High Power Factor AC-DC Line-Frequency Resonant Converter for Deeply Varying Loads

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***Abstract* - AC-DC line frequency resonant converter is described, where in each half-cycle of network voltage the capacitor and inductor of an oscillatory circuit are parametrically switched from series into parallel and vice versa. The reactive power of the capacitor and the inductor compensate mutually both in case of series and parallel connection. Therefore the power factor is very high from no-load to short-circuit. This converter fits very well to supply arc furnaces. Then there is no need for the costly and fast reactive power compensator and filter circuits. The operating principle of the converter and a real operating converter with rated power 8.4 MW supplying steel-melting arc furnace are described.**

I. INTRODUCTION

The main direction of research and development in the area of converter technology is currently study and implementation of high frequency switch-mode converters. High frequency enables to reduce weight and dimensions of capacitors, inductors and transformers. To feed the switch-mode converters, usually a full-bridge diode rectifier connected directly to the network is used. The filter capacitor is connected to the DC side of the rectifier. Such solution is cheap and everything is OK if total number of such pulse converters is not high.

In case the majority of consumers are equipped with switch-mode converters (this may happen in the near future), such cheap solution cannot be used any more. THD of diode rectifiers with smoothing capacitor on the AC side is 70...100% in one-phase circuits and 30...40% in three-phase circuits. Such high THD is not acceptable in the network. Presumably THD norms on line side current of electrical equipment are coming more strict, as more "bad" consumers are coming up. THD could be improved for example with an auxiliary step-up converter between the rectifier bridge and the smoothing capacitor. This causes inevitably step-up of the price and reduction in efficiency.

Higher harmonics of non-sinusoidal high frequency currents of switch-mode converters reach radio frequency (0,1...10MHz). The inside busbars of these converters as well as the network side and load side connection cables emit radio waves as radio transmitter aerial. Therefore, the converters are mounted into metal cabinets and connection cables are equipped with filters. But no screening and no filter acts 100%. Besides, filter problems do not inevitably cause problems in converter functioning. Therefore there are also converters without filters. As the power rating and total number of switch-mode converters is coming up total pollution of environment with electromagnetic radiation is taking place. Radio broadcasting in the band 0,1...1,6MHz has within the last two decades become almost impossible in Europe. This indicates that the natural disturbance level has been exceeded. Therefore one should be careful when using high-frequency converters. If the price of a high frequency and a network frequency converter are about the same at the same quality level, the network frequency converter should be preferred. Especially at higher power rates.

Switch-mode converters are also a source for acoustic noise. To avoid noise the switching frequency has to be at least 20...30kHz. Due to such frequency the upper unit power limit of low voltage converters is about 100kW. At high power ratings the converter has to be of modular architecture, that means parallel operation of converters with limited power. Due to limited unit power, efficiency does not grow together with the power rating as it appears with line frequency converters. Also the price of the converter per 1kW is not falling as it appears with line frequency converters. Therefore, the phase-controlled thyristor rectifier is cheaper at high power ratings. But power factor of the converter is falling significantly when controlling the phase-controlled thyristor converter. This causes flicker at deeply and steeply fluctuating loads. Flicker could be reduced with a dynamic reactive power compensator, but this is very expensive. For powerful and deeply controlled converters a better solution is needed, than a switch-mode converter or a phase-controlled thyristor rectifier.

II. AC-DC LINE-FREQUENCY RESONANT CONVERTER WITH ALTERNATION OF SERIES AND PARALLEL RESONANT MODE

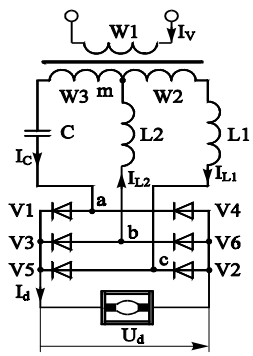

Fig. 1. Single-phase converter with two secondary winding

To supply a powerful fluctuating load (for example arc furnace) it is suitable to use a resonant converter with alternation of series and parallel mode (SPA-converter)[1, 2, 3]. In Fig. 1 single-phase diode-rectifier SPA resonant converter is shown. The converter has two secondary windings (W2 and W3) connected in series. Winding W2 and

inductor L1 form a phase shift circuit, the current of which (I_{L1}) lags the voltage in phase. Winding W3 and capacitor C form another phase shift circuit, the current of which (I_C) leads the voltage in phase. The common point of windings m is connected to the rectifier bridge through an additional inductor L2.

