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Adaptive Compensation of Reactive, Unbalanced and DC Currents of AC Arc Furnaces

Abstract. *The arcs in AC arc furnaces at the furnace calm operation can be regarded as bi-directional and the arc currents of the furnace are symmetrical. This could be not true in the first, uneasy phase of the furnace operation The extinction of the arc in one direction causes the arc current asymmetry and a DC component occurs in the arcs' currents. This DC component shifts the working point of the furnace transformer towards its saturation which causes additional distortion of the current and it contributes to energy loss in the transformer. Since AC arc furnaces can stand for one of the highest power loads in distribution systems, thus with very high disturbance capacity, compensation of the DC current could be important both for technical and economic reasons. The DC current can be compensated, along with the reactive and unbalanced currents, by an adaptive reactance compensator built of thyristor switched inductors with thyristors fired asymmetrically. The article presents a rationale for the selection of thyristors' firing angles that enables the reduction of the DC component of the AC arc furnace current along with its reactive and unbalanced currents. The presented rationale is illustrated with an example of such compensation.*

Streszczenie. *W spokojnej fazie wytopu pieca łukowego prądu przemiennego, jego prąd zasilania może być traktowany jako symetryczny. Nie jest tak jednak w pierwszej fazie wytopu. Łuk może być zerwany całkowicie lub w jednym tylko kierunku, co może powodować, że prąd zasilania traci symetrię, oraz może się w nim pojawić składowa stała. Ze względu na nieliniowość rdzenia transformatora pieca, składowa taka może powodować nie tylko wzrost odkształceń prądu, lecz także wzrost strat energii. Składowa stała prądu może być kompensowana, wraz z prądem biernym i prądem niezrównoważenia, adaptacyjnym kompensatorem reaktancyjnym z induktorami włączanymi tyrystorem. Wymaga to jednak asymetrycznego ich załączania, to jest kąty zapłonu tyrystorów włączonych w kierunku dodatnim prądu i w kierunku ujemnym muszą być wzajemnie różne. Artykuł przedstawia metodę wyznaczania kątów zapłonu tyrystorów tak, aby kompensator redukował nie tylko prąd bierny i prąd niezrównoważenia pieca, lecz także składową stałą tego prądu. Metoda ilustrowana jest w artykule przykładem takiej kompensacji.* ***(Adaptacyjna kompensacja składowej stałej prądu zasilania pieca łukowego prądu przemiennego)***

Keywords: Thyristor switched inductors, Currents' Physical Components, CPC, unbalanced current.
Słowa kluczowe: Induktory włączane tyrystorem, Składowe fizyczne prądów, CPC, prąd niezrównoważenia.

Introduction

The continuously increasing demand for steel, combined with the increasing share of arc furnaces in its production leads to an increase in the number and the power of arc furnaces located in metallurgic plants. Some of these furnaces are built as AC arc furnaces. Their very simplified structure with the furnace transformer is shown in Fig. 1.

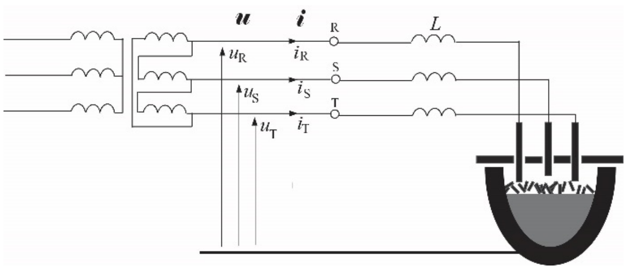

Fig. 1. The structure of an AC arc furnace with a furnace transformer.

Unfortunately, AC arc furnaces are not friendly loads for distribution systems. Highly variable, distorted, random, and asymmetrical currents [8, 10, 13] drawn by such furnaces make them one of the nastiest loads. They can disturb the operation of other equipment supplied from the common distribution system. Apart from disturbing, such currents increase the energy loss in the furnace transformer and the distribution equipment. Taking into account that such arc furnaces are not low-power devices, but their power could be in the range of several hundreds of MVA, the reduction of the harmful components of the furnace current could have major economic importance.

The voltages and currents at the furnace terminals are nonperiodic and random. Nonetheless, because the energy to the furnace is delivered only by the fundamental harmonics of voltages and currents, they can be considered semi-periodic [19], which means that in each interval of the supply voltage period T duration they can be decomposed into the Currents' Physical Components (CPC).

In a single period T of the supply voltage, the current of one of three arcs approaches zero, thus six ignitions of these arcs can occur in such a period. Thus, each period T is divided into six intervals. Since the electrodes do not have symmetry with the melted metal, at each change in the direction of one arc's current, the electrical parameters of the furnace can change [1, 2, 3, 9]. Even if the arc's plasma parameters, due to thermal inertia, do not change in a single period T, the electrical parameters of the furnace can change six times a period T.

