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THE INFLUENCE OF REACTIVE POWER COMPENSATION METHODS ON THE BURNING CHARACTERISTICS OF SHUNTED ELECTRIC ARC IN AN ORE REDUCTION FURNACE

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ВПЛИВ МЕТОДІВ КОМПЕНСАЦІЇ РЕАКТИВНОЇ ПОТУЖНОСТІ НА ХАРАКТЕРИСТИКИ ГОРІННЯ ШУНТУВАННОЇ ЕЛЕКТРИЧНОЇ ДУГИ В РУДОВІДНОВЛІВНІЙ ПЕЧІ

The purpose of the work was to study the effect of compensation on the stability of the combustion of an electric arc in the furnace bath.

Methodology: The results of the research of operating furnaces by traditional methods, such as measurement and oscillography of the form of voltage and current on the electrodes during the smelting of ferroalloys, were used.

Results: Schemes of transverse capacitive compensation on the high or medium voltage side and longitudinal capacitive compensation in the medium voltage circuit of the furnace transformer are used for Electric ore reduction furnaces. Electric ore reduction furnaces are large consumers of reactive power, and their power has already reached such an amount that the value of the inductive voltage drop becomes unacceptably large; and their natural power factor does not exceed the value of 0.6 – 0.7. Compensation of the reactive power of the longitudinal compensation devices is traditionally resolved by usage of capacitor banks. Determined that longitudinal compensation devices are based on the phenomenon of voltage resonance, then if there are active, inductive and capacitive resistances in the furnace circuit – the arc burns continuously, even in the case of partial compensation. This mode occurs at a power factor of about 0.85. In case of full compensation of the inductive component of resistance of the furnace circuit, the mode of arc burning changes and becomes intermittent.

Scientific novelty: Determined that with a fixed value of the power factor and the value of conductivity bc, it is very difficult to achieve ideal current resonance, and when bc = −⌂bl+bl+⌂blc the burning mode of the electric arc will be continuous; however, if the capacitive conductivity becomes more inductive, overcompensation is possible. In the case of transverse compensation, the total power of the furnace unit should be approximately 10% higher.

Practical significance: The results obtained can be used for a reasoned selection of reactive power compensation installations for existing ore reduction electric furnaces. With full compensation of the reactive power (transverse and longitudinal), the arc burning mode of the ore reduction furnace becomes intermittent.

Keywords: *electric ore reduction furnace, longitudinal and transverse compensation of reactive power, electric arc, stability of arc burning, capacitor bank system, operator`s model, remnant part, identification.*

Introduction. A significant number of electricity consumers constantly load the network with the reactive component of consumed power; and this load is constantly increasing. The implementation of reactive power compensation devices makes it possible to increase the reliability of electric networks and increase the power transmission capacity of an energy system.

Among a number of advantages from the use of reactive power compensation devices, the following can be noted:

1. Energy consumption savings – the implementation of reactive power compensation devices involves reducing the level of energy consumption up to 40–50% of the total volume.
2. Increasing the service life of equipment – compensation means increase the service life of furnace transformers.
3. Cost savings for the installation of underwater power networks – installation of the reactive power compensation system during the design and construction stages of new structures allows us to significantly save costs on the installation of the distribution network.
4. Improvement of the power supply quality – usage of reactive power compensation makes it possible to suppress network disturbances and minimize phase asymmetry.
5. The compensation device allows us to avoid fines from the electricity supplier for the deterioration of the value of the power factor.

The main consumers of reactive power are:

- asynchronous electric motors that consume 40% of the total power;
- electric furnaces – 8%;
- converters – 10%;
- transformers of all stages of transformation – 35%;
- power lines – 7%[1].

The most effective and efficient way to reduce consumption from the reactive power network is the use of reactive power compensation capacitor units (capacitor banks, CB) [1]. The use of reactive power compensation capacitor units allows:

- to unload power transmission lines, transformers and distribution devices;
- to suppress network disturbances, reduce phase asymmetry;
- to make distribution networks more reliable and cost-effective;
- to reduce the level of higher harmonics.

