Nov. 10, 1964 W. DÜCHTING 3,156,754

ARRANGEMENT FOR BALANCING THE POWER TRANSMISSION LINE TO A POLYPHASE ARC FURNACE

Filed Nov. 8, 1961 2 Sheets-Sheet 1

Fig. 1

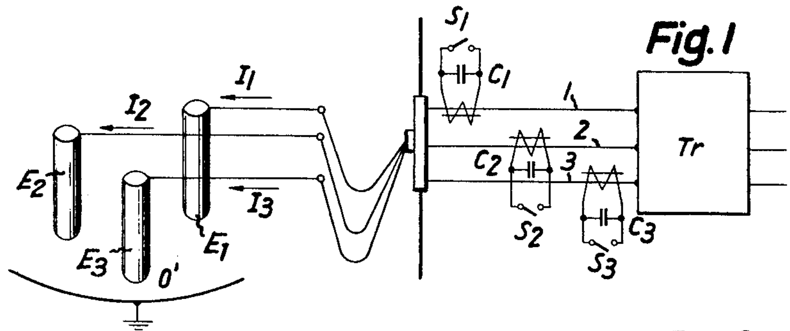

Fig. 2

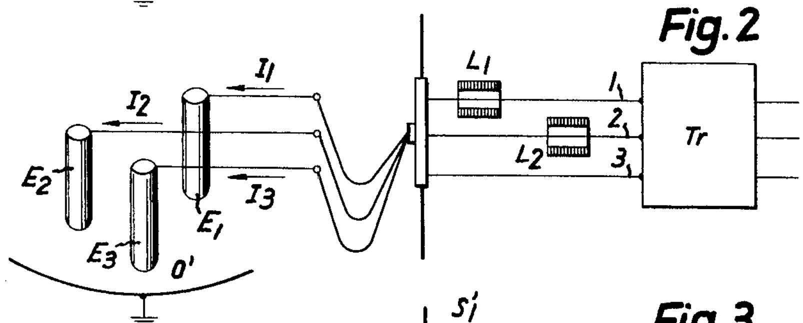

Fig. 3

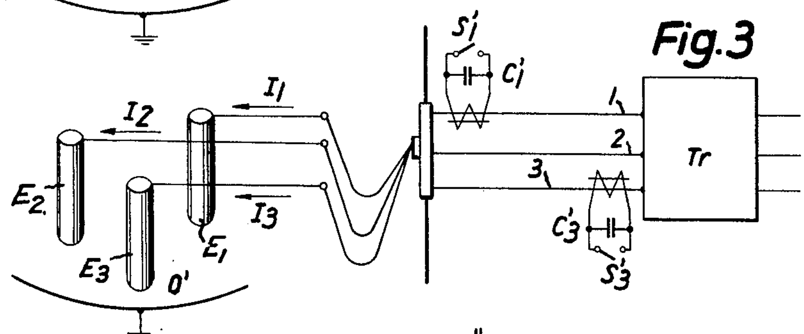

Fig. 4

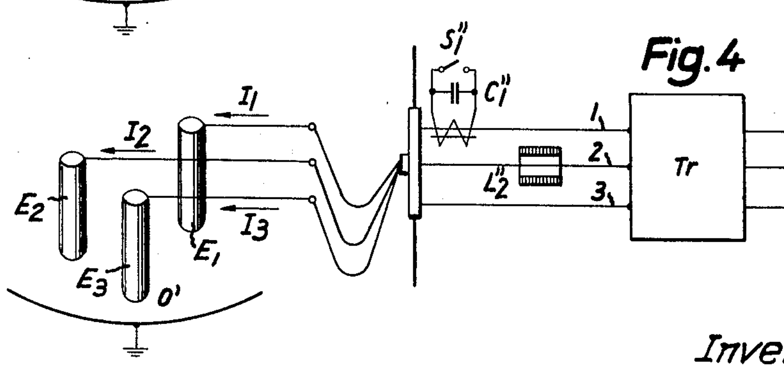

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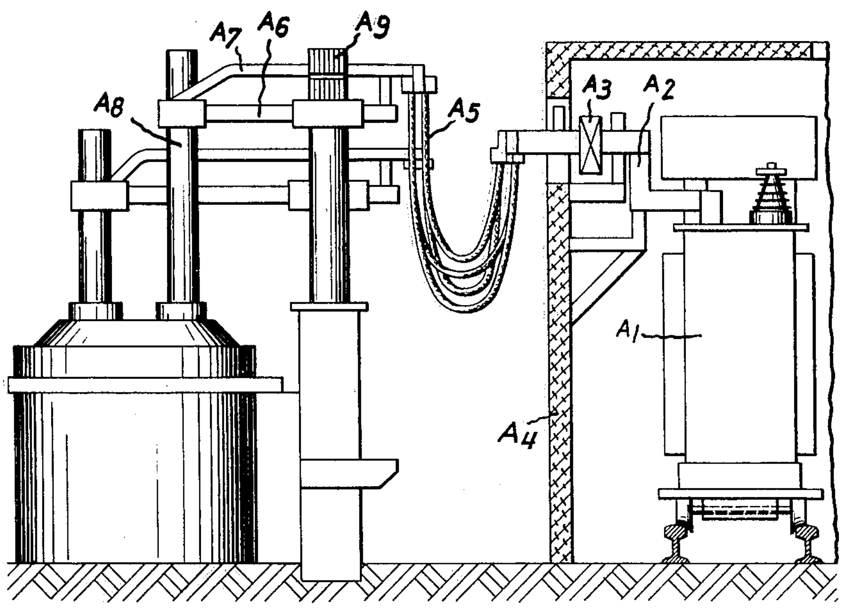
Fig. 5