According to the CPC-based power theory [15, 19], the useless and harmful component of the AC arc furnace current is composed of

1. A reactive current,
2. An unbalanced current,
3. Current harmonics,
4. A DC current,
5. A high-frequency noise current.

A set of voltages and current samples taken over the period T is needed for the current decomposition into the CPC, meaning the active, reactive, unbalanced currents and the DC component. All these currents are random, but inside of the observation window of T duration, they describe [12, 16] power properties of the furnace.

These currents contribute to energy loss in the furnace transformer and the distribution equipment, as well as degrade the supply quality (SQ) in the distribution system which supplies the furnace. Therefore, additional equipment is usually installed to reduce some of these currents.

The most common are compensators of the reactive current [11, 17] and harmonic filters for reducing the current harmonics. A bit more advanced is the compensation of the unbalanced current by a reactance balancing compensator

[15]. A high-frequency noise current can be compensated only by switching compensators [18]. As to the authors' best knowledge, there are no facilities for compensation of the DC current, however, and therefore, this article is devoted just to this issue.

The values of the components (1)-(5) of the arc furnace current are provided by a Digital Signals Processing (DSP) system which processes the voltage and current samples obtained from the analog to digital (A/D) converters. Instrumentation transformers (IT) serve usually as voltage and current sensors.

Instrumentation transformers do not transform DC compo-nents of the line currents and consequently, there is not much information in published results on DC components in AC arc furnaces supply lines, however.

DC currents in AC arc furnace supply lines

The anode and the cathode of an arc in AC arc furnaces switch their position twice each period T. For half of the period, the carbon electrode serves as the anode, and for the next half of the period, the melted iron serves for it. Since the electrode and the melted iron have different geometries, the arc properties change [1, 6, 9] with the current direction. It was reported in [2] and [3]. Consequently, the voltage-current relationship of the arc in AC arc furnaces, $i = f(u)$ is not an odd function, i.e., $f(-u) \neq -i$.

At such a voltage-current relationship, the arc current does not have the half-period negative symmetry, i.e.,

$$i(t \pm \frac{T}{2}) \neq -i(t) .$$

In the utmost situation, the arc in one of two directions is not even fired thus the arc can become unidirectional.

Such a current can contain not only odd-order harmonics i_1, i_3, i_5, …, but also even-order harmonics, i_2, i_4, i_6,…, including a DC component I_0.

The presence of the even order harmonics in the arc furnace supply current is commonly known [16, 17] and even the resonance harmonic filters are installed at the furnace terminals for their reduction. At the same time, the presence of the DC component in the arc supply current of AC arc furnaces was rarely reported. This is because instrumentation transformers or Rogowski coils are commonly used for this current measurement, and these devices do not detect DC currents. Nonetheless, there are published reports [8, 10, 12, 13, 16, 17] on the presence of DC components in the AC arc furnace current. According to [17] it could be even of the order of 36% of the fundamental harmonic.

Apart from the AC arc nonlinearity, also ON/OFF switch-ing of the furnace transformer can cause a DC component in the supply line of the arc furnace.

The arc nonlinearity can create a DC current on the secondary side of the furnace transformer but, of course, it cannot be transformed to the primary side. Similarly, the ON/OFF switching creates a DC current on the primary side of the furnace transformer, but it cannot be transformed to the secondary side. These DC currents cannot be transformed to the other side of the transformer by the induction phenome-non. The magnetic core's nonlinearity makes it possible, however. These DC currents create a constant magnetic flux that shifts the working point on the hysteresis loop of the core towards its saturation. This shift causes such a distortion of the current on both sides of the transformer that harmonics of the even-order, along with a DC current, can occur at both sides of the furnace transformer.

Since instrumentation transformers or Rogowski coils do not detect DC currents, DC sensors are needed for that. It can have the form shown in Fig. 2.

The voltage between two points, a and b, on the surface of the arc furnace supply conductor can be measured for that. The measurement circuit is coupled with a very strong mag-netic field of the supply conductor, however, so that the sensor provides the voltage

(1) $$u_r(t) = u_{ab}(t) - \frac{d}{dt}\Phi_r(t)$$

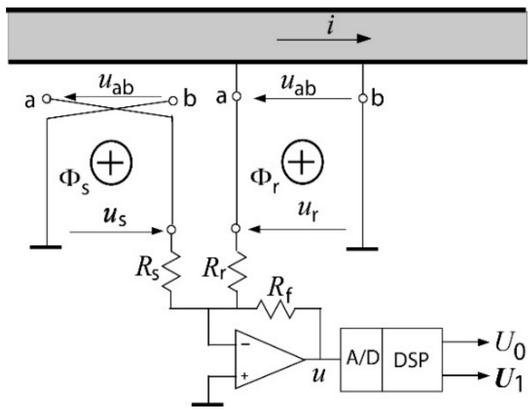

Fig. 2. A DC current sensor.