A. Current characteristics of the converter

In case the converter is loaded with an electric arc varying in length, the arc could be seen as the source of opposite e.m.f. As the electric arc voltage varies, the converter output current also varies and it is suitable to use curves in the form $I_d=f(U_d)$. When the opposite e.m.f. changes, the line current (I_V) also changes and also the currents through

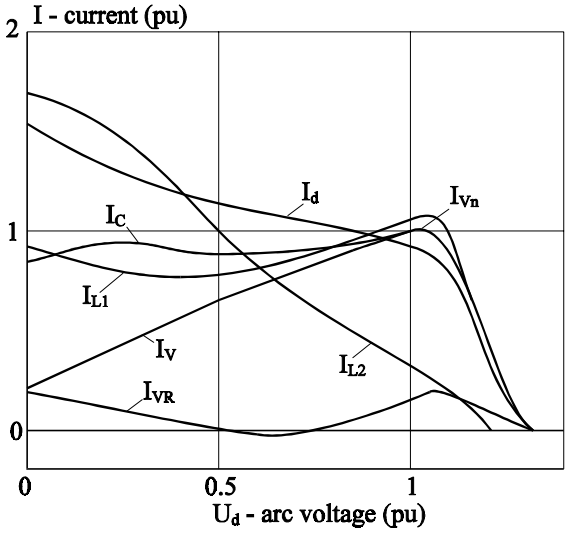

Fig. 2. The output current (I_d), network current (I_v), capacitor bank current (I_C), current of the main inductor (I_{L1}) and additional inductor (I_{L2}) as a function of the arc voltage U_d of the converter with a single-phase diode-rectifier used in ESTA power supply

reactive elements change: I_C - through the capacitor C; I_{L1}- through reactor L1 and I_{L2} - through reactor L2. It is shown on Fig. 2. In comparison with an ordinary diode rectifier the characteristics have the following peculiarities.

- The maximum value of the line current (I_v on Fig. 2) is in general the same as rated value (I_{Vn}). Moving from the nominal point to short circuit the line current does not increase as usually but decreases. By changing the load the primary winding of the transformer cannot be overloaded.
- The current of the capacitor bank (I_C) and the main inductor (I_{L1}) does not vary much if changing from nominal condition to short circuit (usually changes up to 10...20 %). This means, that in general it is not possible to overload the capacitor bank, main inductor and the secondary windings of the transformer.
- When overcoming from nominal operation to short circuit, the rectified current (I_d) will increase more than the currents of the secondary circuit I_C and I_{L1}, but this is still small (approximately 1.7 times). Such change corresponds to about the operating mode of a current source. When overcoming from nominal current (I_{dn}) to no-load (I_d=0) the voltage (U_d) does not change more than 1.3...1.7 times. This corresponds to about the operating mode of a voltage source.
- The reactive component of the line current is small in all operation modes (I_{VR} on Fig. 2). In the range of nominal current the reactive component is usually inductive and the amount is 10...40 % from nominal current.

The line current I_V does not vary proportionally to the rectified current I_d like it is in the conventional diode bridge rectifier. There are two reasons for this. Firstly, the primary current I_V will change also, when the secondary currents I_C and I_{L1} do not change, but the phase angle between them changes. This corresponds to commonly known reactive power compensation. Secondly, the change of the phase angle of the currents I_C and I_{L1} changes also the amount of the rectified current. In case the phase shift angle between the currents I_C and I_{L1} increases the rectified current increases. To explain such behaviour of the rectified current let us follow the commutation of the rectifier diodes.