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ARRANGEMENT FOR BALANCING THE POWER TRANSMISSION LINE TO A POLYPHASE ARC FURNACE

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17 Claims. (Cl. 13—9)

The present invention relates to the balancing of the power transmission line for a polyphase arc furnace, more particularly, to an arrangement of additional impedances which include ohmic resistances and capacitative and inductive reactances in at least two conductors of a 3-phase power transmission line so that the energy conversion of the electrode arcs in the arc furnace is equal.

In the operation of polyphase arc furnaces the same impedance is used to regulate the phases of the power transmission line in order to obtain equal currents therein. However, the energy exchange between the individual electrodes which are respectively connected to the conductors of the power transmission line is not equal. As a result of the differences in the energy exchanged between the several electrodes the refractory lining of the furnace in the vicinity of the out-of-balance electrode is placed under undue stress and accordingly this portion of the refractory lining requires repairs well in advance of the time for repairing the refractory lining as a whole.

The different energy exchanges between the electrodes is caused by the various reactances and resistances in the conductors from the arc furnace transformer to the tips of the electrodes. In particular, however, the differences are caused by the parallel arrangement of the copper bus bars and cables of the power transmission line and of the various solid iron members of the arc furnace structure itself.

In order to balance the power transmission line so as to obtain equal arc voltages at all of the electrodes, it has been previously proposed to employ a double-wound or bifilar construction of the conductors in fixed or non-tiltable arc furnaces such as used in the production of ferro-silicon alloys.

In tillable arc furnaces it has been proposed to solve the above problem by selecting different operating voltages when using an equal current in order to compensate for the variations in the energy exchange between the electrodes.

Other solutions have also been proposed for the above-stated problem. 3-phase inductance coils have been connected into the primary circuit of the arc furnace transformer to provide additional capacitative energy. Another solution proposed the insertion of two additional reactances in the outer conductors in order to compensate for the mutual induction coefficients or to provide an additional reactance into the central conductor. In determining the amount of the additional reactance to be inserted in the conductors it was necessary to proceed on a basis of ideal conditions. In this procedure the ohmic resistances of the three electrode circuits were equalized and the self-induction coefficients of the three phases were assumed to be similar. In addition, the coefficient of mutual inductance of an outer conductor with respect to the central conductor was assumed to be equal to the coefficient of mutual inductance with the central conductor and the other outer conductor. Measurements have shown, however, that these assumptions had no basis and as a result the additional reactances as computed deviate considerably from the amount of reactance actually necessary to be inserted in the conductors. By means of the such calculated additional impedances it is not possible to obtain such an accurate balancing as can be obtained with the additional impedances arranged according to the present invention or with impedances the values of which deviate from the values effecting the complete balancing by approximately ±30%.

One reason for the reactances in the several conductors being unequal is to be seen in that the self-inductivity of an electrical conductor depends upon the permeability of the arc furnace structure. Such permeability is large as compared with that of air and thus cannot be neglected. Since this structure will always by asymmetrical as to the different conductors, the respective influence will be different from conductor to conductor. Furthermore, eddy currents will be induced in the furnace structure, and this again will occur in a different relationship to the various conductors. All these various influences can for all practical purposes not be calculated initially so that in particular the differences in the self-inductances among the various conductors cannot be anticipated quantitatively.

It was therefore necessary either to proceed on a trial and error basis or to make calculations resulting in balancing values which were not as accurate as the balancing values obtained by means of additional impedances arranged according to the invention. Impedances calculated and made in accordance with the present invention permit a degree of symmetry and balancing of the power transmission of better than 6%, even if the balancing impedances deviate from the correct and calculated values by up to 30%.

It is therefore the principal object of the present invention to provide an arrangement for balancing the power transmission line to a polyphase arc furnace.

It is a further object of the present invention to provide accurately calculable impedances which are to be inserted in at least two conductors of a 3-phase power transmission line leading to an arc furnace in order to balance the power transmission line and thereby achieve equal exchange of energy between the electrodes of the arc furnace.

The present invention essentially comprises the insertion of additional balancing impedances into one or more of the conductors of a power transmission line leading from the arc furnace transformer to the arc furnace. These balancing impedances may be in the form of ohmic resistances and reactances both capacitative and inductive. Combinations of both capacitative and inductive reactances may be inserted onto various of the conductors.

The determination of the exact amount of the balancing impedance which is to be added in order to balance the power transmission line is calculated according to equations to be subsequently set forth in detail. As a result of actual calculations carried out on existing arc furnace installations it has been found that the calculated impedances are accurate. With these calculations it is also possible to obtain a 0% error so that the degree of symmetry of the power transmission line is 100% or the line is perfectly balanced. Since with the prior art it was not possible to obtain balancing values as accurate as the balancing values obtained by additional impedances arranged according to the invention or by impedances the values of which deviate about ±30% from the values effecting the complete balancing, it is apparent that the present invention discloses an accurate manner of determining the precise amount of impedance to be inserted into a power transmission line to balance the line.