with the induced component that can be much higher than the voltage drop between points a and b. This induced voltage can be compensated by another sensor that provides the voltage

(2) $$u_s(t) = u_{ab}(t) + \frac{d}{dt}\Phi_s(t) .$$

When these two sensors are geometrically identical as much as possible and superimposed one over another, so that

(3) $$\Phi_s(t) \approx \Phi_r(t) .$$

Then, assuming that $R_s = R_r$, the differential signal at the amplifier output is

(4) $$u(t) = -\frac{R_f}{R_r}[u_r(t) + u_s(t)] = -2\frac{R_f}{R_r}u_{ab}(t) = -2\frac{R_f}{R_r}r\,i(t) .$$

This voltage, sampled by an A/D converter, provides data for a Digital Signals Processing (DSP) system which calculates the mean value of this voltage U_0. It is proportional to the line current DC component but the coefficient proportionality, meaning the resistance r between points a and b, is not a known parameter. Thus, the value U_0 cannot be recalculated to the value I_0. A process of calibration of such a sensor is needed.

A sensor with a common instrumentation current transfor-mer can be used for that. Such a sensor enables measure-ment of the AC component line current $i(t)$ so that the calculation of the rms value of the line current fundamental harmonic I_1. Having this value, the amplification coefficient $2R_f/R_r$ can be selected such that the DC sensor will provide the same value I_1. One should observe, however, that the skin and proximity effects elevate the resistance r with frequency, from its value r_0 for the DC component, to r_1 for the current fundamental harmonic. This increase depends on the geometry of the supply line and its dimensions. Its calculation is beyond the scope of this paper, however. Modeling of electromagnetic fields of the supply conductors is needed for that.

CPC of arc furnaces' supply current

For increasing the arc stability, inductors are commonly con-nected in the supply lines of the furnace. Their inductance is selected such that the furnace's reactive power Q is approxi-mately equal to the active power P, so the furnace at the quiet state, specified as state s0, operates at the power factor approximately equal to λ = 0.7. To improve it to the unity value, a shunt reactance compensator is needed.

An AC arc furnace, as observed from the distribution sys-tem with a symmetrical sinusoidal voltage, can be regarded [19] as a three-phase unbalanced, current harmonics genera-ting load (HGL), including a DC component.

A reactance compensator does not have any capability of compensating the load-generated current harmonics. It can be done only by a resonant harmonic filter (RHF) or a swit-ching compensator (SC). Therefore, from the perspective of reactance compensation, the arc furnace can be regarded as a linear load with a sinusoidal current, meaning other compo-nents of the current other than the fundamental can be ignored. Consequently, the furnace supply current can be decomposed in the frame of the Currents' Physical Compo-nents-based power theory, into the vectors of the active, reactive, unbalanced currents and the furnace-generated harmonic current

$$\boldsymbol{i} = \boldsymbol{i}_{\mathrm{a}} + \boldsymbol{i}_{\mathrm{r}} + \boldsymbol{i}_{\mathrm{u}} + \boldsymbol{i}_{\mathrm{G}} \tag{5}$$

defined in [4]. It was assumed at decomposition (5) that the furnace is supplied with a sinusoidal voltage.

When all three arcs are fired then it can be assumed that currents are symmetrical and only the reactive current contri-butes to power factor decline. When one of the three arcs is not fired, an unbalanced current occurs in the supply line, reducing the power factor well below the value λ = 0.7. It could be of the order λ = 0.4.

Compensator location

Like the reactive current, the unbalanced current can be com-pensated [5] by a reactance compensator. For loads of the power and the structure variable in a wide range, as it is with arc furnaces, the compensator should have an adaptive property, which can be achieved with thyristors switched inductors (TSI).

The compensator can be located on the primary or the secondary side of the furnace transformer. It depends on the location of the arc stabilizing inductors. Usually, due to lower current ratings, these inductors are located on the primary side of the furnace transformer, so the compensator and harmonic filters are located as shown in Fig. 3.

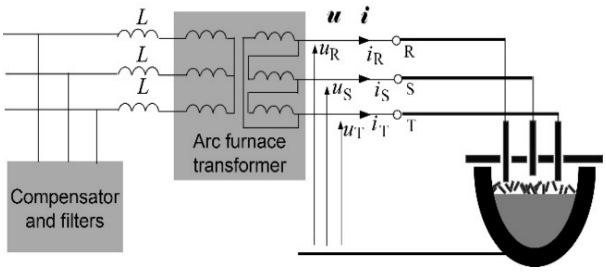

Fig. 3. An arc furnace with inductors at the primary side of the furnace transformer.