B. The converter diagram of commutation

To analyse the circuit on Fig. 1 at commutations it is most suitable to use computer simulation. By simulation it is possible to determine instants of turning on and off the valves V1...V6 in electrical degrees related to the supply voltage U_v crossing zero (angle υ=0° on Fig. 3). As the electric arc voltage U_d (being the load) varies the instants of turning on and off of these valves also vary.

When simulating the converter at different values of voltages U_d from zero to no-load and recording instants of turning on and off the diodes at every voltage U_d, it is possible to get the curves of turning on and off as functions from the converter output voltage U_d. These curves are on Fig. 3a.

From Fig. 3a it is also possible to determine the current circuits corresponding to on and off states of different diodes. Around nominal current area the current circuits and their variation order is the same as for conventional three-phase rectifier.

Similarly to a three-phase rectifier we can also name the intervals as commutational intervals, when simultaneously are turned on two valves from the anode group or cathode group. The commutation takes place between the currents of reactive components L1, L2 and C. In nominal mode there are three different commutational intervals in each half period that are marked with γ_p, γ_C and γ_L. The current circuits corresponding to these intervals are shown on Fig. 3b.

Between the commutational intervals of nominal mode there are three intervals, where only 2 diodes are turned on.

These intervals are marked with υ_C, υ_{LC} and υ_L. The current circuits corresponding to these intervals are shown on Fig. 3c.

From Fig. 3a one can see that when electric arc voltage varies (this is determined by length of arc), big changes occur in commutation of rectifier bridge diodes. When overcoming from nominal mode to short circuit the interval γ_p is continuously growing. As can be seen from Fig. 3b, the circuit corresponding to γ_p is when capacitor C and inductor L1 operate in parallel. When overcoming from nominal mode to no-load the interval υ_{LC} is increasing. From Fig. 3c one can see, that the circuit corresponding to this interval is the one, where capacitor C and inductor L1 are connected in series. In most operating modes including nominal mode in each half-cycle of line voltage the capacitor C and inductor L1 are switched from parallel into series and vice versa. There is a parametric alternation of parallel and series resonant mode.

We would like to stress, that all these interval variations and corresponding circuit changes occur without valve control. All valves are diodes. If the diodes V2 and V5 would be replaced by thyristors, we get a new diagram of commutation curves (like Fig. 3a) for each thyristor firing angle α, because changing the firing angle α of one valve causes the change in duration of on and off states of all uncontrolled valves.

From Fig. 3b we can see, that the currents i_C and i_{L1} are of opposite direction during the commutational interval γ_p. These currents also pass the transformer secondary windings in the opposite direction. The sum of currents goes through the common point m of the windings to inductor L2 (Fig. 1). Therefore the transformer windings W2 and W3 are switched in parallel during γ_p. If the current is zero in one of the windings, then it could be looked at as a special case of parallel operation of the transformer windings. The current in one of the secondary windings is equal to zero in intervals υ_L and υ_C between commutations. During the interval υ_{LC} between commutations the currents i_C and i_{L1} are of the same direction and equal. Also the currents in the transformer windings W2 and W3 are of the same direction and equal. The transformer windings are operating in series then. During the commutational intervals γ_L and γ_C the currents i_C and i_{L1} are of the same direction, although they are not equal in size. Within these intervals the transformer windings are operating in series, but loaded unequally.