Other objects and advantages of this invention will be apparent from the accompanying description when taken in conjunction with the following drawings, wherein

FIGURE 1 is a schematic view of the arc furnace installation of the present invention showing the addition of balancing capacitative reactances on the three conductors of the power transmission line;

FIGURE 2 is a schematic view of the arc furnace installation of this invention showing an additional balancing inductive reactance on the central conductor and an additional balancing inductive reactance on one of the outer conductors;

FIGURE 3 is a schematic view of the arc furnace installation of this invention showing the addition of two capacitative balancing reactances on the outer conductors;

FIGURE 4 is a schematic view of the arc furnace installation of the present invention showing an additional inductive balancing reactance on the central conductor and an additional capacitative reactance on one of the outer conductors; and

FIGURE 5 is an elevational view of the arc furnace installation of the present invention showing the added balancing impedances mounted on the supporting arms for the electrodes.

In order to balance the 3-phase power transmission line wherein the conductors are respectively connected to the electrodes of the arc furnace, balancing impedances are inserted in the conductors of the power transmission line. These balancing impedances will have values which might deviate from the value required for the symmetry of the balancing impedance by an amount not greater than plus or minus 30% of the actual impedance. Accordingly, these impedances will have a minimum accuracy of plus or minus 30% of the value of the actual impedance whereas it has not been possible to obtain by additional impedances used in the prior art such accurate balancing values as can be obtained by means of additional impedances arranged according to the invention, or by additional impedances the values of which deviate by about ±30% from the values at which a complete balancing is effected.

In the following calculations the following symbols shall be used:

r_i, r_j, r_k are the ohmic resistances in the conductors pertaining phases *i*, *j*, *k*, respectively and leading from the transformer to the electrodes in the furnace. *i*, *j*, *k* represent conventional phases RST respectively or a cyclic permutation thereof. Wherever the sign (−) is being used in the following, it denotes an anticyclic permutation of the phases. R when used in the equations is the arc resistance which for purposes of calculation is freely selectable. X_{ii}, X_{jj}, X_{kk} is the self-inductivity of the conductor pertaining to phases *i*, *j*, *k*, respectively. X_{ik} is the mutual or coupling inductivity as between the conductors of phases *i* and *k*. V_{2v} is the secondary transformer voltage and I is the average current in each phase, voltages and currents assumed similar for each phase. X_i, X_j, X_k will denote the balancing impedances to be inserted in phase conductors 1, 2, 3, respectively, in accordance with the invention.

The value of the balancing impedances would be as follows:

$$(1)\quad Z_j=B(\pm)\sqrt{\frac{3}{3}}(r_i-r_k)+(X_{ij}-X_{ik})-(X_{jj}-X_{jk})$$

using the abbreviation:

(2)

$$B=\frac{1}{3}\sqrt{\begin{aligned}&3(U_{2v}/I)^2-(r_i+R)^2-(r_j+R)^2-(r_k+R)^2\\&-2(r_i+R)(r_j+R)-2(r_i+R)(r_k+R)\\&-2(r_j+R)(r_k+R)\end{aligned}}$$

Upon computing, the positive sign indicates inductive and the negative sign capacitive impedance values.

While Equation 1 denotes the general rule, the following specific possibilities are included:

Additional balancing capacitative reactances can be provided as additional balancing impedances in the three conductors of the power transmission line with the balancing reactances having the following value

$$(3)\quad X_{jC}=(\pm)\sqrt{\frac{3}{3}}(r_i-r_k)+(X_{ij}-X_{ik})-(X_{jj}-X_{jk})$$

wherein *i*, *k* and *j* are the phases and *r* is the ohmic resistance. Formula 3 follows from Formula 1 with $B=0$ this latter equation now becomes an equation determining R.

Equation 1 can also be written $Z_j=B+B_j$ with

$$B_j=(\pm)\sqrt{\frac{3}{3}}(r_i-r_k)+(X_{ij}-X_{ik})-(X_{jj}-X_{jk})$$

Among these three values B_j, i.e., B_1, B_2, B_3, there is for a given furnace a smallest, a largest and a medium value to be denoted B_{min}, B_{max}, B_{med}, respectively. Whenever one selects the value B to equal the absolute value of one of these three values B_{min}, B_{max}, B_{med}, only two of the three conductors need balancing impedances to attain the object of the invention. The following possibilties exist:

The first arrangement of but two impedances involves the insertion of an additional balancing inductive reactance in the central conductor and in one outer conductor wherein the balancing inductive reactance has the following value

$$(4)\quad X_{jL}=B_{max}(\pm)\sqrt{\frac{3}{3}}(r_i-r_k)+(X_{ij}-X_{ik})-(X_{jj}-X_{jk})$$

wherein *i*, *k* and *j* are the phases and *r* the ohmic resistance and B_{max} is the maximum value of B_1, B_2, B_3 as defined. How this is to be computed from the equations of the additional reactances will be described more fully below.

