**Analysis of operating modes of electric arc furnaces and problems with power supply**

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**Abstract.** Electric arc furnaces are the main unit in the production of steel raw materials, and in recent years their capacity and energy consumption have been increasing. At the same time, the problems that electric arc furnaces cause during their operation are also increasing, such as: voltage drops in the network during startup, the release of high-order harmonics into the network, the appearance of various noises during operation, etc. Any electrical technological devices used in industry cause various changes in the power supply system during startup, during operation and when turned off (disconnected from the network). Due to the increase in the power of electric arc furnaces, increasing their efficiency and developing energy-saving modes is currently attracting the attention of scientists. The power consumption of modern arc furnaces has increased sharply and currently amounts to 120–150 MW. Reducing its energy consumption, even by a few percent, can save a lot of electricity due to the large power consumption. This article will address issues related to the startup, operation, and shutdown processes of electric arc furnaces. The characteristics and designs of electric arc furnaces are reviewed. Potential problems associated with the operation of furnaces in the electrical network are identified.

**INTRODUCTION**

Electric arc furnaces, even with the smallest power, cause the introduction of high harmonics into the network. Electric arc furnaces consume large currents, measured in thousands and tens of thousands of amperes. Such currents cause a significant voltage drop even with small active and inductive resistances in the electrode supply circuits. Therefore, the furnace transformer is placed very close to the furnace, in a special furnace substation. One of the problems that arise in the operation of arc furnaces is the violation of the composition of the molten metal, and this problem is directly related to the electrical mode of the furnace, and this problem is eliminated by adjusting the state of its electrodes, depending on the characteristics of the furnace [1-4]. Due to the violation of the electrical mode, the electrodes come too close to the surface of the molten metal, in some cases they can even sink into the molten metal and the electrode becomes part of the metal. In this case, the metal composition changes, changing the properties of the produced steel or cast iron, which negatively affects its quality. In addition, during the operation of the furnaces, periodic voltage fluctuations occur in the power supply system. This phenomenon is called the flicker effect. In this case, the voltage in the network periodically fluctuates, causing lighting devices to flicker, engines to vibrate, and protective devices to malfunction [5-9].

The excitation system plays an important role in ensuring uninterrupted and stable operation of synchronous generators. The excitation system of synchronous generators generates a magnetic field in the generator rotor windings and allows automatic adjustment of the voltage of the generator stator windings from the output clamps. Today, the efficiency, reliability of these systems in power plants directly affects the overall quality of operation of the generator [10-13].

**EXPERIMENTAL RESEARCH**

Power supply of furnaces and its problems. The power supply of arc steel melting furnaces is divided into two types: individual power supply and group power supply. (Fig 1.)



**FIGURE 1.** Individual power supply scheme for arc steel melting furnaces

1 – furnace, 2.5 – current transformers, 3 – furnace transformer, 4 – reactor (used to limit short-circuit currents and ensure arc stability), 6 – switching device for protection and operational functions, circuit breaker, 7 – disconnector (indicating disconnection from the network), 8 – voltage transformer, 10 – disconnector for connecting the reactor to the grid, 9 – maximum current protection against emergency short circuits, 11 – maximum current protection for overload protection.

The lines for supplying electricity to the furnace are mainly flexible power cables or busbars. Furnace transformers are connected to 6–10 kV networks, large furnace transformers are connected to 35 kV networks, and some very large furnace transformers are supplied from 110 kV networks. This voltage is then reduced to the nominal operating voltage of the furnace by the furnace transformer and varies accordingly in the range of 800–1400 V, depending on the melting period (Fig 2.) [14-16].



