda_{42}/\Lambda_{22}\Lambda_{44}$

After removing the node Θ_4, the graph model of the thermal process has the form with three unknowns (Fig.4). We will exclude the node Θ_3 and get two loops with the following transfers $\Lambda_{13}\Lambda_{31}/\Lambda_{11}\Lambda_{33}$ and $\Lambda_{23}\Lambda_{32}/\Lambda_{22}\Lambda_{33}$ (Fig.5).

Exclude transmission loops $\Lambda_{13}\Lambda_{31}/\Lambda_{11}\Lambda_{33}$ and $\Lambda_{23}\Lambda_{32}/\Lambda_{22}\Lambda_{33}$ from the graph shown in Fig.5 and excluding the node Θ_2 we obtain a graph model with formation of a loop with transmission $\Lambda_{12}\Lambda_{21}/\Lambda_{11}\Lambda_{22}$ thermal process with two desired thermal parameters (Fig.6).

Excluding transmission loop $\Lambda_{12}\Lambda_{21}/\Lambda_{11}\Lambda_{22}$ from the graph model shown in Fig.7, we obtain the final thermal model of the process of melting metal in the induction crucible furnace (Fig.8).

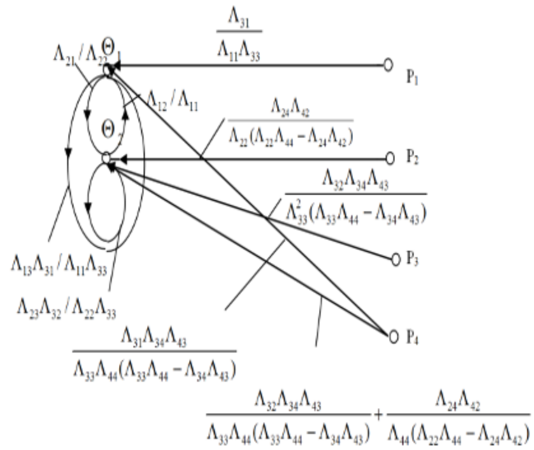


Fig.5. After being excluded Θ_3 from the graph

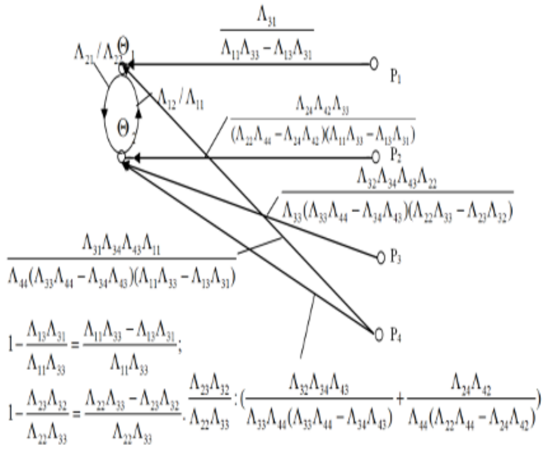


Fig.6. After being excluded of transmissions $\Lambda_{13}\Lambda_{31}/\Lambda_{11}\Lambda_{33}$ and $\Lambda_{23}\Lambda_{32}/\Lambda_{22}\Lambda_{33}$

Excluding the node Θ_2 we get a thermal model with one unknown thermal parameter (Fig.7).

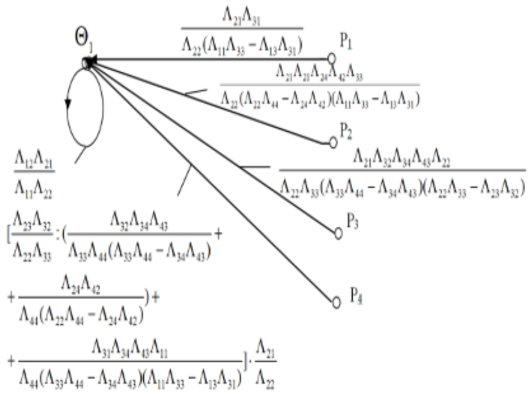


Fig.7. After being excluded Θ_2 from the graph

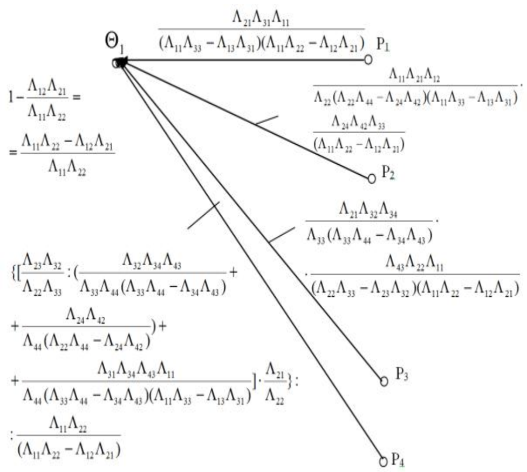


Fig.8. Final thermal model of melting metal process in induction crucible furnace.

To implement the algorithm for solving the problem, a program was compiled.

Thus, the presented mathematical graph model has a non-complex algorithm and easily programmed on personal computers that allows to optimize process of receiving liquid metal in the induction crucible furnace on the basis of control and management power (P_1, P_2, P_3, P_4) and thermal (for example, Λ_1, etc.) parameters. In addition, according to the presented graph conversion method, it is possible to obtain a graph model of an inductor with the desired thermal parameter Θ_2 if it is necessary to optimize the thermal mode of operation of the inductor.

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