According to a second possibility within the scope of this invention the power transmission line can also be balanced by providing the two outer conductors with additional balancing capacitative reactances according to the following values

(5)

$$X_{kC'}=B_{min}(\pm)\sqrt{\frac{3}{3}}(r_j-r_i)+(X_{jk}-X_{ji})-(X_{kk}-X_{ki})$$

wherein *i*, *j* and *k* are the phases, *r* the ohmic resistance in the respective phases and B_{min} is equal to the smallest of the values of B_1, B_2, B_3 as defined above.

The invention further includes the insertion of an additional balancing inductive reactance in the central conductor and an additional balancing capacitative reactance in an outer conductor having the following values

(6)

$$X_{jLC''}=B_{med}(\pm)\sqrt{\frac{3}{3}}(r_i-r_k)+(X_{ij}-X_{ik})-(X_{jj}-X_{jk})$$

wherein *i*, *j* and *k* are the phases, *r* the ohmic resistance and B_{med} is the intermediate value of B_1, B_2 and B_3.

In this invention the power transmission lines can also be balanced by providing additional ohmic resistances in the three conductors which resistances have the following values

(7)

$$r_{jR}-r_{kR}=(\pm)\sqrt{\frac{3}{3}}[(X_{jj}-X_{ii})+(X_{kk}-X_{ii})+2\{(X_{ji}-X_{jk})+(X_{ki}-X_{kj})\}]+(r_k-r_j)$$

wherein *i*, *j* and *k* are again the three phases, r_j the ohmic resistance and the additional ohmic resistance r_{iR}, r_{jR}, r_{kR} for one conductor is arbitrarily selected.

In the following, the rules expounded above shall be given more in detail and with specific reference to the drawings. For complete calculation I refer to my paper in "Elektrowärme," vol. 19, 8 (1961), having a title which reads in translation "Fundamentals for Balancing Polyphase Arc Furnaces."

In order to basically determine the additional balancing impedances which are necessary to be added, the ohmic resistances and self-reactances of the various phases **1**, **2**, **3** as indicated in the drawings and *i*, *j* and *k* as indicated in the description of the invention for purposes of clarity which phases are coming out of the transformer T_r are assumed to be different so that the following relationships hold:

$$(8)\qquad r_1 \neq r_2 \neq r_3 \text{ and } X_{11} \neq X_{22} \neq X_{33}$$

The mutual or coupling reactances are as follows:

$$(9)\qquad X_{12}=X_{21} \neq X_{23}=X_{32} \neq X_{13}=X_{31}$$

In the event additional balancing reactances X_1, X_2 and X_3 and/or balancing ohmic resistances r_{1R}, r_{2R} and r_{3R} are utilized as the additional balancing impedances of the several phases, the following vector voltages can be obtained between the phases **1**, **2** and **3** and the melt of the furnace O':

$$(10)\qquad \begin{aligned} \overline{V}_{10'}&=[(r_1+R_1)+j(X_{11}+X_1)]J_1+jX_{12}J_2+jX_{13}J_3 \\ \overline{V}_{20'}&=jX_{21}J_1+[(r_2+R_2)+j(X_{22}+X_2)]J_2+jX_{23}J_3 \\ \overline{V}_{30'}&=jX_{31}J_1+jX_{32}J_2+[(r_3+R_3)+j(X_{33}+X_3)]J_3 \end{aligned}$$

Since it is desired to have a symmertical current system, a symmetrical voltage triangle and an equal arc voltage at equal currents, the invention provides for a general rule regarding the provision of additional balancing impedances and values of the additional balancing reactances to achieve the foregoing conditions are as follows:

(11)

$$X_1=B(\pm)\sqrt{\frac{3}{3}}(r_3-r_2)+(X_{31}-X_{32})-(X_{11}-X_{12})$$

$$X_2=B(\pm)\sqrt{\frac{3}{3}}(r_1-r_3)+(X_{12}-X_{13})-(X_{22}-X_{23})$$

$$X_3=B(\pm)\sqrt{\frac{3}{3}}(r_2-r_1)+(X_{23}-X_{21})-(X_{33}-X_{31})$$

wherein

$$B=\frac{1}{3}\sqrt{\begin{aligned}&3(U_{2v}/I)^2-(r_1+R)^2-(r_2+R)^2-(r_3+R)^2\\&-2(r_1+R)(r_2+R)-2(r_1+R)(r_3+R)-2(r_2+R)(r_3+R)\end{aligned}}$$

This is the general rule to attain perfect balancing of the arc furnace. In these equations U_{2v} is the line voltage of the secondary winding of the arc furnace transformer and R the arc resistance. I is the phase current. In addition we have the three abbreviated equations:

$$(12)\qquad X_1-B=B_1,\ X_2-B=B_2,\ X_3-B=B_3$$

(See Equation 1 supra.) The symbols $(-)$ represent anticyclic phase order permutation.

All of the values necessary for the computation of Equation 11 can be determined by each arc furnace by impedance measurements. These measurements are done by withdrawing all of the electrodes from the melt in the furnace and lowering two of the electrodes to contact the melt surface so that there is no arc therebetween. The third electrode remains above the melt.

The values of the additional balancing reactances as computed in Equation 11 are at a minimum when the coefficient B occurring in Equation 11 is equal to zero.