Unfortunately, at such a location, the compensator does not reduce energy loss in the arc furnace transformer. It has to be connected at the secondary side of this transformer. It means, however, that inductors for the arc stabilization are connected also on the secondary side, as shown in Fig. 4, which is not very common. However, only at such a location, the compen-sator can have the capability of reducing transformer's cur-rents which not contribute to energy transfer but only to its loss in transformer's windings.

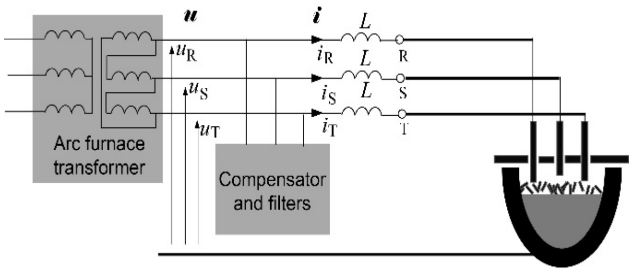

Fig. 4. An arc furnace with inductors at the secondary side of the furnace transformer.

Reactive and unbalanced currents compensation

Before the TSI-based adaptive compensator is developed, the branch susceptances of a fixed-parameters compensator have to be calculated.

A TSI-based adaptive compensator can compensate, however, only the fundamental harmonic of a load reactive and unbalanced currents. Fundamentals of a reactance com-pensation in the presence of the supply voltage harmonics were developed in [5, 18]. This approach, confined to the fundamental harmonic, is as follows.

Any three-phase load supplied from a three-wire line with a sinusoidal symmetrical voltage has [7] an infinite number of equivalent circuits shown in Fig. 5.

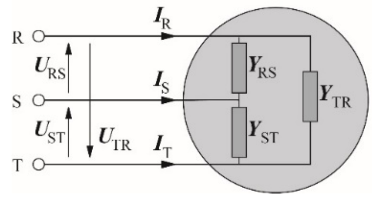

Fig. 5. An equivalent circuit of a three-phase load.

Since there is an infinite number of such circuits, one admittance can be assumed to have zero value. Let this is $\boldsymbol{Y}_{\mathrm{RS}}$ admittance, namely, $\boldsymbol{Y}_{\mathrm{RS}}$ = 0. This assumption changes the equivalent circuit to the form shown in Fig. 6. The line-to-line admittances in this equivalent circuit can be measured at the load terminals, with

$$\boldsymbol{Y}_{\mathrm{ST}} = \frac{\boldsymbol{I}_{\mathrm{S}}}{\boldsymbol{U}_{\mathrm{ST}}}, \qquad \boldsymbol{Y}_{\mathrm{TR}} = -\frac{\boldsymbol{I}_{\mathrm{R}}}{\boldsymbol{U}_{\mathrm{TR}}}\,. \tag{7}$$

For such a circuit the equivalent susceptance

$$B_{\mathrm{e}} = \mathrm{Im}\{\boldsymbol{Y}_{\mathrm{ST}} + \boldsymbol{Y}_{\mathrm{TR}}\} \tag{8}$$

and the unbalanced admittance

$$\boldsymbol{Y}_{\mathrm{u}} = -(\alpha B_{\mathrm{TR}} + \alpha^{*} B_{\mathrm{RS}}), \qquad \alpha = 1\mathrm{e}^{j2\pi/3} \tag{9}$$

can be calculated.

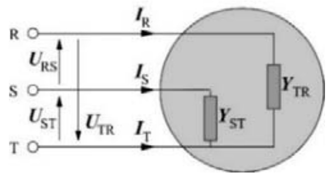

Fig. 6. An equivalent circuit of a three-phase load.

Having these two parameters, the branch susceptances T_{RS}, T_{RS}, and T_{RS} of the reactance balancing compensator, shown in Fig. 7, can be calculated [5, 18] from the formulas

$$T_{\mathrm{RS}} = \frac{1}{3}(\sqrt{3}\,\mathrm{Re}\,\boldsymbol{Y}_{\mathrm{u}} - \mathrm{Im}\boldsymbol{Y}_{\mathrm{u}} - B_{\mathrm{e}})$$

(10) $$T_{\mathrm{ST}} = \frac{1}{3}(2\,\mathrm{Im}\,\boldsymbol{Y}_{\mathrm{u}} - B_{\mathrm{e}})$$

$$T_{\mathrm{TR}} = -\frac{1}{3}(\sqrt{3}\,\mathrm{Re}\,\boldsymbol{Y}_{\mathrm{u}} + \mathrm{Im}\,\boldsymbol{Y}_{\mathrm{u}} + B_{\mathrm{e}})\ .$$

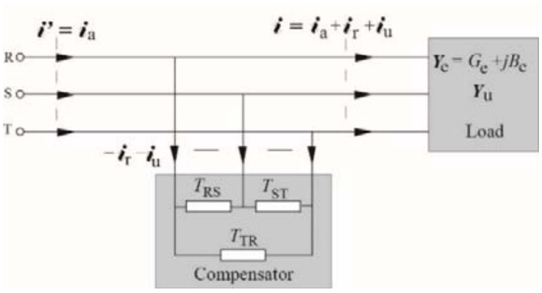

Fig. 7. A load with a reactance balancing compensator.

