Investigation of Possibilities to Compensate Reactive Power and Shape of Consumed Current at Operation of Electrical Arc Furnace

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***Abstract*–Electrical arc furnace operation and problems arising are discussed. Propositions on compensation system for reactive power and shape of current at unsymmetrical current consumed are explained. Analysis of transistor based system harmonic influence is provided.**

I. INTRODUCTION

Operation of electrical arc large scale furnace arises some problems disadvantageous for electric supply system: because of pseudo-probable character of load (existence of electric arc) consumed an active and reactive power is changing in large range and on pseudo-probable law. That in its turn arise variations as shape as also magnitude of network voltage and it can imply on other consumers connected to the network. Cut to the bone consumed reactive power decreases capacity of network link because of voltage drop in conductors and it's impossible obtain full power of furnace that is crucial for efficiency of operation. For improvement it's necessary introduce compensators of reactive power and it is subject of this scientific paper.

II. CHARACTERISTICS OF ELECTRIC EQUIPMENT AND ITS OPERATION REGIMES OF ELECTRICAL ARC FURNACE

Simplified supply scheme of electric arc furnace is presented in Fig. 1.

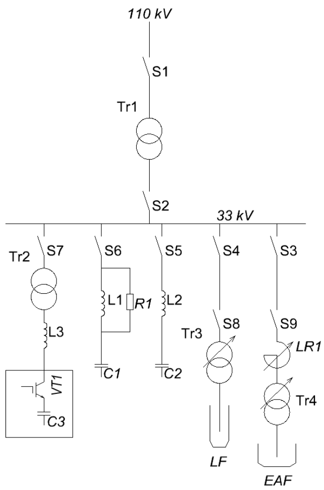


Fig. 1. Single-line scheme of the electrical utility.

Supply is provided from industrial network of 110 кV with frequency 50 Hz. Through switch S1 voltage is connected to network transformer Tr1 with power 120 MVA, which reduce voltage to 33 кV, and through switch S2 it is connected to electrical equipment supply grid.

The utility comprises furnace's transformer Tr4 of 100 MVA, transformer Tr3 of system ladle-furnace with power 16 MVA, two harmonic filters - H71 L2-C2 and H3 L1-R1-C1 (each of 25 MVA at 50 Hz) – and dynamic compensator L3-VT1-C3, connected to the substation's grid through transformer Tr2 of 64 MVA. As switches for connection to the bus bar 33 кV an ele-gas and vacuum ones are applied. Furnace's transformer Tr4 is connected to the bus bar through series reactor LR1. As furnace transformers as also reactor have taps for voltage regulation under load.

Diagrams describing operation regimes of electric arc furnace is convenient calculate on base of substitution scheme presented in Fig. 2. In the scheme elements L1-R1 substitute series reactor, L4-R4, L5-R5 – the primary and secondary windings of furnace transformer, L3-R3 – impedance of magnetizing branch of transformer, L2-R2 – substitute the short grid (conductors from secondary of transformer to electrodes of furnace) and R_{arc} – resistance of electric arc.

