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Long lasting transients in power filter circuits

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The practice of operating AC electrical arc furnace power supply systems has shown that energizing unloaded furnace transformer can cause long lasting transients in filter circuits of static VAR compensators used in the supply systems. Examination of the supply system configuration impact on switching transient behaviour has been carried out by example of a 50 MVA arc furnace unit. The transient analysis has been carried out through simulating by Matlab/Simulink software.

KEYWORDS: inrush current, arc furnace transformer, harmonic filter, switching transient

1. Introduction

Increasing impact of nonlinear loads on power systems drives using harmonic filters as means to mitigation of the concern. High voltage harmonic filters have wide application in heavy and mining industry where power electronic and electric arcing devices essentially impact on the supply system. Nowadays arc furnaces are very essential in steel making companies for production of high-quality steel. According to this scenario the Alternating Current Electric Arc-Furnaces (AC-EAF) are being very important and disturbing loads on power systems.

AC arc furnaces are classified to complex loads with nonlinear and time varying load characteristic, which can cause many problems to the power system quality, including voltage dips, harmonic distortion, unbalances loads and flicker. The practice of operating AC electrical arc furnace in industrial power supply has shown, that equipment installed in the systems is affected overvoltages and overcurrents through normal operation arc furnace transformer switching. Changes of electricity consumption during melting process depends mainly on quality of the stock, accuracy of control circuits and thermal processes as well. Statistical data informed, that the number of transformer energization occurs 20 to 40 times a day [1, 2]. The typical steel making cycle process in electrical arc furnace include:

- arc ignition period (start of power supply),
- boring period,
- molten metal formation period,
- main melting period
- meltdown period,

– meltdown heating period.

Each of the cycle is characterized by the active power changes and the number of switching required, with a trend to decrease and stabilization of processes in the last cycles. The first period during metal formation is characterized by the highest power consumption and 60-80% of the total energy consumption within a technological cycle. In the following periods there are lower power fluctuation caused by arc stabilization.

In order to ensure electromagnetic compatibility of alternating current electric arc furnace with power supply systems, there are a lot of technical solutions. The most effective power quality improvement based on Static Var Compensator (SVS) installation [3,4]. The SVC operating units has shown that method of precisely time controlled switching thyristor-reactor series group has positive impact on compensation reactive power, voltage and current phase balancing and reduction of voltage fluctuations. In addition, harmonic filters as capacitive power source in SVC unit are used for reduce of voltage distortion in the supply network.

The purpose of this paper is to study the impacts of supply power system and SVC harmonic filters configurations on transient currents under energizing unloaded furnace transformer unit in a typical industrial power system. To analyze this phenomenon the Matlab/ Simulink Software [5] has been chosen because of there are known limitations in the filed testing with respect to the circuit condition and the number of times that the test can be carried out. The analysis has shown comparative transient performances.

2. Transformer inrush current

Medium power transformer for steel making processes are characterized by typical ratings: S_n = 15...55 MVA, $U_{z(\%)}$ = 3,1…8,2 %, $I_{o(\%)}$ = 1,08…1,3 %. The main difference between typical power transformer and arc furnace unit is the presence of large number of bars, which are located on the low side.

Arc furnace transformer energizing in the examined supply system occurs several times a day and is associated with a high magnitude of the inrush current. Initial magnitude of the medium power transformer inrush current could reach values of 7 to 10 times full-load current and will decay with time until a normal exciting current value is reached. Energization inrush currents occur, when a system voltage is applied to a transformer at a specific time, when the normal steady-state flux should be at different value from that existing in the transformer core. For the worst case energization, the flux in the core may reach even a maximum of over twice the normal flux $\Phi_o = (2,0…2,3)\Phi_m$. For the flux values the transformer core will be driven into deep saturation, causing very high magnitude of inrush current [6]. The magnitude of inrush transformer current depends on such factors as supply voltage magnitude at time of energizing, source impedance, residual flux in the core and transformer size and its design as well [7]. Example waveforms of phase inrush currents under energizing 50 MVA arc transformer taken on field measurements is shown in Figure 1.