The compensator with susceptances calculated according to these formulas can compensate entirely the reactive and unbalanced current only when the load remains unchanged.

Adaptive reactance compensator

The AC arc furnaces are loads with the power varying in a wide range. Adaptive compensators are needed for their compensation.

An adaptive reactance compensator can be built of bran-ches composed of thyristor switched inductors (TSI). Since the switched inductors generate current harmonics, with dominating the third order, a filter of this harmonic is needed in each compensator's branch. Their structure is shown in Fig. 8.

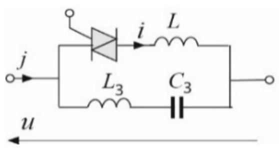

Fig. 8. A TSI with a filter of the 3rd order harmonic.

With the change of the firing angle α from zero to 90°, the susceptance of the compensator's branch changes from its minimum value

(11) $$T_{\min} = \frac{9}{8}\omega_1 C_3 - \frac{1}{\omega_1 L}$$

to its maximum

(12) $$T_{\max} = \frac{9}{8}\omega_1 C_3\,.$$

These two limits of the branch susceptance specify the value of the branch inductance and capacitance, namely, they should be equal to

(13) $$L = \frac{8}{9\omega_1}T_{\max}\,,\qquad C_3 = \frac{1}{\omega_1(T_{\max} - T_{\min})}\,.$$

The components of the compensator that have fixed parameters, meaning the filters of the third harmonic can form a separate compensator, which combined with the filter of other harmonics, can be used for the compensation of the reactive power Q of the arc furnace. The remaining part of the compensator with TSI, shown in Fig. 9, can be designed in such a way that it will not compensate the reactive but the unbalanced current.

When a TSI compensator is used as a compensator of the unbalanced and/or the reactive currents, thyristors in each branch are switched with a delay of 180 deg. Any DC current is produced by thyristors fired in such a way. When this condition is not satisfied, then a DC current occurs in the com-pensator and it can be used for compensation of the DC currents produced by the arc furnace. For that purpose, the control of a TSI-based compensator with thyristors switched asymmetrically in the positive and negative direction of the branch current, as shown in Fig. 10, has to be analyzed. The adjective "asymmetrically" means that the firing angles of thyrsitors in particular branches of the compensator, α and β, are not mutually equal.

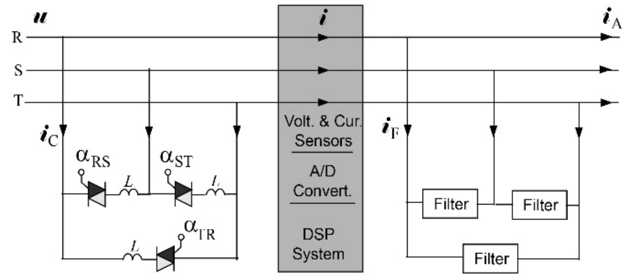

Fig. 9. A structure of the balancing compensator and filters.

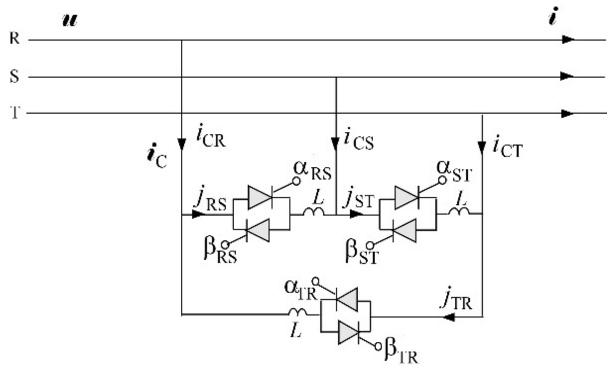

Fig. 10. A balancing compensator with asymmetrically switched thyristors.

The firing angles of thyristors in the positive and the nega-tive direction in each branch have to be selected such that at the same time the unbalanced currents and the DC currents of the arc furnace are compensated.