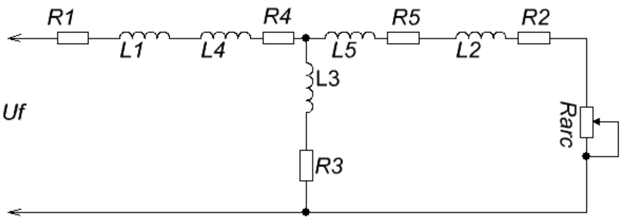
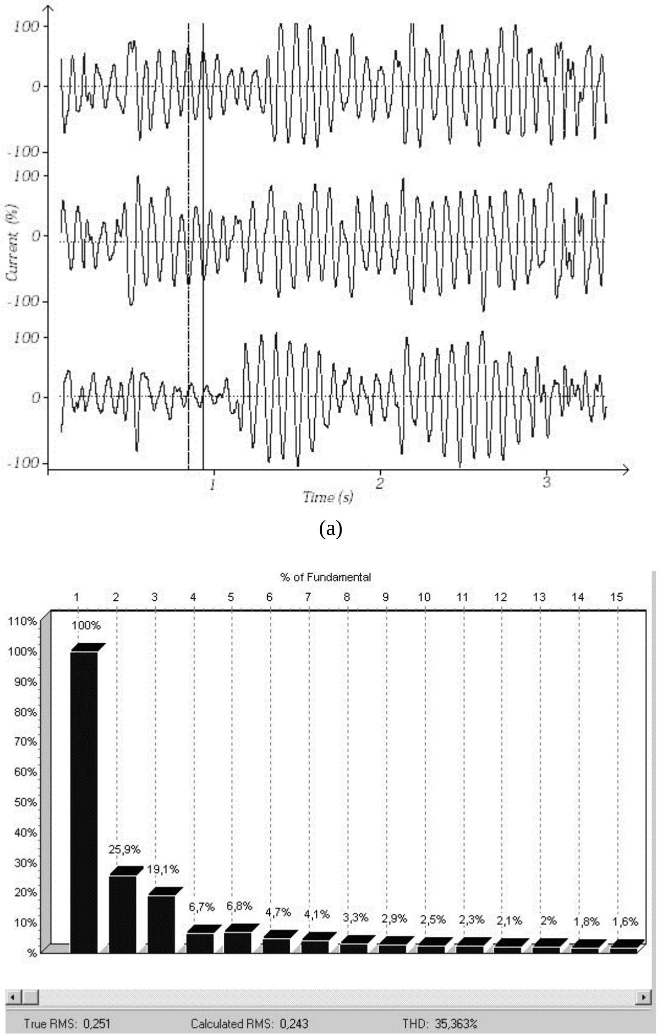


Fig. 2. Substitution scheme for one phase of electrical arc furnace.

Substitute parameters of reactor and transformer and at variation of resistance of arc it's possible obtain set of characteristic curves for each operation regime. At really operation in continuous to compare with melting cycle duration only one step of transformer is operating, i.e., regulation range is preset. Accurate adjusting of arc's power is realized by lifting and lowering of an electrode, i.e. adjusting of current; such adjusting can be presented as moving of operation point along applied curve. Taking it into account can be concluded that averaged meanings of the active and reactive powers are changing in duration of melting.

III. Typical Oscillograms of Electric Arc Furnace Operation

In Fig. 3.a. is presented oscillogram of current in circuit of furnace transformer at existence of arc on cool burden. As it can be seen really character of load is pseudo-probable; by the way can be noted that instantaneous meanings can change repeatedly stepwise in the cycle of supply voltage arising distortion of supply sinus shape voltage.



(a) (b)

Fig. 3. Oscillogram of current (a) and distribution table (b) of harmonics.

If harmonic distribution is examined (Fig. 3,b), then it can be seen that distribution corresponds to the one for rouse-colored noise. Really it's impossible take into account all factors influencing arc burning – as thermo-dynamic as also electro-magnetic ones. Therefore at modeling of processes it can be accepted that R_{arc} (Fig. 2) has variations in function of control signal of generator of rouse-colored signal. From view point of compensation of reactive power and correction of supply voltage shape the burning on the cool burden is most difficult case by speed and variations in term of cycle.

For example at ignition of arc in the very first instant takes place electrode touching of burden, i.e. short-circuiting and usually unsymmetrical under situation of different resistances of burden's metal under each electrode. This ignition process usually takes about 10 cycles of supply voltage as result of which electric arc arises and take place rising of electrodes. From view point of compensation at this process difficulties can arise only stepwise change of power in touching instant.

When arc is firing and burden is as liquid iron then arc is covered by slag and its thermal characteristics are stable. Similarly stable is also column of ionized gas in which electrical arc is operating. Therefore values of current are changing slow and in small range, THD factor is on 2%; level when shape of current is close to sinus one. This case in respect to compensation is simplest because time duration for current changes is in range of tenth cycles of supply voltage.

It can be accented that currents in phases are unsymmetrical (Fig. 3) and it have to be respected at organization of compensation system.