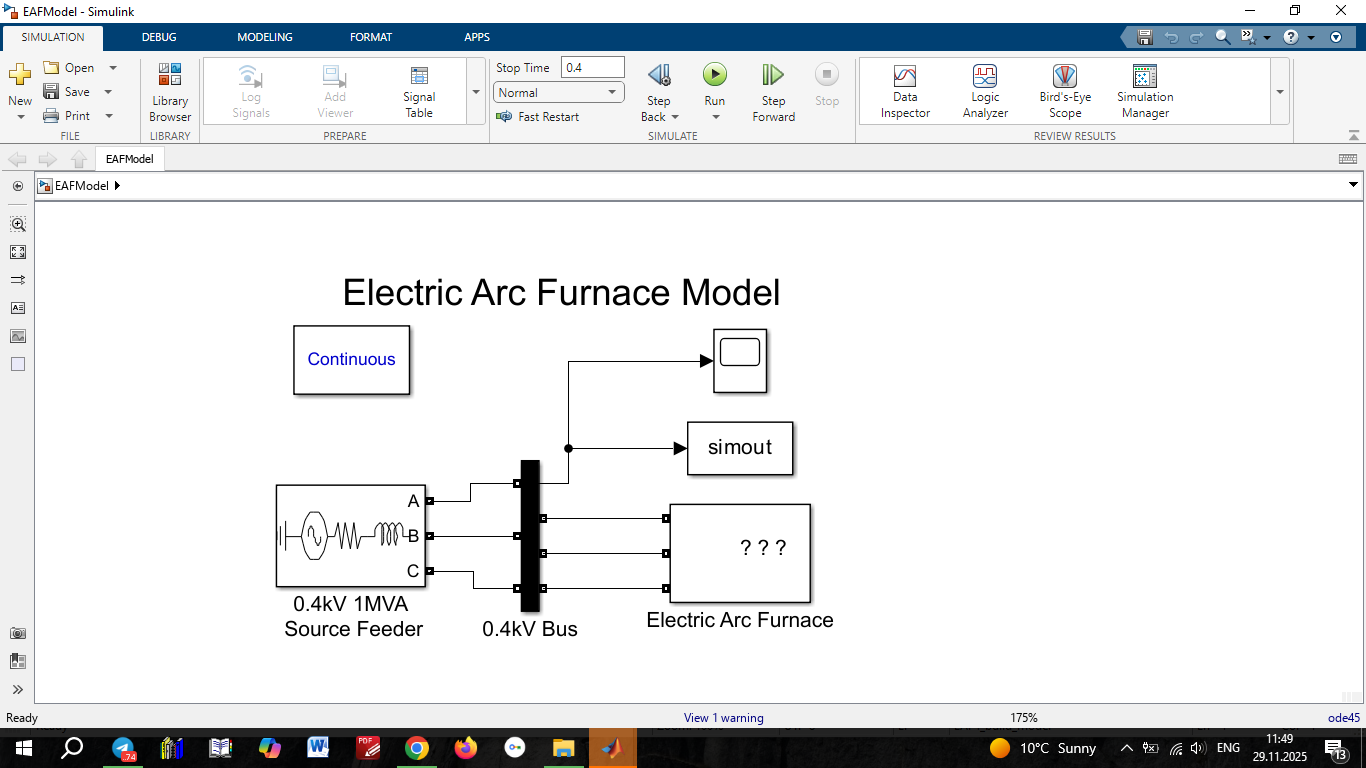
**FIGURE 2.** Group power supply diagram of arc steel melting furnaces

1 – current conductors, 2 – electric arc furnaces, 3 – transformers, 4 – compensation devices, 5 – reactors, 6 – circuit breakers, 7 – main step-down substation.

Furnaces have high power and their load varies sharply, which causes significant fluctuations in the current and voltage values in the network. This leads to false operation of relay protection and automation operating on current and voltage. To eliminate this problem, at the design stage, the furnace power should not exceed 40% of the substation power, and reactors should be installed on the high-voltage side of the furnace transformer. At the same time, it is advisable to use filter-compensating devices [17-19]

**RESEARCH RESULTS**

During the operation of the furnaces, a flicker effect occurs in the supply network. This effect occurs even if the furnace power is small, but if the furnace power is large, this effect is more pronounced. As an example, we will examine the flicker effect in the normal operating mode of a furnace with a capacity of 1MVA, operating at a voltage of 0.4 kV in the Simulink library of the MATLAB software (Fig 3.).