Since harmonics of the compensator's currents have to satisfy the relationship

$$j_{\mathrm{RS}n} - j_{\mathrm{TR}\,n} = i_{\mathrm{CR}\,n}$$

(14) $$j_{\mathrm{ST}\,n} - j_{\mathrm{RS}n} = i_{\mathrm{CS}n}$$

$$i_{\mathrm{CR}\,n} + i_{\mathrm{CS}n} + i_{\mathrm{CT}\,n} = 0$$

thus, the complex rms (crms) values of the fundamental har-monic of TSI branches are equal to

$$\boldsymbol{J}_{\mathrm{RS1}} = \frac{1}{3}(\boldsymbol{I}_{\mathrm{CS1}} - \boldsymbol{I}_{\mathrm{CR1}})$$

(15) $$\boldsymbol{J}_{\mathrm{ST1}} = \frac{1}{3}(-2\boldsymbol{I}_{\mathrm{CS1}} - \boldsymbol{I}_{\mathrm{CR1}})$$

$$\boldsymbol{J}_{\mathrm{TR1}} = \frac{1}{3}(\boldsymbol{I}_{\mathrm{CS1}} + 2\boldsymbol{I}_{\mathrm{CR1}})$$

while the DC component of these currents should have the mean values

$$J_{\mathrm{RS0}} = \frac{1}{3}(I_{\mathrm{CS0}} - I_{\mathrm{CR0}})$$

(16) $$J_{\mathrm{ST0}} = \frac{1}{3}(-2\,I_{\mathrm{CS0}} - I_{\mathrm{CR0}})$$

$$J_{\mathrm{TR0}} = \frac{1}{3}(I_{\mathrm{CS0}} + 2\,I_{\mathrm{CR0}})\,.$$

The DSP system of the compensator can provide the values on the right sides of formulas (15) and (16), so the needed values on the left sides of these formulas can be calculated.

Thyristors' firing angles selection

The crms value of the current fundamental harmonic and the mean value of the DC component in each branch of the com-pensator depend on the firing angles of thyristors connected in the positive and the negative direction of the branch's cur-rent. This dependence is identical for each branch of the TSI compensator, thus it is enough to find this dependence for only one of them, thus ignoring, as shown in Fig. 11, indices RS, ST, and TR.

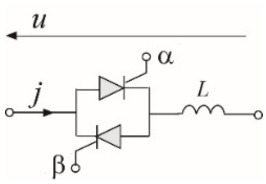

Fig. 11. A TSI branch with a separate firing angles control.

The current of the branch is a sum of currents of thyristors connected in the branch current's positive and negative direc-tions, shown in Fig. 12, namely

$$j(t) = j^{\mathrm{p}}(t) + j^{\mathrm{n}}(t)\,. \tag{17}$$

The symbol j^{s} in this figure denotes the steady-state current of the branch with both thyristors in the ON state.

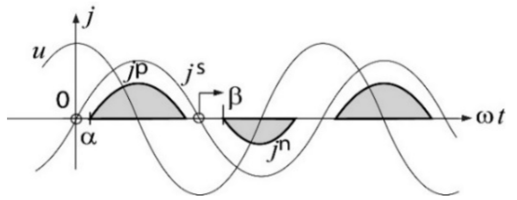

Fig. 12. Current components in a TSI branch with a separate firing angles control.

The complex rms value of the fundamental harmonic of such a current is

$$\boldsymbol{J}_1 = \frac{U_1}{2\pi\,\omega_1 L}[2(\pi-\alpha-\beta)+\sin 2\alpha+\sin 2\beta]e^{-j\frac{\pi}{2}} = \tag{18}$$
$$= f_1(\alpha,\beta)$$

and its mean value

$$J_0 = \frac{\sqrt{2}\,U_1}{\pi\,\omega_1 L}(\cos\alpha - \cos\beta) = f_0(\alpha,\beta) \tag{19}$$

For each needed value of the compensator branch current fundamental harmonic crms value $\boldsymbol{J}_1$, there is an infinite num-ber of pairs of thyristors' firing angles (α, β) at which that value $\boldsymbol{J}_1$ can be obtained. When these angles can have only dis-crete values that differ by $\Delta\alpha$, there is a finite number M of such pairs. For example, if $\Delta\alpha$ = 1 deg, then in the range of the firing angle change from 0 to 90 degrees, there is no more than 90 of such pairs, thus M is not higher than 90^{o}. The same is valid as to firing angles needed for producing by the compensator the branch current of the DC component mean value J_0.

Having the formula (18), a look-up table for angles α, β changing in the range from 0 to 90 deg with the step $\Delta\alpha$, meaning of the dimension (M x M), for the crms value of the branch current fundamental harmonic $\boldsymbol{J}_1$ can be created.

$$J_1^{\mathrm{d}} = \begin{bmatrix} \boldsymbol{J}_1^{\mathrm{d}}(0,0) & \ldots & \boldsymbol{J}_1^{\mathrm{d}}(0,\beta) & \ldots & \boldsymbol{J}_1^{\mathrm{d}}(0,90) \\ \ldots & & \ldots & & \ldots. \\ \boldsymbol{J}_1^{\mathrm{d}}(\alpha,0) & \ldots & \boldsymbol{J}_1^{\mathrm{d}}(\alpha,\beta) & \ldots & \boldsymbol{J}_1^{\mathrm{d}}(\alpha,90) \\ \ldots & & \ldots. & & \ldots \\ \boldsymbol{J}_1^{\mathrm{d}}(90,0) & \ldots & \boldsymbol{J}_1^{\mathrm{d}}(90,\beta) & \ldots & \boldsymbol{J}_1^{\mathrm{d}}(90,90) \end{bmatrix} \tag{20}$$

The upper index "d" means that such a value results from the formula (19). This is not the needed crms value of the branch current fundamental harmonic.