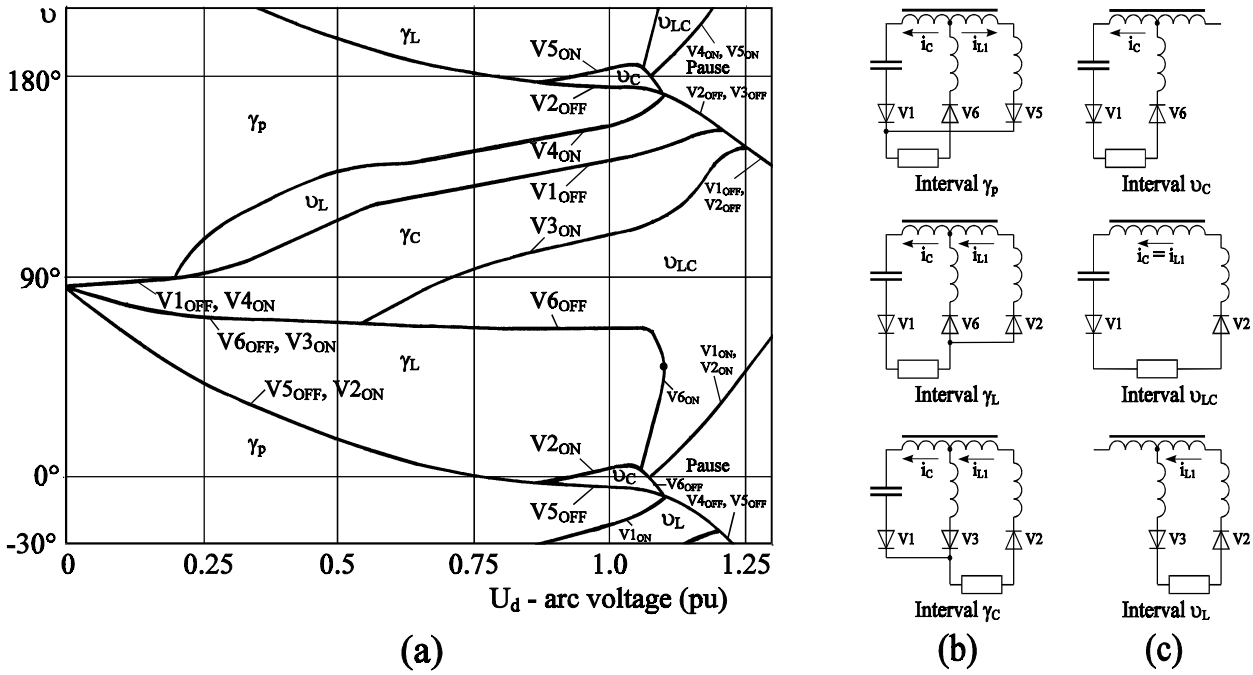

Fig. 3. Curves of turning on and off instants of the converter diode rectifier bridge of one phase according to relative output voltage (U_d) and current circuits corresponding to three different commutational intervals (b) and to three intervals between commutations (c)

Based on the diagram on Fig. 3, it could be said that during the intervals υ_L, γ_p, and υ_C the transformer windings are operating in parallel and during the intervals γ_L, υ_{LC}, and γ_C these windings are operating in series. "Switching-over" from series operation to parallel takes place each half-cycle. When the durability of parallel operation increases, the average transformation ratio for one half-cycle also increases. Such phenomena of smooth variation of the transformer ratio is unusual and original.

C. Self-adjustment to load

Switching-over of the reactive elements from series connection to parallel and vice versa occurs together with switching-over of transformer windings. The parallel oscillatory circuit is current restricting during short-circuit. For the supply network its impedance is high and low current is drawn from the network. Thereby the current in the oscillatory circuit is much higher and this higher current is rectified. On the contrary to previous, impedance of the series oscillatory circuit is very low. The current drawn from network is in this case determined by load (arc) impedance. The circuit operates then as ordinary rectifier. When arc voltage changes, the ratio between parallel connection and series connection changes as well. The converter operating mode is self-adjusting to arc voltage. The range of self-adjustment is from no-load to

short-circuit. The converter characteristics are opposite at the ends of this range.