Electric ore reduction furnaces (ORF) are large consumers of reactive power. The process technology of these furnaces ensures the stability of reactive power consumption and the absence of sharp jumps in its value. A change in the electrical mode on these furnaces can only occur periodically, due to a change in the quality of the charge materials, the failure of some units or due to the need to adjust the power. According to the requirements of the technology, the increase in the power of the ORF is accompanied by a significant increase in the values of the operating currents of the Electrodes with a relatively slow increase in the useful voltages [1]. In this case, there is a sharp increase In the inductive component of the voltage drop in the electrical circuit of the furnace installation, and, as a result, a decrease in its power factor. The power of modern ORF has already reached such an amount that the magnitude of the inductive voltage drop becomes unacceptably large, and their natural power factor does not exceed the value of 0.6…0.7 (for example, RPZ-48(63) furnaces for smelting ferrosilicomanganese).

The use of rational schemes and constructions of short networks does not allow to obtain values of reactance smaller than the limit values. This is explained by the fact that an increase in the number of conductors in the short network phase above a certain value does not lead to a significant decrease in the reactance of the furnace installation. At the same time, a significant part of the reactance (40–60%) is contributed by the resistances of the furnace circuit elements and the furnace bath, which cannot be changed without disrupting the technological process. In the works of Dantsis Ya. B. and Zhilov G. M., it was shown that for ORF there is a certain limit power from 8 to 70 MVA (depending on the alloy that is smelted), above which, it is necessary to use longitudinal capacitive compensation in order to ensure the operation of the furnace on the ascending branch of the operating characteristic [1].

Compensation of the reactive power of the ORF is traditionally solved by the use of CB. For ORF, schemes of transverse capacitive compensation on the high or medium voltage side and longitudinal capacitive compensation in the medium voltage circuit of the furnace transformer are used [2–8]. The advantages of LCD include equalizing the load by furnace phase, auto-regulation of reactive power when the current changes, improving the operating characteristics of the furnace installation due to the increase in the resulting power factor of the furnace working circuit. The disadvantages of LCD are the potential occurrence of ferroresonance and overcurrents in dynamic operating modes of the electric furnace. To prevent this phenomenon, furnace transformers with reduced magnetic induction (that is, bulkier and more expensive than conventional furnace transformers), as well as automatic capacity regulators of capacitor banks are used for working with LCD [4–7]. It was noted that for processes with an extended arc, furnaces using LCD for power factor correction operate with a power factor not exceeding 0.85 to ensure stable arc burning [9]. With longitudinal compensation, since the compensating electrical capacitors are turned on in series with the load in the main circuit, the reactive power of the capacitor depends on the magnitude of the current flowing through the electrode of the arc furnace, and therefore changes with the fluctuation of reactive power under load. This allows us to perform reactive power compensation in real time without changing the voltage of working busbar. It should be noted that in longitudinal compensation, compared to transverse compensation, the secondary voltage of the furnace transformer may increase due to the voltage of the boosting transformer. The latter can increase the active power consumed by the furnace

[10], but it is necessary to take into account the non-sinusoidal parameters of currents and voltages.

It was shown in works [11, 12] that for the effective use and consumption of electrical energy by a high-power linear load in the sinusoidal long-range mode, it is advisable to use schemes of longitudinal compensation of reactive power with inclusion capacitors in the higher voltage winding of the longitudinal connection transformer, which makes it possible to increase the efficiency of the power supply devices of electric arc furnaces, reduce power losses in the power supply system and the short network of the furnace by 1.6 times, and reduce the full load in the power transformer by 1.36 times.

The purpose of the research. Based on the above, it can be seen that the use of LCD in ORF is justified, however, the relationship between the methods of compensation of reactive power and the nature of arc combustion in the furnace bath should be clarified and detailed.

Main results. The impossibility of reducing the reactance of the furnace circuit leads to a decrease in the natural power factor of the ORF with an increase in their power and makes it necessary to use installations, for example, longitudinal capacitive compensation, which provide automatic compensation of the reactive voltage drop. The method of compensation, in which the capacitive resistance of the capacitor bank is connected in series with the load resistance, is called longitudinal compensation (Fig.1).