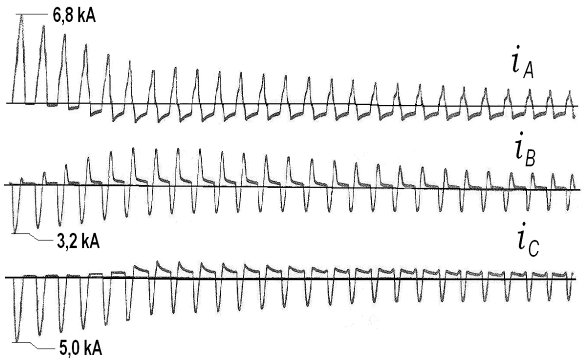


Fig. 1. Transformer energization currents

The inrush current waveform associated with transformer energization state includes both even and odd harmonics, which decay with full time until the transformer magnetizing current reaches steady state. The most predominant harmonics, during transformer energization are second, third, fourth and fifth in descending order of magnitude. Figure 2 shows Fourier analysis which was carried out for the examined arc furnace unit (for current of phase A).

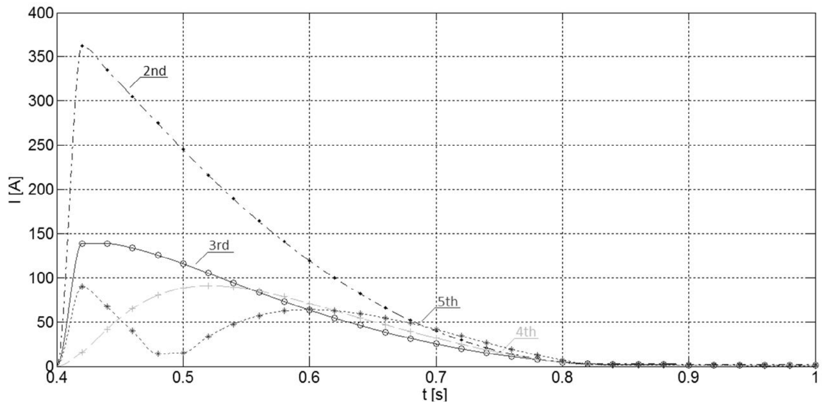
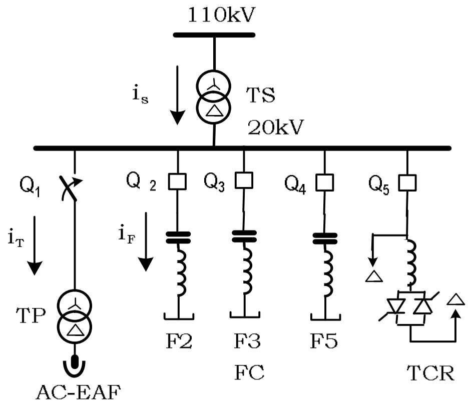


Fig. 2. Harmonic currents during 50MVA arc transformer energization

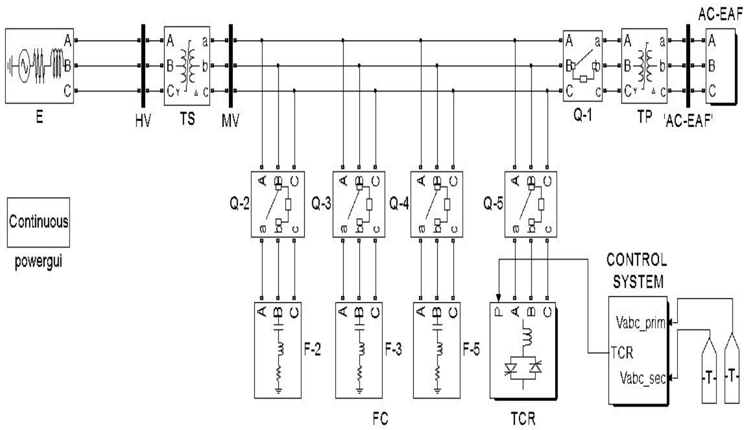
When arc furnace transformer is energized from bus including power filters or capacitor banks, the inrush current can excite resonant magnification of the current harmonics in the supply system. This phenomenon produces overvoltages and overcurrents on capacitors and reactors of the compensating circuits, that can lead to the equipment damage [8].