**FIGURE 3.** Diagram of an electric arc furnace in MATLAB software.

Through this simulation, we can observe the flicker effect manifesting itself separately in each phase. The flicker effect occurs due to the instability of the arc formed in the furnace or the abrupt change in the resistance of the electric arc and electrodes. This situation creates additional waste in short-circuit networks and above. This situation once again confirms the need for correct, smooth and fast control of the operating modes of the furnaces. Due to the change in voltage and current at the specified intervals, it causes disruption of the operating modes of other devices supplied from the network to which the furnace is connected, as well as additional waste in the network [20-21].



**FIGURE 4.** Manifestation of the flicker effect by phases

Observation of flicker effect in a 3-phase network in general.

Reactors are inductive in nature, which leads to an increase in the total reactive (inductive) resistance of the network and a decrease in the network voltage. This solution creates a problem, namely, a decrease in reactive power in the network. To solve the next problem that arises, it is necessary to install reactive power compensation devices in the furnace supply network. Because 80–100% of the power consumed by the furnaces is reactive power.

When designing short-circuit networks, attempts are made to reduce and equalize their active and inductive resistances in phases, as well as mutual inductance between individual phases. The inequality of inductance between individual phases of a short-circuit network leads to the transfer of power from one phase to another. However, in a symmetrical supply, despite the equal active resistance and current of the furnace, the arc powers are different. As a result, the power of one phase increases (wild phase), and the power of the other decreases (dead phase).

Problems caused by oven operating modes:

According to the value of the current in the furnace, it is divided into 3 types:

1. Salt operating mode (no arcing I=0 A);

2. Normal mode (I=IN);

3. Operational short-circuit mode (I=Ish.c)

In electric arc furnaces, the wild phase is the highest leading phase, and the dead phase is the highest lagging phase. The heat is not evenly distributed over the volume of the metal being melted in the furnace bath. As a result, part of the lining is eroded faster than the rest, since an arc with a high temperature is formed at the wild phase electrode, and an arc with a relatively low temperature is formed at the dead phase electrode. Although the total power of the furnace usually remains unchanged, the power imbalance has a negative effect on the operation of the furnace. This causes uneven heat distribution throughout the furnace and is the biggest factor preventing the efficient operation of the furnace. The corrosion of the lining part in the area where the wild phase is located accelerates, and the electrode consumption of this phase increases. In addition, due to the uneven generation and distribution of heat, it has a negative effect on the quality of the steel raw material. To overcome the above problems, it is necessary to achieve phase symmetry and equal distribution of the power of the arcs generated by the electrodes. There are several ways to do this. One of them is to correctly select the connection group of short lines (Figure 2) [22]

The following connection group scheme is used on short lines:



**FIGURE 5.** Schematic of short arc furnace lines

1. Triangle connection on the transformer busbar

2. Symmetrical triangle

3. Triangle connection of electrodes

Scheme 1 has the least symmetry, scheme 3 has the greatest symmetry, scheme 2 is the most widely used. A short circuit with a triangular conductor is considered the most promising. This scheme is similar to scheme 1, the only difference is that the conductors connecting the electrodes to the transformer bus are located not in the same plane, but at the vertices of an equilateral triangle. This design gives the lowest asymmetry coefficient (5–8%), since the mutual inductances of all phases are equal. The above-mentioned conductor design is used in high-power furnaces.

If the power consumed by the furnace is 40% (depending on the power of the furnace, this share can be 25%) or more of the power of the network supplying it, a flicker effect will occur during arc ignition and during the melting of the charge. To eliminate this phenomenon, it is necessary to effectively adjust the electrical regime of the furnaces.