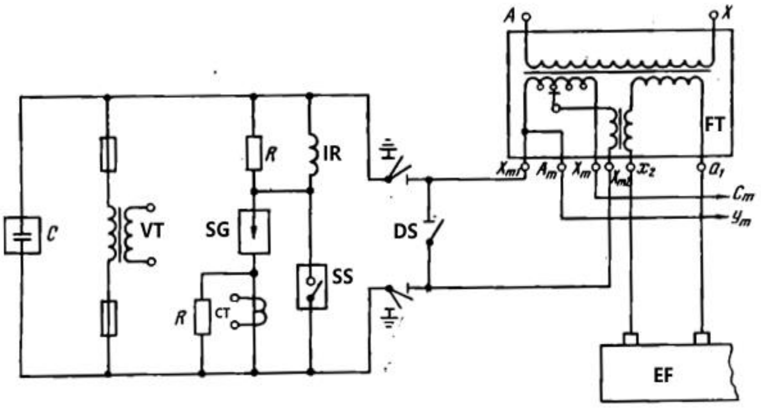

Fig. 1. The schematic diagram of longitudinal-capacitive reactive power compensation for electric furnace RPZ-63I1:
FT – furnace transformer, EF – electric furnace, C – capacitor bank,
VT – voltage transformer, CT – current transformer, SS – shunt switch,
DS – disconnect switch, R – additional active resistance, IR – inductive resistance,
SG – spark gap (for protection of the capacitor bank from overvoltage) [1]

A feature of the application of longitudinal compensation is that it causes an increase in the voltage on the consumer's busbars, which depends on the load current. This is explained by the fact that in the secondary circuit there is a voltage drop in the capacitor directed opposite to the voltage drop in the inductance. The value of the capacitive resistance can be selected in such a way that the modulus of the secondary voltage vector will be equal to or greater than the primary voltage. From this follows the possibility of using longitudinal compensation as a means of voltage regulation, and turning on the LCD is equivalent to switching the furnace to a higher voltage level of the furnace transformer, but with a higher value of the power factor. For example, for the RPZ-63I1 furnace, this corresponds to switching from 4th to 1st tap, but the power factor increases from 0.55 to 0.89, and the phase power – from 11.37 MW to 14.2 MW, the half-phase voltage – from 51.1V to 90.3V. Subsequently, since longitudinal compensation devices are based on the phenomenon of voltage resonance, in the presence of active, inductive and capacitive resistances in the circuit of the furnace, even in the case of partial compensation, as noted by a number of authors [3, 4], the arc burns continuously (Fig. 2, b). This mode occurs at a power factor of about 0.85. At the same time, the amplitude of zero-crossing voltage shift at triple frequency is maximum, which indicates the intensity of the arc discharge under the furnace electrodes. Since the magnitude of zero-crossing voltage shift is a function of the power of the arc discharge in the furnace circuit, the change in the amplitude of this voltage indicates the change in the power of the arc discharge in the furnace bath.

The operation of the RPZ-63I1 furnace with the specified power factor is characterized by the amplitude of the zero-crossing voltage shift from 10 to 12 V, which indirectly indicates the power of the arc discharge in the furnace. It was also experimentally established that the electrical mode of operation of the furnace does not remain stable during the entire melting period. After the release of the alloy, the operating mode of the furnace is relatively more stable than during the melting process. During this period, the arc discharge in the sub-electrode space of the bath has a relatively small power. Subsequently, the power of the arc discharge increases and the amplitude of the zero-crossing voltage shift increases from 6-8 V by 1.5-1.8 times (up to 12 V).

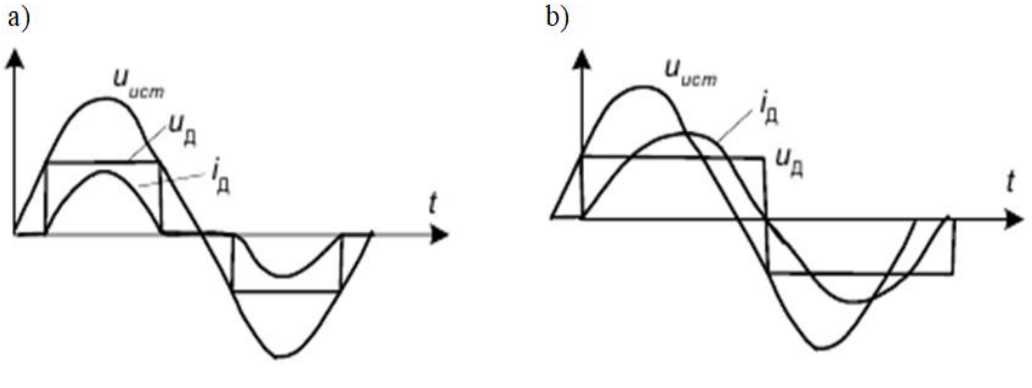

Fig. 2. Mode of arc burning at:
a) compensation of the inductive component of resistance of the furnace circuit,
b) active-inductive load