These minimum additional balancing reactances which would then having the following values

$$(13)\qquad X_{1C}=(\pm)\sqrt{\frac{3}{3}}(r_3-r_2)+(X_{31}-X_{32})-(X_{11}-X_{12})$$

$$X_{2C}=(\pm)\sqrt{\frac{3}{3}}(r_1-r_3)+(X_{12}-X_{13})-(X_{22}-X_{23})$$

$$X_{3C}=(\pm)\sqrt{\frac{3}{3}}(r_2-r_1)+(X_{23}-X_{21})-(X_{33}-X_{31})$$

are primarily capacitative and substantially contribute to the improvement of the cos φ and in addition reduce the potential which still exists. Cos φ is the power factor.

The arc resistance during this preferred balancing of the arc voltage is as follows:

$$(14)\qquad R_C=\frac{1}{3}\left[\frac{U_{2v}}{I}\sqrt{3}-(r_1+r_2+r_3)\right]$$

In the drawings, wherein like reference symbols indicate the same parts throughout the various views, in FIGURE 1 the electrodes of the arc furnace are indicated as E_1, E_2 and E_3 and being in contact with the melt in the furnace indicated as O'. The 3-phase power transmission line has conductors **1**, **2** and **3** which lead from the secondary of an arc furnace transformer T_r. The conductors are then connected through groups of flexible cables to the conductors I_1, I_2 and I_3, mounted on the supporting arms of the electrodes, which are respectively connected to the arc furnace electrodes.

The power transmission line of FIGURE 1 is provided with additional balancing capacitative reactances on each of the conductors. These balancing reactances comprise laminated iron cores having air gaps which surround the conductor and coils positioned on the iron cores. Capacitors C_1, C_2 and C_3 are then connected to the coils and switches S_1, S_2 and S_3 are connected across the capacitors in order to bypass or shunt the capacitors when the electrodes are short-circuited. The balancing capacitors have values calculated in accordance with Equation 13.

If a capacitative coupling is not feasible because of economic or technical reasons, the power transmission line can be balanced by adding two inductive reactances X_{2L} and X_{1L}. This is accomplished by positioning laminated iron cores L_1 and L_2 having air gaps around the conductors **1** and **2**. The value of these additional inductive balancing reactances is obtained from Equation 11 if the term B is not 0, such as in Equations 13 but has the value of

(15)

$$B=\left|\frac{1}{3}\sqrt{\begin{aligned}&3(U_{2v}/I)^2-(r_1+R)^2-(r_2+R)^2\\&-(r_3+R)^2-2(r_1+R)\cdot(r_2+R)\\&-2(r_1+R)\cdot(r_3+R)-2(r_2+R)\cdot(r_3+R)\end{aligned}}\right|=|B_{max}|$$

wherein B_{max} is the greatest of the three values B_1, B_2 and B_3 computed as follows:

$$(15a)\qquad B_1=(\pm)\sqrt{\frac{3}{3}}(r_3-r_2)+(X_{31}-X_{32})-(X_{11}-X_{12})$$

$$B_2=(\pm)\sqrt{\frac{3}{3}}(r_1-r_3)+(X_{12}-X_{13})-(X_{22}-X_{23})$$

$$B_3=(\pm)\sqrt{\frac{3}{3}}(r_2-r_3)+(X_{23}-X_{21})-(X_{33}-X_{31})$$

These three values are readily determined solely on the basis of the existing impedance values in the conductors between electrodes and transformers. The largest one is thus easily determinable therefrom. In using this numerical value for a B_{max}, and substituting it into Equation 11 by virtue of the Relation 15, one of the X_1, X_2, X_3 values will be zero and the two others are then calculated accordingly. The drawing shows inductances in lines **1** and **2**, thus, for this example it was assumed $B_3=B_{max}$, so that now there follows:

$$X_1=B_{max}-B_1$$
$$X_2=B_{max}-B_2$$

Hence, two additional reactances are needed for the balancing. The arc resistance resulting from this balancing is

$$(16)\qquad R_L=\frac{1}{3}[\sqrt{3(U_{2v}/I)^2-9B^2_{max}}-(r_1+r_2+r_3)]$$

This arc resistance is smaller than the arc resistance in a purely capacitative balancing such as set forth in Equation 14 since the root in Equation 11 because of the stronger inductive reactances must now adopt a positive value which, at a constant line voltage and a constant current, produces a reduction of the arc resistance.

The energy between the arc furnace electrodes can also be balanced by positioning additional balancing capacitors on the outer conductors 1 and 3 such as illustrated in FIGURE 3. In this arrangement capacitors C_1 and C_3 are connected to coils positioned on laminated iron cores surrounding the conductors 1 and 3. Switches S_1 and S_3 are connected across the balancing capacitors C_1 and C_3. The value of the additional reactances in the conductors 1 and 3 can be determined by Equation 11 if B is assumed to be as follows:

(17)

$$B=\left|\frac{1}{3}\sqrt{\begin{array}{l}3(U_{2v}/I)_2-(r_1+R)^2-(r_2+R)^2\\-(r_3+R)^2-2(r_1+R)\cdot(r_2+R)\\-2(r_1+R)\cdot(r_3+R)-2(r_2+R)\cdot(r_3+R)\end{array}}\right|=|B_{min}|$$

wherein B_{min} is the smallest value of the values B_1, B_2 and B_3 determined from Equation 15*a*, and the two capacitances are then determined by introducing this B_{min} in lieu of B into Equation 11.