Regulation the electrical mode of the ovens:

The operating modes of arc steelmaking furnaces are unstable and constantly change during operation. Changes in the electrical mode occur mainly as a result of uneven loading and uneven melting of the metal mass, and the distance between the electrode and the metal being melted changes, which in turn directly affects the length and intensity of the arc formed. In this case, the electrodes are divided into wild, dead and normally loaded. As a result, electromechanical transients occur in the furnace. The electrode located in the wild phase consumes a large amount of power, and melting in that area occurs faster, while in the dead phase, on the contrary, the arc intensity decreases and the metal melts slowly or does not melt at all, while the normally loaded electrode operates as specified in the passport value. This leads to mechanical stress and even breakage of the electrodes. The mechanical strength of the electrode can withstand these stresses, but another problem arises: the electrodes are placed too close to the molten metal, and the electrode is not lifted after the additional metal is loaded, so the electrode is immersed in the molten metal. The metal, which is far from the arc formation area, begins to thicken and causes one of the electrodes to remain in the melt when the dome opens.

Electrical control in arc steelmaking furnaces is of great importance for their efficient and economical operation. Two main methods are used to control electrical control:

1. Adjusting the voltage entering the furnace (changing the voltage on the secondary winding of the furnace transformer);

2. Changing the arc resistance, i.e. changing its length.

Modern devices use both methods. Discrete adjustment is carried out by switching the secondary voltage stages of the transformer, while fine adjustment is carried out using a drive mechanism.

The control of the electrode drive mechanisms is carried out by automatic power regulators.

Automatic power regulators must provide the following:

1. Automatic arc ignition;

2. Automatic elimination of arc interruptions and operational short circuits;

3. Fast operation of approximately 3 seconds to eliminate arc interruptions and operational short circuits;

4. Aperiodic nature of the adjustment process;

5. The ability to continuously change the input power to the furnace in the range of 20–125% of the nominal value and maintain it with an accuracy of 5%;

6. Stop the electrodes in the event of loss of supply voltage.

The nature of the control is divided into two types: periodic and aperiodic. The difference between these two types is that in the periodic control system, the adjustment process oscillates around the desired value and requires additional adjustments, that is, if the electrode drops too low or, conversely, rises too high, the adjustment process does not stop until the electrode reaches the desired level. In aperiodic control, these shortcomings are not observed, that is, the adjustment is smooth and continuous and does not require additional adjustments. This method is the most optimal solution for increasing the efficiency of the furnace by adjusting the position of the electrodes. Because the electrode is raised or lowered to the desired position in one go and stops [24-53].

The aperiodic nature of the control process is necessary to prevent the electrodes from dipping into the molten metal, which can fill it with carbon and spoil the solution. It also prevents the electrodes from breaking when in contact with a solid charge. This requirement provides protection against the above-mentioned situations during emergency or operational shutdown of the furnace. As can be seen from the electrical modes of the furnace, the active power and arc power consumed by the furnace have a clearly defined maximum. Therefore, a given value of the active power entering the furnace can be achieved with two different values of efficiency and cosφ. This uncertainty does not allow the use of furnace controllers that respond directly to the active power. To stabilize the desired operating point according to the electrical characteristics, the phase impedance (U/I) is kept constant. Such controllers are designed on the differential principle [23].

**CONCLUSIONS**

The methods for increasing the efficiency and energy efficiency of electric arc furnaces are not limited and can be increased using several methods. By choosing the right power supply, it is possible to eliminate waste and problems caused by short circuits. By correctly and accurately controlling the electrical regimes, it is possible to reduce not only energy consumption, but also resource consumption. By resource we mean the premature failure of the structural parts of the furnace and the reduction of electrode consumption. The even distribution of heat throughout the melting medium leads to uniform wear of different parts of the lining, otherwise one part will wear out prematurely and heat will escape into the environment through the rapidly worn part, which will lead to the premature completion of current and major repairs. The unevenness of arc formation in phases causes electromechanical transients, which lead to their breakage. In conclusion, it can be said that the correct adjustment of the electrical modes of arc furnaces allows you to prevent the breakage of electrodes, their inclusion in the solution, and changes in the composition of the solution.

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