In the case of full compensation of the inductive component of the resistance of the furnace circuit, the mode of arc burning changes and becomes intermittent (Fig.2, a); the power of the arc discharge in the sub-electrode gap is significantly reduced. So, the main advantage of longitudinal compensation is automatic voltage regulation when the load of the consumer changes. Longitudinal compensation capacitor batteries are included in the winding circuit of the step-up transformer. The reduced capacitive resistance XC does not depend on the transformation coefficient of the electric furnace transformer, on the current value and remains constant in all modes of operation of the furnace. The inclusion in the circle of the furnace installation of the LCD requires a special approach to the issue of choosing the magnitude of the operating currents and voltages of the ORF transformers. At the same time, it is necessary, to reasonably choose the parameters of the furnace transformer and capacitor bank taking into account the given performance of the furnace and the optimal value of the power factor for setting.

Transverse compensation is widespread in a number of ORF installations, arc steelmaking, induction (industrial frequency) electric furnaces [1, 3]. However, such a scheme does not relieve the electrical equipment of the furnaces. For partial or complete unloading from the reactive power of furnace transformers, it is recommended to use other schemes.

When using capacitors to compensate for reactive power, it must be taken into account that current shocks and overvoltages occur when the CB is turned on and off, as well as when its sections are switched. This is caused by the presence of an oscillating circuit, which consists of the battery capacity and the inductances of the network and the transformer. The switching current of an uncharged CB can be 5 to 15 times higher than its nominal current, and overvoltages can reach three times the value of the phase voltage. Voltage fluctuations that occur during switching processes limit the permissible power of CB, which is 6…15 MVAR at a network voltage of 35 kV and 20…90 MVAR at a voltage of 110 kV. For powerful furnaces (ore reduction and arc furnaces) it is commensurate with the required compensation power. Therefore, individual compensation is mainly used for these types of furnaces [3].

The capacitor battery of the Japanese furnace is connected to a special winding of a 22 kV furnace transformer with a capacity of 3x27 MVA. The battery with a capacity of 54 MVAR is equipped with throttles that limit the switching currents of the sections. At the same time, for example, studies of the use of transverse compensation of reactive power on the RKG-75 electric furnace (Tanabe company) according to the scheme (Fig. 3) in the smelting of ferrosilicomanganese show that the compensation device increases the useful voltage of the electrode by almost 10%, providing an increase in the useful active furnace power at 21 taps of the furnace transformer by 1…2% with a decrease in the electrode current by 5…6 kA, an increase in the power factor from 0.65 to 0.91, phase voltage – from 127 V to 142 V, which is equivalent to switching the furnace transformer from 21 to 25 degrees of voltage and is included in the theory of current resonance.

The condition of resonance of currents is the equality of conductivities bl = bc. The smallest changes in the inductive resistance of the furnace circuit cause changes in this ratio due to the increase/decrease of bl. Therefore, with a fixed value of the power factor and the value of bc , it is very difficult to achieve ideal current resonance, and when bc = −⌂bl + bl + ⌂bl the burning mode of the electric arc will be continuous, which corresponds to Fig.2, b, however, if the capacitive conductivity becomes greater than the inductive one, overcompensation is possible.