In addition to short circuit current restriction the self-adjustment to load is useful in case of loads, that require more current when voltage is decreased below nominal voltage. The transformer windings of the LAR-converter will operate in parallel during a part of half-cycle of network voltage in case of decreased load voltages. Therefore, the output current of the converter increases, but the current in the transformer windings does not increase. The transformer windings need not to be designed for maximum load current as in traditional rectifiers and the installed capacity of the transformer will be less.

D. Partial thyristor control

Current control by replacing diodes V2 and V5 (Fig. 1) by thyristors is possible only partly, because the diodes V1,

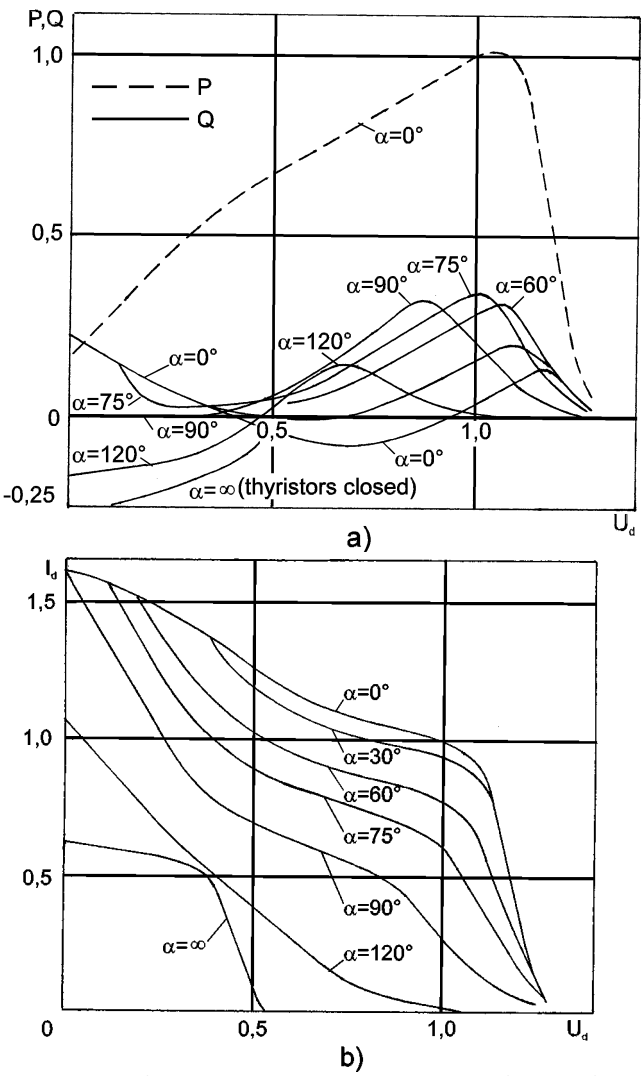

Fig. 4. Variation of the ESTA power supply parameters as a function of the arc voltage U_d in case of different thyristor firing angles α; (a) - active power P and reactive power Q; (b) - rectified current I_d

V3, V4, V6 do not change the rectified voltage. If the arc voltage U_d is more than half of the nominal voltage U_{dn} ($U_d > 0.5U_{dn}$), the current may be controlled freely without restrictions (see Fig. 4b). In case of lower arc voltages ($0<U_d<0.5U_{dn}$) it is only possible to reduce the current up to half nominal.

The reactive power Q (see fig. 4a) increases when controlling. The reactive power is maximal, when in case of nominal arc voltage the firing angle α=75° is used. But the maximal value of Q is considerably less than in usual thyristor rectifier, where maximal reactive power exceeds active power.