It is pointed out that the power factor of the arc furnace can be considerably improved by balancing of the power transmission line by the use of capacitors.

Proceeding next to FIGURE 4 the power transmission line is balanced by inserting an additional inductive balacing reactance L''_2 in the central conductor 2 and an additional balancing capacitative reactance C''_1 into one of the outer conductors such as 1. The value of these additional balancing reactances can be determined from Equation 11 if the root term B is assumed to be as follows:

(18)

$$B=\left|\frac{1}{3}\sqrt{\begin{array}{l}3(U_{2v}/I)^2-(r_1+R)^2-(r_2+R)^2\\-(r_3+R)^2-2(r_1+R)\cdot(r_2+R)\\-2(r_1+R)\cdot(r_3+R)-2(r_2+R)\cdot(r_3-R)\end{array}}\right|=B|_{med}|$$

wherein B_{med} is the intermediate value of B_1, B_2 and B_3 determined by Equations 15*a* and 11 in a manner analogous to those aforedescribed.

The balancing reactances in FIGURE 4 are obtained by positioning a laminated iron core having an air gap and indicated as L''_2 surrounding the conductor 2 and a capacitor C''_1 connected with a coil positioned on a laminated iron core surrounding the conductor 3.

The present invention also provides for the balancing of the power transmission line by adding additional balancing ohmic resistance into the conductors. These addition ohmic resistances can be determined from Equation 10 if therein the values $X_j=0$ are being assumed and the ohmic loss resistance of the conductors r_j, which are known, are supplemented by ohmic resistances r_{jR} to be determined. The equations now will only yield the differences between respective two such supplemented ohmic resistors, but this indicates that one such resistance is, in fact, arbitrarily selectable.

(19)

$$r_{1R}-r_{2R}=(\pm)\frac{\sqrt{3}}{3}[(X_{11}-X_{33})-(X_{22}-X_{33})+2\{(X_{13}-X_{12})+(X_{23}-X_{21})\}]+(r_2-r_1)$$

$$_{2R}-r_{3R}=(\pm)\frac{\sqrt{3}}{3}[(X_{22}-X_{11})+(X_{33}-X_{11})+2\{(X_{21}-X_{23})+(X_{31}-X_{32})\}]+(r_3-r_2)$$

$$r_{3R}-r_{1R}=)\pm)\frac{\sqrt{3}}{3}[(X_{33}-X_{22})+(X_{11}-X_{22})+2\{(X_{32}-X_{31})+(X_{12}-X_{13})\}]+(r_1-r_3)$$

It is pointed out that one of the additional balancing ohmic resistances is arbitrarily selected.

The additional balancing ohmic resistance can be obtained by reducing the cross-sectional area of the conductors. In order to eliminate the heat because of these energy losses, the conductors can be cooled at those places where they are provided with reduced cross-sectional areas. For cooling, the conductors comprise a plurality of hollow conductors interconnected by a non-magnetic material such as a plastic and water circulated through the hollow conductors.

With particular reference to FIGURE 5, the physical arrangement of the above-mentioned additional balancing impedances will next be described. There is illustrated herein an arc furnace transformer A_1 with the compensated leads originating from the secondary winding of the transformer and connected at A_2 in a delta. Current transformers A_3 are provided and are connected between the delta connections. The conductors of the power transmission line are then passed through a wall A_4 into the furnace chamber and are connected to flexible copper cables A_5 which, in turn, are connected to water-cooled conductor tubes A_7 which are mounted on supporting arms A_6 of electrodes A_8.

The supporting arms and the conductors mounted thereon are arranged in parallel for relatively long lengths of about several meters. This straight line arrangement of the conductors eliminates axial components of the magnetic fields which would result in excessive interference. In addition, because of the water-cooling the conductors can have a smaller cross-section than would be possible if the conductors were air-cooled.

The additional reactances A_9 are mounted on the supporting arms. Because of the smaller cross-section of the conductors, the weights of these additional reactances can be reduced.

In the event the additional reactances A_9 are positioned in the vicinity of the wall A_4, these reactances are then influenced by the fields of the conductor cables and by the triangle connections. These influences cannot be controlled.

The additional reactances A_9 are mounted on the supporting arms so that a minimum of a bending moment is produced on the arms. Since the weight of the additional reactance is of the order of only a fraction of the weight of the electrode supporting arms themselves and of the electrode, the regulating speeds of the electrodes are not essentially affected.

With the arrangement of this invention it is also possible to provide for the balancing of the high voltage side of the arc furnace transformer. When used for this purpose, the values of the additional impedances such as the reactances or ohmic resistances are converted by the factor of the square of the voltage ratio of the transformer. It is apparent that these resistances will be changed when the transformer is connected to a line of another voltage. These additional resistances can either be positioned in the line on the voltage side or can be coupled by transformers.