IV. Tasks Solved at Compensation of Reactive Power and Shape of Current

For proper understanding of compensation tasks have to be regarded cases as follows:

1) Fast distortions of shape of voltage and current as result of initial ignition of arc and at consequence fast changes of power in duration even of one cycle;
2) Slow distortions, changes of magnitudes of voltage and currents without changes in shape, i.e. so named as flickering:
   a – as result of slow changes of value of current in duration of some cycles (liquid phase of melting);
   b – by changing of operation point of arc power regulator;
   c – by switching of step taps either of transformer or reactor (changing of regulation range).

For compensation at slow changes (variants b, c) reactive power compensation device have to operate with small response speed and transient time can be more as half cycle of supply voltage, i.e. $T_d \geq 1\cdot 10^{-2}\,s$. When shape of current have to be improved to the sinus one (fast changes) a compensator have to operate as an active filter with response time much smaller as half cycle: $T_d \leq 1\cdot 10^{-2}\,s$.

As consequence time constant of device τ_{comp} have to be smaller as half cycle and components of the constant are as follows:

$$\tau_{comp} = \tau_m + \tau_{cs} + \tau_p\,, \qquad (1)$$

where τ_m - is time constant of measurement circuits;

τ_{cs} - time constant of control circuits;

τ_p - time constant of power part of compensator (switches, reactive elements).

Except of high response speed compensation device must operate in unsymmetrical current case.

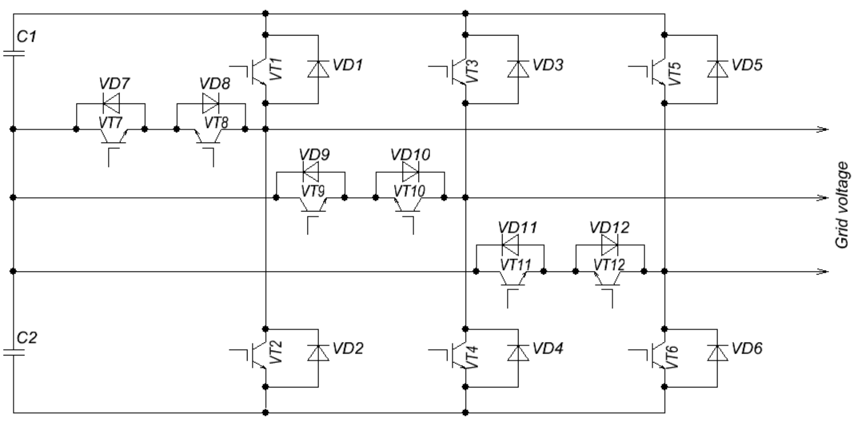


Fig. 4. Electrical scheme of dynamic compensator of reactive power.

V. Solutions Available on Compensation of Reactive Power

It's known solutions and time constants at power more than 1 Mvar as follows:

1. Synchronous compensators with time constant $\tau > 1 \cdot 10^{-1} s$;
2. Commutated by thyristors reactors in cooperation with capacitors – its time constant $\tau > 1 \cdot 10^{-2} s$;
3. Free commutated semiconductor converters with reactive load (mostly multilevel) with time constant $\tau > 1 \cdot 10^{-3}$.

The first solution have to be eliminate because of large time constant and excluded possibility operate on unsymmetrical load. Application of thyristor regulated reactors is expectable because of simplicity and cheapness of device only shape of input current is not sinusoidal and response time should be smaller. Free commutated semiconductor converters are one of most prospective solutions and they can operate on asymmetrical load. Wide applied are **Statcom** systems [1] one of which is applied in the discussed utility (see Fig. 4).

Converter is build-up on base of three-level scheme which allow decrease level of self-introduced distortions and therefore shape of the fundamental of output voltage is close to the sinus one (Fig. 5). Let's discuss operation at a positive half-cycle of line voltage U_{AC}. Converter is operating as follows: when $U_{AC} = 0$ all around it then transistors VT7, VT12 are turned-on and current is passing through circuit VT7-VD8-VT12-VD11. When voltage is in range $\left(0; \frac{1}{2} U_{AC}\right)$ transistors VT1, VT12 are working in PWM mode. Current is passing in contour VT1-VT12-VD11-C1. When voltage is in range $\left(\frac{1}{2} U_{AC}; U_{AC}\right)$ on base of PWM operate transistors VT1, VT6 and current passes through contour VT1-VT6-C2-C1. In such way a three levels of output voltage are formed. Charging of capacitors C1 and C2 takes place through diodes VD1-VD6 of rectifier bridge.