A similar look-up table can be created for the mean value of the compensator branch current, namely

$$J_0^{\mathrm{d}} = \begin{bmatrix} J_0^{\mathrm{d}}(0,0) & \ldots & J_0^{\mathrm{d}}(0,\beta) & \ldots & J_0^{\mathrm{d}}(0,90) \\ \ldots & & \ldots & & \ldots. \\ J_0^{\mathrm{d}}(\alpha,0) & \ldots & J_0^{\mathrm{d}}(\alpha,\beta) & \ldots & J_0^{\mathrm{d}}(\alpha,90) \\ \ldots & & \ldots. & & \ldots \\ J_0^{\mathrm{d}}(90,0) & \ldots & J_0^{\mathrm{d}}(90,\beta) & \ldots & J_0^{\mathrm{d}}(90,90) \end{bmatrix} \tag{21}$$

When at the same time, the compensator branch should provide the current that has the crms value of the fundamental harmonic equal to $\boldsymbol{J}_1$ and has a DC component of the mean value equal to J_0, then thyristors should be fired at angles α, and β for which the value of the form

$$|\boldsymbol{J}_1^{\mathrm{d}}(\alpha,\beta) - \boldsymbol{J}_1| + |J_0^{\mathrm{d}}(\alpha,\beta) - J_0| \tag{22}$$

is minimum. Having the look-up tables J_1^{d}, and J_0^{d} calcula-ted and stored in computer memory, a search algorithm that calculates the form (22) can identify the needed pair of firing angles (α, β) for the compensator's each branch. At such a pair, both the fundamental harmonic of the undesirable component of the furnace current along with its DC com-ponent can be eliminated by the same TSI-based adaptive compensator.

Numerical Illustration.

As the numerical illustration of the method discussed in this paper, the same AC arc furnace is used as analyzed in [15]. It is a reference furnace supplied from the transformer with the reactance-to-resistance ratio $X_{\mathrm{s}}/R_{\mathrm{s}}$ = 5. with the secondary voltage rms value U = 700 V. The equivalent resistance of cables, electrodes, and the arc was assumed to be R = 0.25 Ω, the equivalent reactance $\omega_1 L$ = 1Ω. It was assumed that the arc ignites when the arc's voltage is higher than U_0 = 300V. At such assumptions, the furnace operates [15] with the power factor λ = 0.71 and the apparent power of the furnace is S = 0.49 MVA. Such assumptions simplify modeling, while the results obtained for the reference furnace can be easily recalculated to for that of a real furnace, or at least provide information on mutual proportions of some major electrical quantities.

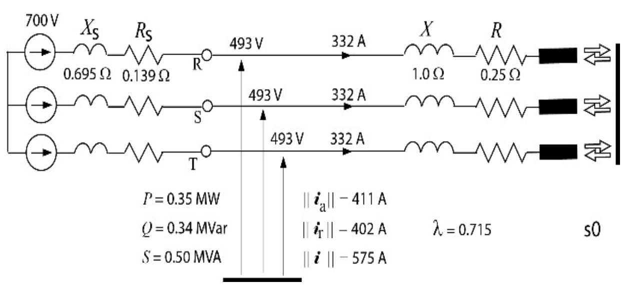

Fig. 13. Equivalent parameters of the AC arc furnace and results of its analysis at symmetrical (state s0) operation.

Results of modeling the furnace with regard to supply voltages and currents rms values and powers in state s0 are shown in Fig. 13.

When the arc in line S extinguishes (state s1), then voltages, currents, powers, and the power factor change to values shown in Fig. 14.

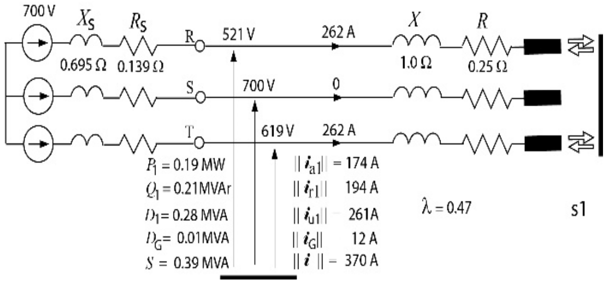

Fig. 14. Results of the arc furnace analysis at two-arcs (state s1) operation.