Thus it can be seen that the present invention provides an accurate arrangement for the determination of additional impedances to be inserted into the conductors of a power transmission line for balancing this arrangement. Not only can this arrangement be used to balance a power transmission line so as to obtain an equal energy of exchange between the electrodes of an arc furnace, but also to balance the high voltage side of a transformer.

It will be understood that this invention is susceptible to modification in order to adapt it to different usages and conditions and, acordingly, it is desired to comprehend such modifications within this invention as may fall within the scope of the appended claims.

What is claimed as this invention is:

1. An arrangement for balancing the power transmission line of a polyphase arc furnace, and comprising an arc furnace having three electrodes therein, a 3-phase power transmission line having three conductors with said

conductors being respectively connected to said furnace electrodes, and additional balancing impedances in said power transmission line which impedances have the following value

$$Z_j=B(\pm)\frac{\sqrt{3}}{3}(r_i-r_k)+(X_{ij}-X_{ik})-(X_{jj}-X_{jk})$$

wherein indices *i*, *j*, *k* denote three phases and permutations thereof, with (—) denoting anticyclic permutations and + thereabove cyclic permutations, *r* being the ohmic conductor resistance, X the reactance thereof with similar indices in a pair of indices denoting self-reactance, unequal indices in a pair of indices denoting mutual reactance, and

$$B=\frac{1}{3}\sqrt{\begin{array}{l}3(U_{2v}/I)^2-(r_i+R)^2-(r_j+R)^2-(r_k+R)^2\\-2(r_i+R)(r_j+R)-2(r_i+R)(r_k+R)\\-2(r_j+R)(r_k+R)\end{array}}$$

wherein R is the arc resistance.

2. An arrangement for balancing the power transmission line of a polyphase arc furnace, and comprising an arc furnace having three electrodes therein, a 3-phase power transmission line having three conductors with said conductors being respectively connected to said furnace electrodes, and capacitative balancing reactances in said three conductors having the following values of

$$X_{jC}=(\pm)\frac{\sqrt{3}}{3}(r_i-r_k)+(X_{ij}-X_iR)-(X_{jj}-X_{jk})$$

wherein indices *i*, *j*, *k* denote three phases and permutations thereof, with (—) denoting anticyclic permutations and + thereabove cyclic permutations, *r* being the ohmic conductor resistance, X the reactance thereof with similar indices in a pair of indices denoting self-reactance, unequal indices in a pair of indices denoting mutual reactance.

3. An arrangement for balancing the power transmission line of a polyphase arc furnace as claimed in claim 2 wherein said capacitative balancing reactances comprise laminated iron cores having coils thereon with a core surrounding each of said conductors, and capacitors connected across each of said coils.

4. An arrangement for balancing the power transmission line of a polyphase arc furnace as claimed in claim 3 and further comprising switches connected across said capacitors for bypassing said capacitors when said electrodes are short-circuited.

5. An arrangement for balancing the power transmission line of a polyphase arc furnace and comprising an arc furnace having three electrodes therein, a 3-phase power transmission line having three conductors with said conductors being respectively connected to said furnace electrodes, and inductive balancing reactances in the center and one outer conductor and having the values of

$$X_1-B=B_1=(\pm)\frac{\sqrt{3}}{3}(r_3-r_2)+(X_{31}-X_{32})-(X_{11}-X_{12})$$

$$X_2-B=B_2=(\pm)\frac{\sqrt{3}}{3}(r_1-r_3)+(X_{12}-X_{13})-(X_{22}-X_{23})$$

$$X_3-B=B_3=(\pm)\frac{\sqrt{3}}{3}(r_2-r_1)+(X_{23}-X_{21})-(X_{33}-X_{31})$$

wherein

$$B=\frac{1}{3}\sqrt{\begin{array}{l}3(U_{2v}/I)^2-(r_1+R)^2-(r_2+R)^2-(r_3+R)^2\\-2(r_1+R)(r_2+R)-2(r_1+R)(r_3+R)-2(r_2+R)(r_3+R)\end{array}}$$

and wherein B equals the maximum value of B_1, B_2 and B_3, and R is the arc resistance, with (—) denoting anticyclic phase permutation.

6. An arrangement for balancing the power transmission line of a polyphase arc furnace as claimed in claim 5, wherein said inductive balancing reactances comprise iron cores having air gaps therein.

7. An arrangement for balancing the power transmission line of a polyphase arc furnace and comprising an arc furnace having three electrodes therein, a 3-phase power transmission line having three conductors with said conductors being respectively connected to said furnace electrodes, and capacitive balancing reactances in the center and one outer conductor and having the values of

$$X_1-B=B_1=(\pm)\frac{\sqrt{3}}{3}(r_3-r_2)+(X_{31}-X_{32})-(X_{11}-X_{12})$$

$$X_2-B=B_3=(\pm)\frac{\sqrt{3}}{3}(r_1-r_3)+(X_{12}-X_{13})-(X_{22}-X_{23})$$

$$X_3-B=B_3=(\pm)\frac{\sqrt{3}}{3}(r_2-r_1)+(X_{23}-X_{21})-(X_{33}-X_{31})$$

wherein

$$B=\frac{1}{3}\sqrt{\begin{array}{l}3(U_{2v}/I)^2-(r_1+R)^2=(r_2+R)^2-(r_3+R)^2\\-2(r_1+R)(r_2+R)-2(r_1+R)(r_3+R)-2(r_2+R)(r_3+R)\end{array}}$$

and wherein B equals the minimum value of B_1, B_2, and B_3 and R is the arc resistance, (—) denoting anticyclic phase permutation.