E. Suppression of higher harmonics in the converter

Reactive elements C and L1 form series oscillatory circuit that is tuned to approximately network frequency. During

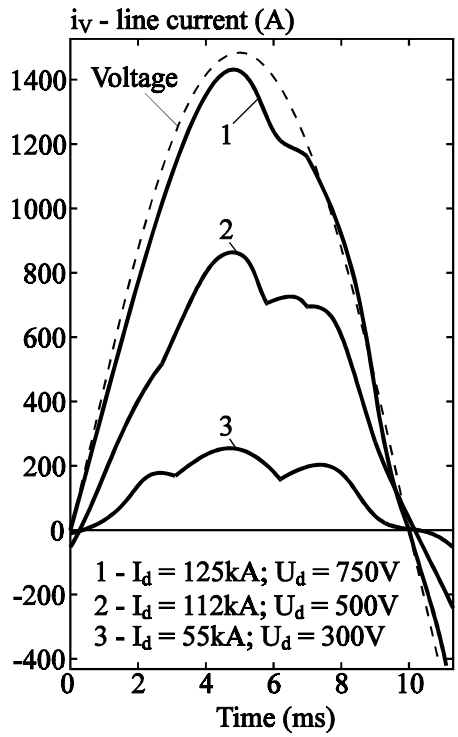

Fig. 5. Line current waveforms at nominal mode (curve 1) and at controlling the arc furnace current I_d and voltage U_d (curves 2 and 3)

interval υ_{LC}, oscillatory circuit L1, C is switched in series with rectifier bridge. This oscillatory circuit is a filter for higher harmonics. Due to long commutational angles (if $U_d<1.0$, then $\gamma_p=18°$, $\gamma_C=26°$ and $\gamma_L=63°$), the speed of current variations is also low. This also decreases the amount of higher harmonics in the network. Maximal values of higher harmonics in the line current compared to rated current are approximately the following: 5-th harmonic - 7 %, 7-th harmonic - 4 %, 11-th harmonic - 1.5%. Line current waveforms for a rated power supply 94MW with partial thyristor control are shown on Fig. 5 (computer simulation).

F. Variability of converter characteristics and parameter distribution factors:

One phase of the converter transformer includes two secondary windings (W2 and W3 on Fig. 1). Voltages of these windings can be chosen as equal or different. This choice is characterized by the ratio of no-load voltages

$$K_E = \frac{U_{WC0}}{U_{WL0}}, \qquad (1)$$

where

U_{WC0} - no-load voltage of the capacitive branch supply winding;

U_{WL0} - no-load voltage of the inductive branch supply winding.

Factor K_E could be named the converter voltage distribution factor.

One phase of the converter includes two inductors (L1 and L2 on Fig. 1). The ratio between additional inductor (L2) and main inductor(L1) inductive reactances

$$K_L = \frac{x_{L2}}{x_{L1}} \qquad (2)$$

could be named the inductance distribution factor, where

x_{L2} - inductive reactance of additional inductor;

x_{L1} - inductive reactance of main inductor.

The reactive load in the transformer secondary windings can, in the short-circuit mode, compensate mutually either totally or partly. This is characterized by the ratio between reactive powers of the transformer secondary windings:

$$K_Q = \frac{Q_{LK}}{Q_{CK}}, \qquad (3)$$

where

K_Q - reactive power distribution factor for the short-circuit mode;;

Q_{LK} - reactive power of the inductive branch in case of short-circuit;

Q_{CK} - reactive power of the capacitive branch in case of short-circuit.

Values of distribution factors K_E, K_L and K_Q are chosen. This choice affects converter characteristics. The characteristics of the SPA resonant converter are determined if its circuit and distribution factor values are given.

Converters with the same circuit and distribution factors can have different nominal voltages and currents, but they have the same power factor, the shape of output characteristic, the same amount of current higher harmonics, etc. For different consumers it is possible to use versions of SPA converters with different distribution factors.

III. PRACTICAL RESULTS

Two of arc furnaces with line frequency resonant converters power sources are erected at moment and both are in operation in Chelyabinsk, Russia.