3. Modeling AC-EAF power supply system

Under modelling high power AC-EAF electrical power supply system should be taken into account the following factors: short circuit power at the point of connecting furnace or group of them, their number and type, rated power of furnace transformer, impedance frequency characteristics of the supply system as well as characteristics of units using to improve the electromagnetic compatibility of AC-EAF on industrial power supply system [1,2]. Topology of industrial system supplying point of furnace transformer connection depends on: steel plant production structure, number and power of arc furnaces which are supplied. The supply system internal connection, during furnace transformer switching-on has impact on magnitude and behaviour of filter transient currents. This paper examines a case study of an electric arc furnace (EAF) supply system shown in Figure 3a.



a



b

Fig. 3. Topology of AC-EAF industrial power supply system with SVC unit:
a - single phase diagram of the supply system, b - SIMULINK – model of the simulated system

The examined industrial power supply system involves HV 110kV bus supplying MV 20 kV bus by means of step down wye-delta connected power transformer TS, with the primary neutral solidly grounded. 50 MVA arc furnace transformer TP of Yd1 windings connecting is supplied by 20 kV bus.

The SVC unit is connected to the same bus from where AC-EAF is supplied, and it is used in parallel to AC-EAF to provide fast reactive power and voltage regulation support.

SVC design on installation in an AC electric arc furnace system consists of Thyristor Controlled Reactor (TCR) in parallel with Harmonic Filter Circuit (FC). A TCR consists of thyristor veristack made of anti-parallel and series connected thyristors with snubber circuit. The snubber circuit is used for overvoltage protection of thyristors and to supply auxiliary power to thyristor electronic card.

A 3-phase, 6-pulse TCR comprises three single-phase TCR's connected in delta. The inductor in each phase is split into two halves, one on each side of the anti-parallel–connected thyristor pair, to prevent the full ac voltage appearing across the thyristor valves and damaging them if a short-circuit fault occurs across the reactor's two end terminals. The current in the reactor is phase-controlled by varying the firing angle of the thyristor valve. In this way, the reactive power output is continuously variable over a range equivalent on the rating power of the reactor. At maximum var absorption, the TCR is in full conduction ant the var output is the sum of the TCR and filters reactive power. At maximum var injection, the TCR is off and the var output is determined by the filters. So, SVC behaves like shunt connected variable impedance, which either generates or absorbs reactive power in order to regulate voltage level at the point of common coupling.

The arc furnace unit and compensation units TCR and FC are connected to 20 kV bus through the appropriate breakers. The individual filters are sized to supply 5, 22 and 15 Mvar for 2^{nd}, 3^{rd} and 5^{th} harmonic filters respectively.

FC consists of three AC harmonic filters, which are presented in calculations by three parameters: a capacitance, an inductance and a resistance. Single tuned filters cause a low impedance at the tuned frequencies and reduce harmonic content in the AC industrial network to acceptable limits.

Reactive power of FC unit is the sum of the reactive power for each harmonic filter: $Q_{F2} + Q_{F3} + Q_{F5} = Q_{FC}$. Moreover, the parameters of individual harmonic filters strictly depends on the arc furnace and TCR harmonic levels. In this case as well should be taken into account filter capacitance and inductance variations as an effect of environment conditions and manufacturing tolerances. For most capacitor banks, capacitance value variation due to environmental conditions are within ±2% and manufacturing tolerances – within (-5%...+10)%. Consequently, the possible shifts of the filters capacitance are in the range of (-7%...+12)%. In case of reactor inductance the manufacturing tolerances is assumed within ±3%. So, the possible range of variation of the resonance point h_r is in the range of

$0.93h \leq h_r \leq 1.05h$. In practice it is assumed, that a filter resonance point h_r should be chosen by 2…10% below the accurate resonant frequency h of the filter. That leads to shift of the impedance frequency characteristic resonant points to lower values. Operation of industrial filter circuits tuned over an ideal resonant frequency has shown that filters of FC cause resonance magnification for the other harmonic currents. In the Table 1 are shown the FC harmonic filters parameters in consideration of their variations.

Table 1. Parameters of the Filter Circuit

Filter	Tuning	Capacitance, μF	Inductance, mH	Resistance, Ω	I_{nom} , A
F2	1.86	28.30	103.59	0.27	144.34
F3	2.79	152.01	8.57	0.07	632.49
F5	4.65	113.90	4.12	0.04	433.01

The TCR unit with fast acting regulator ensures the SVC capability to change its reactive power output following the plant reactive load closely. Depending on the system topology, the arc furnace transformer can be supplied from power unit in a range of 80 to 160 MVA.