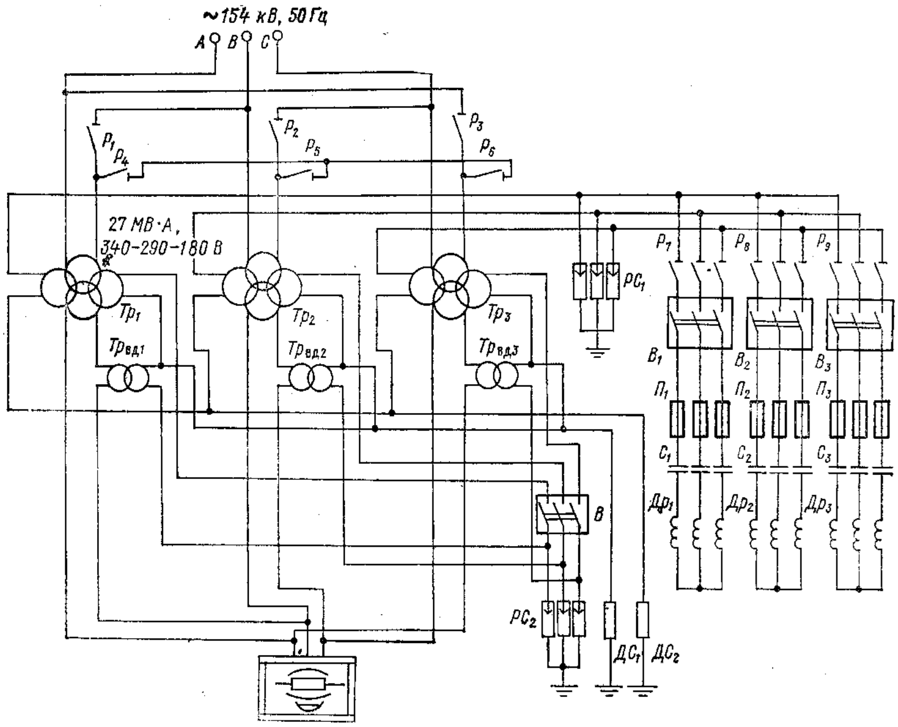

Fig. 3. Schematic diagram of the inclusion of capacitor banks during transverse compensation of the “Tanabe” ore reduction furnace:
P1, P2, P3 – disconnectors, B1, B2, B3 – high-voltage switches, P7, P8, P9 – fuses, RC1, RC2 – discharge resistors, DC1, DC2 – additional resistors [1]

In the compensation scheme proposed in this case, the total power of the furnace unit is approximately 10% higher than required, and the natural power factor does not change and is equal to 0.65, which corresponds to the conclusions of the authors [4, 5].

Conclusions.

1. With full compensation of the reactive power (transverse and longitudinal), the arc burning mode of the ore reduction furnace becomes intermittent.
2. Automatic support of required power factor value within certain individual limits sufficient for continuous burning of the electric arc is required.
3. When connecting the reactive power compensation unit LCD, the natural power factor of the electric furnace installation does not change.

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АНОТАЦІЯ

Метою роботи було дослідження впливу компенсації на стійкість горіння електричної дуги у ванні печі.

Методика. були використані результати дослідження діючих печей традиційними методами, такими як вимірювання та осцилографія форми напруги та струму на електродах під час виплавки феросплавів.

Результати. Схеми поперечної ємнісної компенсації на стороні високої або середньої напруги та поздовжньої ємнісної компенсації в колі середньої напруги пічного трансформатора використовуються для електричних рудовідновних печей. Електричні рудовідновлювальні печі є великими споживачами реактивної потужності, їх потужність вже досягла такої величини, що величина індуктивного падіння напруги стає неприпустимо великою, а природний коефіцієнт потужності не перевищує значення 0,6 – 0,7. Компенсація реактивної потужності пристроїв поздовжньої компенсації традиційно вирішується використанням конденсаторних батарей. Встановлено, що пристрої поздовжньої компенсації засновані на явищі резонансу напруги, то якщо в ланцюзі печі є активний, індуктивний та ємнісний опори – дуга горить безперервно, навіть у разі часткової компенсації. Цей режим виникає при коефіцієнті потужності близько 0,85. При повній компенсації індуктивної складової опору кола печі режим горіння дуги змінюється і стає переривчастим.

Наукова новизна. Встановлено, що при фіксованому значенні коефіцієнта потужності та значенні провідності bc дуже важко досягти ідеального резонансу струму, а при bc = −⌂bl+bl+⌂blc режим горіння електричної дуги буде безперервний; однак, якщо ємнісна провідність стає більш індуктивною, можлива надмірна компенсація. При поперечній компенсації загальна потужність топкового агрегату повинна бути приблизно на 10% вище.

Практичне значення. Отримані результати можуть бути використані для обґрунтованого вибору установок компенсації реактивної потужності існуючих рудовідновних електропечей. При повній компенсації реактивної потужності (поперечної і поздовжньої) режим горіння дуги рудовідновної печі стає переривчастим.

Ключові слова: *електрична рудовідновна піч, поздовжня та поперечна компенсація реактивної потужності, електрична дуга, стійкість горіння дуги, система конденсаторних батарей, модель оператора, залишкова частина, ідентифікація.*