TABLE 1
MAIN PARAMETERS OF POWER SOURCES ***ESTA***

	ESTA-1/190	ESTA-8.5/450	ESTA-94/750-T2
Rated power, MV·A	1.0	9.2	98
Arc nominal voltage, V	190	446	750
Arc nominal current, kA	4.8	19	125
Short-circuit current, kA	8.6	32	125
Nominal power factor	0.99	0.995	0.99
Mains current THD innominal conditions, %	8	6	6
Minimal permissible supply network short-circuit power, MV·A	20	120	2000
Installation power of capacitorbanks, MV·A	0.70	6.9	84
Total installation power of AC reactors, MV·A	0.54	5.7	62
Method of current stabilizing and control	paramet-rical + tap changer	paramet-rical + tap changer	paramet-rical + with thyristors

Power source ESTA-1/190 has been used for previously AC-supplied furnace modifying. Former furnace transformer and stepwise voltage regulator are still in use. The whole converter was placed in the existing transformer substation. The furnace is used for ferro-alloys manufacturing since 1987.

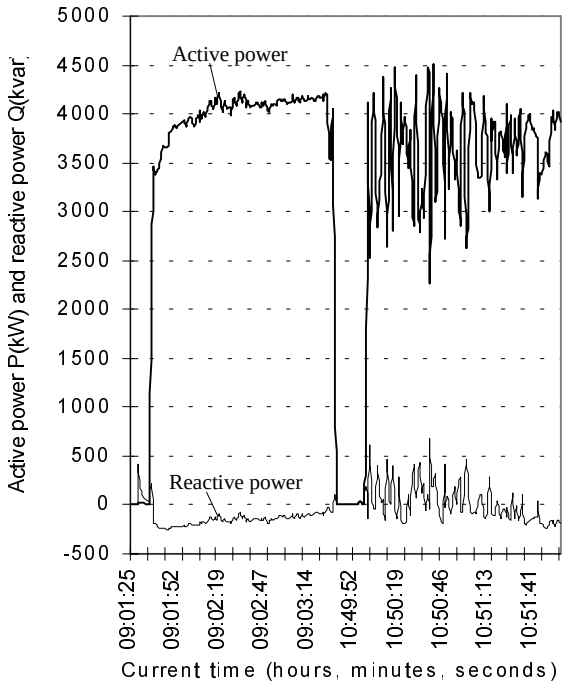

Fig. 6. Active and reactive power of power source ESTA - 8,5/450 in operation

The ESTA-8.5/450 power source was built to replace steel melting arc-furnace DC thyristor power source. The former furnace transformer and its voltage tap-changer have also been used, but transformer secondary windings are re-applied. The scheme without thyristors is used.

The main parameters of power sources ESTA-1/190 and ESTA-8.5/450 are shown in Table 1. In the same table one can also find parameters of ESTA-94/750-T2, which has been designed but not built up yet.

The main aim in designing the ESTA power source was to minimize the negative influence applied to supply network (voltage fluctuations, harmonics of high order). The results obtained are in accordance with previous theoretical research.

For example on Fig. 6 recorded changes of active and reactive power of the power supply ESTA-8,5/450 operating in two different modes are shown. The first mode shows the start of melting (first two minutes) the scrap. Comparing to traditional power supplies fluctuations of active and reactive power are very small and the amount of reactive power is also very small. The second mode shows the part of melting when oxygen is added. This causes "boiling" of the melted metal. Boiling parts of metal cause multiple short circuits between the electrode and melted metal.

Therefore fluctuations of active power are quite high. Simultaneous fluctuations of reactive power are much less (about 20% of the average value of active power). The recorded amount of reactive power fluctuations is in correlation with alterations of the reactive component of mains current (I_{VR}) shown on Fig. 2, as a result of computer simulations.

In addition to the main results some other positive results are reached. Furnace operation noise is lower than with thyristor source. Before modifying there was not enough of supply power. And now there is a surplus of supplied power. By making use of the effect of reactive power compensation and load self-adapting the DC power increased by 44 %. The point that transformer has not been changed, shows that it is now used more efficiently.

IV. REFERENCES

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