These values at the unidirectional arc in line S (state s2) are shown in Fig. 15.

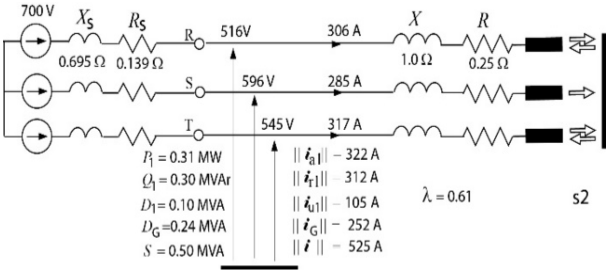

Fig. 15. Results of the arc furnace analysis at the unidirectional arc (state s2) operation.

The waveforms of voltages and currents at the supply termi-nals at this state of operation are shown in Fig. 16.

To reduce the current of the TSI balancing compensator, the reactive power along some furnace-originated current harmonics can be compensated by a fixed-parameter reac-tance compensator. Let us assume, following [15], that this compensator compensates reactive power Q_1 of the furnace in the state s0, along with the second and the third order current harmonics.

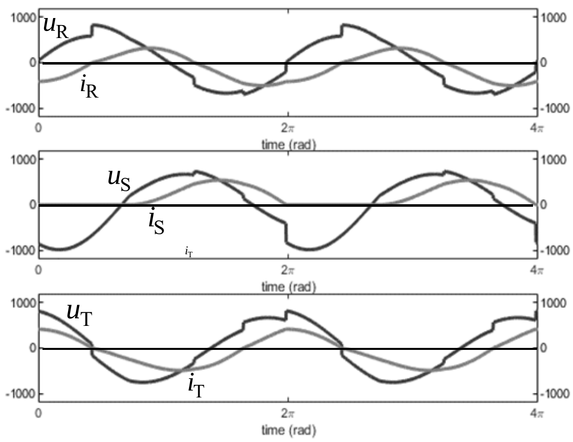

Fig. 16. Waveforms of voltages and currents at the furnace terminals in the arc furnace state s2.

When each branch of the filter compensates half of the reactive power Q_1 of the furnace, then the filter should have the parameters shown in Fig. 17.

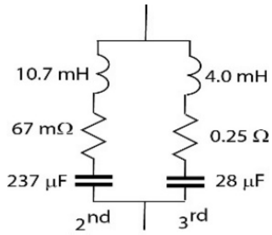

Fig. 17. Parameters of one branch of the fixed-parameter compensator.

Having the reactive power as well as the second and the third order current harmonics compensated by the fixed-parameters compensator, the TSI-based adaptive compen-sator should compensate unbalanced and DC components of the furnace current. A search algorithm that operates accord-ing to formula (22), provides firing angles of the compensator thyristors, such that these two components are eliminated from the furnace supply current, changing their waveforms to that shown in Fig. 18.

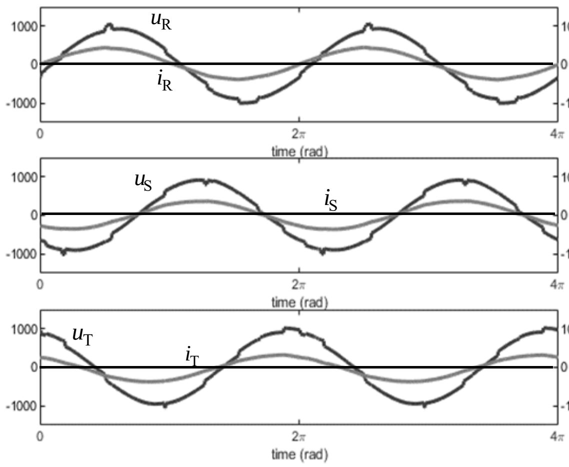

Fig. 18. Waveforms of voltages and currents at the furnace terminals in the arc furnace state s2 after DC current compensation.

The results of the adaptive compensation of the unbalan-ced and DC components of the reference AC arc furnace are compiled in Table 1.

Table 1. The results of compensation.

State:		**s0**		**s1**		**s2**	
Comp.		**No**	**Yes**	**No**	**Yes**	**No**	**Yes**
$\|\boldsymbol{i}_a\|$	A	411	533	174	254	322	443
$\|\boldsymbol{i}_r\|$	A	402	81	194	45	312	65
$\|\boldsymbol{i}_u\|$	A	0	0.2	261	42	105	39
$\|\boldsymbol{i}_G\|$	A	13	10	27	12	252	48
$\|\boldsymbol{i}\|$	A	575	539	370	262	525	452
λ		**0.71**	**0.99**	**0.47**	**0.97**	**0.61**	**0.98**

Conclusions

The paper demonstrates that TSI-based adaptive compen- sator can compensate not only the reactive and unbalanced currents, but also DC currents of AC arc furnaces.

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