For analyze of compensator operation can be build-up substitution scheme presented in Fig. 6. There G1 and G2 – sources of grid and inverter voltages respectively; R1, R2 – line resistance; C1 – inverter load. Inverter operates synchronous with grid, i.e. its output voltage coincides in phase with grid's one.

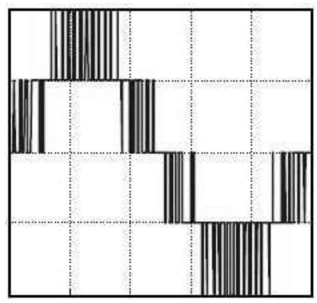


Fig. 5. Shape of voltage on output of three-level converter.

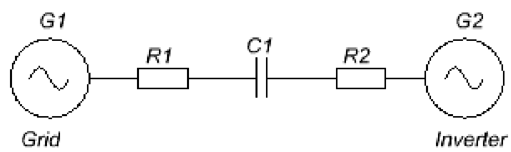


Fig. 6. Substitution scheme for compensator operation.

If instantaneous meanings of voltages of sources G1 and G2 coincide then current in circuit is zero. If instantaneous meanings don't coincide then current in half-cycle change its direction twice, i.e. current has reactive character. Character of current – leading or lagging depends on relation of inverter voltage meanings in respect to grid's. If take into account R1, R2, then rule in accordance with which current is changing can be written as:

$$\dot{I} = \frac{\dot{U}_{G1} - \dot{U}_{G2}}{X_{C1}}, \qquad (2)$$

where $\dot{I}$ - instantaneous meanings of current;

$\dot{U}_{G1}$ - instantaneous meanings of grid voltage;

$\dot{U}_{G2}$ - instantaneous meanings of converter output voltage;

X_{C1} - reactance of capacitor.

If to the source G1 (grid) a load generating or consuming reactive power is connected then measuring the later and changing instantaneous meanings of inverter voltage it's possible dynamically compensate reactive power keeping for utility $\cos\varphi = 1$. At certain high response speed of converter it should be possible operate converter as an active filter [3]. For that to the reference signal for compensation of reactive power can be added signal of harmonic distortions:

$$U_C = U_{C1} + \sum_{1}^{n} U_{Cn} , \qquad (3)$$

where U_C - control signal for commutation of switches of converter;

U_{C1} - sinus shape control signal for compensation of reactive power;

U_{Cn} - non-sinus signal for compensation of distorted shape of current including n - order harmonics.

VI. Disadvantages of Realized Compensation System of Reactive Power

The main disadvantage of existing described previous compensator of reactive power is introducing self-distortions in grid voltage at switching of semiconductors [2]. If provide analysis of shape of the voltage in Fig. 5 then it can be seen that number of switching is 25 per half-cycle, i.e. base frequency of switching is $2500Hz$. Harmonic analysis can be based on equation

$$U_{nm} = \sqrt{A_n^2 + B_n^2} , \qquad (4)$$

where U_{nm} - magnitude of the n-order harmonic;

A_n, B_n - n-order harmonic's components magnitude.

If diagram of voltage (Fig. 5) is shared as:

$\omega_{a0m} \div \omega_{anm}$ - angular speed of each harmonic with voltage U_a;

$\omega_{b0} \div \omega_{bn}$ - angular speed of harmonics with voltage $2 \cdot U_a$;

Then components can be calculated in accordance with (5), (6):

$$A_n = \sum_{0}^{m} \left(\begin{aligned} &\frac{1}{\pi} \int_{\omega_{a0m}}^{\omega_{anm}} U_a \sin(\omega t) \cdot \sin(n\omega t) d\omega t + \\ &\frac{1}{\pi} \int_{\omega_{b0m}}^{\omega_{bnm}} 2 \cdot U_a \sin(\omega t) \cdot \sin(n\omega t) d\omega t \end{aligned} \right), \qquad (5)$$

$$B_n = \sum_{0}^{m} \left(\begin{aligned} &\frac{1}{\pi} \int_{\omega_{a0m}}^{\omega_{anm}} U_a \sin(\omega t) \cdot \cos(n\omega t) d\omega t + \\ &\frac{1}{\pi} \int_{\omega_{b0m}}^{\omega_{bnm}} 2 \cdot U_a \sin(\omega t) \cdot \cos(n\omega t) d\omega t \end{aligned} \right). \qquad (6)$$