SIMULINK model of electric arc furnace consists of power transformer TS, supplied from three phase AC voltage source E. AC-EAF is connected to the secondary winding of arc furnace transformer, which is connected through air blast circuit breaker Q1 to the medium voltage bus as well as the harmonic filters through circuit breakers Q2, Q3, Q4. During energizing unloaded TP, the TCR is running and provide the properly balance of reactive power on medium voltage bus. The simulation model of the supply system and SVC is shown in Figure 3b.

4. Result of simulations

A. Inrush currents of the arc furnace transformer

Magnitude and behaviour of inrush current depend on short circuit power at the bus supplying arc furnace transformer. The short circuit power is mainly influenced the system power transformer unit TS (see fig.3). Simulations have been carried out for worst-case conditions, where residual flux in *A,B,C* cores of the arc transformer was taken as $0{,}6\Psi_{nom}$;0; $-0{,}6\Psi_{nom}$ respectively and instant of switching provided highest magnitude of the inrush current. The experimental results are shown in Table 2. It presents the highest magnitudes of the furnace transformer inrush currents, energized from different power system transformers.

As it can be observed from the Table 2 with lower inductance of industrial network (higher system transformer rating) higher peak will take place.

Table 2. Highest magnitudes of arc furnace transformer inrush currents

Rating of system transformer TS, MVA	80	160
Peak of inrush current, kA	5,78	6,82

B. Harmonic filter configuration impacts the transient

In order to verify the impact of the examined filter circuit configurations on transients during arc furnace transformer switching, tuning precision and connection filters in FC circuit under simulation have been considered. The simulation has been carried for connections of designed filter installation shown in Table 3.

Table 3. Topologies of the filter circuit

FC topology	FC configuration
FC I	Single harmonic filter – F2 or F3 or F5
FC II	All harmonic filters – F2+F3+F5

Figure 4 shows an example of transient currents under energizing arc furnace transformer from 80 MVA system transformer.

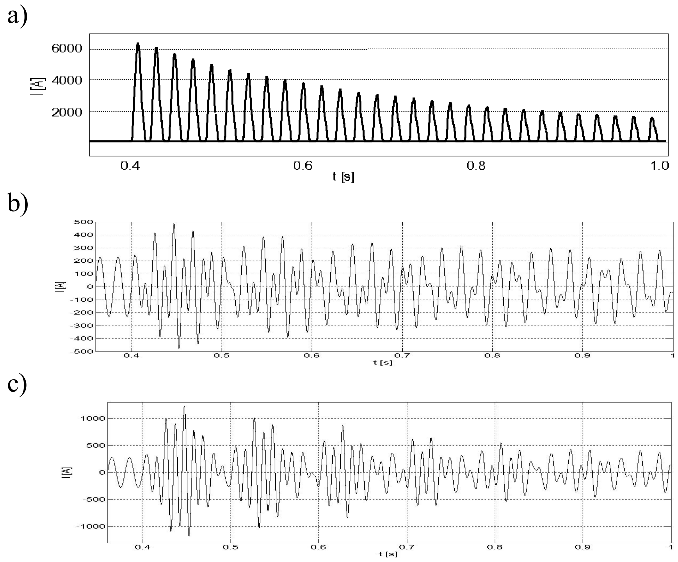


Fig. 4. Transient currents in: a - furnace transformer, b - 2nd harmonic filter for FC I topology, c - 2nd harmonic filter for FC II topology

It can be seen from the oscillograms, that significant difference are observed between the transient characters in the presented cases. Switching-on furnace transformer in the cause of FC II topology causes higher magnitudes of current oscillation and longer duration of transient state in 2nd harmonic filter, than in the case of single 2nd harmonic filter. The transient currents in 3rd and 5th filters less depend on the configurations of the FC and on the rating of system transformer TS. Connecting all harmonic filters in the FC topology increases the quality factor of resonant circuit and reduces transient damping. It influences on the character of transient harmonic oscillations in filter circuits. Magnitudes of the filters transient currents in the examined supply system are shown in Table 4.