8. An arrangement for balancing the power transmission line of a polyphase arc furnace as claimed in claim 7 wherein said capacitative balancing reactances comprise laminated iron cores surrounding said conductors and having coils thereon, and capacitors connected to said coils.

9. An arrangement for balancing the power transmission line of a polyphase arc furnace as claimed in claim 8 and further comprising switches connected across said capacitors to bypass said capacitors when the electrodes are short-circuited.

10. An arrangement for balancing the power transmission line of a polyphase arc furnace, and comprising an arc furnace having three electrodes therein, a 3-phase power transmission line having three conductors respectively connected to said furnace electrodes, and additional balancing impedances in said power transmission line, said additional balancing impedances comprising an inductive balancing reactance on the center conductor and a capacitative balancing reactance on one of the outer conductors with said reactances having the value of

$$X_{1LC}-B=B_1=(\pm)\frac{\sqrt{3}}{3}(r_3-r_2)+(X_{31}-X_{32})-(X_{11}-X_{12})$$

$$X_{1LC}-B=B_2=(\pm)\frac{\sqrt{3}}{3}(r_1-r_3)+(X_{12}-X_{13})-(X_{22}-X_{23})$$

$$X_{3LC}-B=B_3=(\pm)\frac{\sqrt{3}}{3}(r_2-r_1)+(X_{23}-X_{21})-(X_{33}-X_{31})$$

wherein

$$B=\frac{1}{3}\sqrt{\begin{array}{l}3(U_2v/I)^2-(r_1+R)^2=(r_2+R)^2-(r_3+R)^2\\-2(r_1+R)(r_2+R)-2(r_1+R)(r_3+R)-\\2(r_2+R)(r_3+R)\end{array}}$$

and wherein B equals the medium value of B_1, B_2 and B_3 and R is the arc resistance, (—) denoting anticyclic phase permutation.

11. An arrangement for balancing the power transmission line of a polyphase arc furnace as claimed in claim 10 wherein said inductive reactance comprises a laminated iron core having an air gap and surrounding said center conductor and said capacitative reactance comprises a laminated iron core surrounding an outer conductor with a coil positioned thereon and a capacitor connected to said coil.

12. An arrangement for balancing the power transmission line of a polyphase arc furnace, and comprising an arc furnace having three electrodes therein, a 3-phase power transmission line having three conductors with said conductors being respectively connected to said electrodes, and ohmic balancing resistances provided in said

conductors which balancing resistances have the following values

$$r_{jR}-r_{kR}=(\pm)\frac{\sqrt{3}}{3}(X_{jj}-X_{ii})+(X_{kk}-X_{ii})+2\{(X_{ji}-X_{jk})+(X_{ki}-X_{kj})\}]+(r_k-r_j)$$

wherein indices i, k and j denote three phases and permutations thereof, with $(-)$ denoting anticyclic permutations and $+$ thereof cyclic permutations, r with one index being ohmic conductor resistance, r with two indices being ohmic balancing resistance, X being the conductor reactance with similar indices in a pair denoting self-reactance, unequal indices in a pair denoting coupling reactance.

13. An arrangement for balancing the power transmission line of a polyphase arc furnace as claimed in claim 12 wherein said ohmic resistances comprise reduced cross-section areas of said conductors.

14. An arrangement for balancing the power transmission line of a polyphase arc furnace as claimed in claim 13 and further comprising means for cooling said conductors in the area of said reduced cross-section areas.

15. An arrangement for balancing the power transmission line of a polyphase arc furnace as claimed in claim 1 wherein said impedances comprise at least one laminated iron core having an air gap.

16. An arrangement for balancing the high voltage side of an arc furnace transformer, and comprising an arc furnace transformer having a high voltage side and a low voltage side, a 3-phase power transmission line having three conductors connected to said high voltage side of the transformer, balancing impedances in the power transmission line which balancing impedances have the following values

$$Z_j=B(\pm)\frac{\sqrt{3}}{3}(r_i-r_k)+(X_{ij}-X_{ik})-(X_{jj}-X_{jk})$$

wherein indices i, j, k denote three phases and permutations thereof, with $(-)$ denoting anticyclic permutations and $+$ thereabove cyclic permutations, r being the ohmic conductor resistance, X the reactance thereof with similar indices in a pair of indices denoting self-reactance, unequal indices in a pair of indices denoting mutual reactance, and

$$B=\frac{1}{3}\sqrt{\begin{array}{l}3(U_{2v}/I)^2-(r_i+R)^2-(r_j+R)^2-(r_k+R)^2\\-2(r_i+R)(r_j+R)-2(r_i+R)(r_k+R)\\-2(r_j+R)(r_k+R)\end{array}}$$

wherein R is the arc resistance, said balancing impedances being converted by the square of the voltage ratio of the transformer for adaptation to various transformers and voltage sources.

17. An arrangement for balancing the power transmission line of a polyphase arc furnace as set forth in claim 1, said balancing impedances being mounted on said electrode supporting arms.

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