Calculating all components in range $n = [0;40]$, and taking into account that magnitude of supply phase voltage is $U_{mg} = 26940.7V$ it can be obtained that magnitude of total voltage distortions by (4) is $U_{nm} = 6438.9V$. Total harmonic distortion factor is:

$$THD = \frac{U_{nm}}{U_{mg}} \cdot 100\% = 23.9\% .$$

As consequence such level of harmonic distortions arise a stray currents in reactive elements of utility which in its turn arise extra heating and losses in conductors. For elimination of this phenomena can be used passive filters tuned on frequencies of harmonics with highest magnitudes. Such filters are bulky and generate reactive power of fundamental industrial frequency. The later reduce dynamic operation range of reactive power compensator. If necessary for compensation reactive power is Q_n, reactive power generate by passive filters is Q_f, then total power of reactive power compensator have to be:

$$Q_c = Q_n + Q_f . \qquad (7)$$

For scheme of converter discussed in range of n$\leq$ 40 harmonics with magnitude relation respective fundamental above 1% will be as follows:

TABLE I
Harmonics Content in Percents of Network Voltage

n	28	30	34	36	40
%U	3,05	3,78	7,91	7,86	3,74

It should be accepted 5 passive filters tuned on frequencies of the noted harmonics – such measure increase as costs as also size of utility in total.

Another drawback of the scheme Fig. 4 is hard operation regimes of semiconductor switches operating in the scheme on reconnections of capacitor circuits.

VII. Possibilities to Apply Commutated With Thyristors Reactors as Active Filters

Compensators in which thyristors commutate reactors (Fig. 7) have advantage of light operating regimes of switches because current through reactor L1 after turn-on of thyristor $i_L(+0)$ is same as before turn-on $i_L(-0)$. As disadvantage of the system can be regarded a relative large time constant $\tau > 1 \cdot 10^{-2}$.

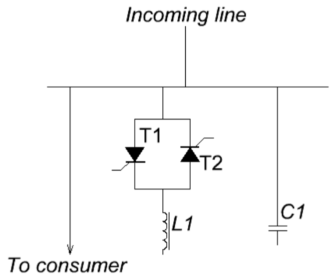


Fig. 7. Application of thyristor regulated reactors as compensators of reactive power.

As it was described previous for correction of shape of consumed current it's necessary to apply multiple switching of thyristor in half-cycle. In system with ordinary thyristors it's impossible because they can't interrupt current flow. Application of contemporary element base can solve this problem using as switches T1, T2 in Fig. 7 new device GCT (Gate Commutated Thyristor). In this case including in reactor circuit clamping GCT circuits it should be possible realize PWM control which will reduce as time constant as also allow operate in regime of an active filtration. For such operation case scheme can be presented as shown in Fig. 8.

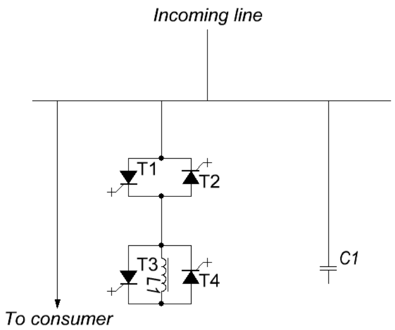


Fig. 8. Scheme of active filter and compensator of reactive power on base of GCT.

VIII. Conclusions

1. Compensation of reactive power and shape of consumed current have to be applied for providing as full power accessible as also optimal operation of arc furnace.
2. Existing solutions for compensation of reactive power have essential drawback – relative large percent of introduced harmonic distortions which can arise as overloading as also operation fault.
3. Semiconductor converters applied for switching of capacitors in compensation system have one extra drawback – hard switching pattern of transistor switches.
4. Fast operating and flexible reactive power compensation system can be achieved applying as switches Gate Commutated Thyristors in circuits of reactors in complex system capacitors-regulated reactors.

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