Table 4. Peak transient currents in filter circuits

Rating of TS, MVA		80		160	
Filter Circuit		I	II	I	II
F2 peak current:	kA	0.49	1.22	0.48	1.05
	p.u. (*)	2.41	5.99	2.36	5.15
F3 peak current	kA	2.11	2.13	1.80	2.16
	p.u.(*)	2.37	2.38	2.02	2.42
F5 peak current	kA	1.95	1.97	1.44	1.89
	p.u. (*)	3.19	3.22	2.35	3.09

*) base value - rated filter current

C. Harmonic filter tuning impacts the transients

The character of transient in filter circuit under transformer energizing is significantly depended on the filter tuning. The furnace transformer inrush current is not depended on FC configuration, but the filter tuning changes the input impedance frequency scan and thus impacts the behaviour of the individual harmonics in the filter circuits. Figure 5 shows behaviour of transient currents under energizing arc furnace transformer from 80 MVA system transformer, when single 2nd harmonic filter is connected to bus. In the case of deviation of the 2nd harmonic filter tuning point to the precise frequency of second harmonic, the resonant conditions provoke increasing value and changing transient character of the second harmonic in the filter circuit. It can be observed from current oscillograms in Fiqures 5b and 5c obtained through simulating, the same arc transformer switching-on conditions when different tuning precise the 2nd harmonic filter.

Similar change of transient currents along with tuning precise shift has been observed in the 5nd harmonic filter circuit. An opposite behaviour has been recorded for the 3nd harmonic filter in the examined supply system. Comparative peaks of the filters transient currents are presented in Table 5.

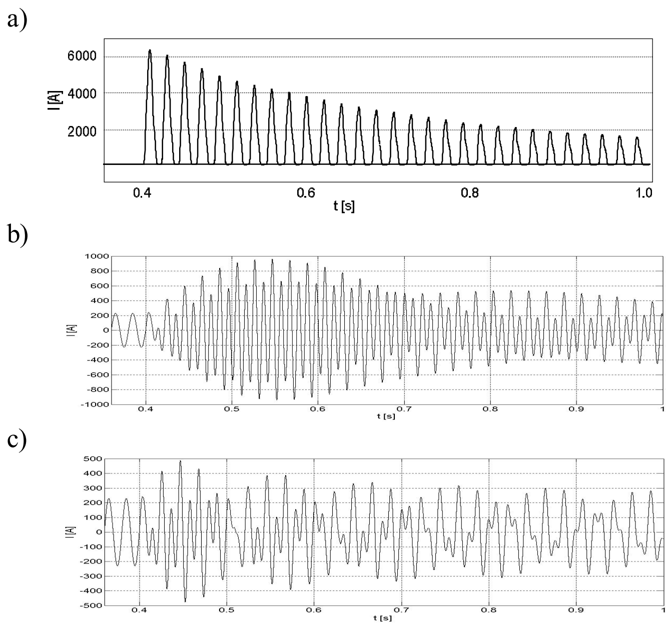


Fig. 5. Transient currents in: a - furnace transformer, b - 2nd harmonic filter tuning to h_r =2.0, c -2nd harmonic filter tuning to h_r =1.86

Table 5. Peak transient currents in filter circuits

Filter	Tuning point, h_r	Current peak	
		kA	p.u.
F2	1.86	0.49	2.14
	2.00	0.96	4.20
F3	2.79	2.11	1.92
	3.00	1.70	1.56
F5	4.65	1.95	2.75
	5.00	2.74	3.74

Simulation results have shown that the transient behaviour is considerably depended on the tuning precise of the filters in compensation device circuits.

5. Conclusions

This paper presents analysis of long lasting transients in filter circuits caused by arc furnace inrush currents in a typical industrial system. Set of comparative simulations has shown, that the transient behaviour is related to frequency scan of the system impedance including filter circuits parameters. This manifested in dependency of the amplitudes and durations of filter transients currents mainly on the three influencing factors: system transformer rating, configuration of the used filter circuit and tuning precise of its individual filters.

Since filter circuit design should take into consideration criteria of steady state and transient duties, individual analysis for every project should be carried out, because impact of transformer inrush current on filter circuit transient currents may vary from one project to another.

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