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Transients impact on power filter circuit sizing

Jurij Warecki, Michał Gajdzica
AGH University of Science and Technology
30-059 Kraków, Al. Mickiewicza 30, e-mail: Michal.Gajdzica@wp.pl

The practice of operating multiple single-tuned filters in AC electrical arc furnace power supply systems has shown, that frequent energizing unloaded furnace transformer can cause damage of the filters. To examination of supply and filter system configuration impact on switching transient and dynamic overvoltages and overcurrents, an example of 50 MVA arc furnace unit was chosen. The transient analysis has been carried out by simulating within Matlab/Simulink Software. Using ANSI/IEEE Standards paper focuses on the selections of ratings for capacitors and air-core reactors used in multiple single-tuned harmonic filters configurations. Comparison of filter reactor and capacitor bank design based on steady state operation and transformer energizing was shown.

KEYWORDS: capacitor, reactor, harmonic filter, transient and dynamic overvoltage, transient and dynamic overcurrent, equipment ratings

1. Introduction

The application involving multiple single-tuned high voltage filter circuits in supply systems has increased rapidly over the past decade. This trend is associated with increasing of use of power electronic switching devices in transmission and industrial power systems and electric arcing devices in industrial installations. Utilities which are supplied by these systems have become more sensitive about harmonics generated by these loads. Consequently, this cause an increase the complex filer design with multiple filter circuit tuned at different frequencies in order to achieve adequate harmonic distortion level, that will meet to standard such as those in ANSI/IEEE Standards [8, 9].

Nowadays a lot of filter banks are design mainly to limit the harmonic distortion to a specified level and deliver the proper reactive power output. The component ratings are often specified based solely on steady state operation and on fundamental and harmonic voltages and currents. In that case, under sizing filter circuit involving single-tuned units, effects of environment conditions and manufacturing tolerances are taken into account as well. 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 [1]. Although this may be applicable and is verify in a single-branch applications. The discussed method is not properly and adequate for components installed in multiple and complex filter circuits. At these applications may occur insulation failures during switching operations. Those failures apply to the capacitors and reactors on the same banks. Unfortunately, similar circumstances and switching transients occurred on all switching operations [6].

The filters failure caused by switching transients are observed often in power supply systems, where are installed Alternative Current Electric Arc Furnaces. The practice of operating AC-EAF has shown that energizing unloaded furnace transformer could cause long lasting transients in filter circuits of static VAR compensators used in the supply systems [4, 5]. Equipment installed in the systems is affected overvoltages and overcurrents through normal operation arc furnace transformer switching. If this phenomenon occurs 25 to 50 times a day, the filter capacitors and reactors may not be able to withstand these overvolatges for an extended period of time. This could reduce capacitor and reactor life time and lead to eventual failures. It has been noted in [7], that duration of the transients and the numbers of occurrences are important factors significantly influence the design of the filter circuits.

The purpose of this paper is to propose a method for designing filters and selecting ratings on capacitor and reactor units in installations involving multiple single-tuned filters. A proposed method for the equipment ratings based on existing IEEE Standards, and data for the selection of ratings for capacitor and air-core reactors used in arc-furnace installations are results of digital transient simulations studies. The switching surge was simulated in a typical medium size industrial power system with several single-tuned harmonic filters. To analyze this phenomenon, the Matlab/ Simulink Software [10] 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.

2. Modeling AC-EAF multiple filter banks

The examined power supply system is shown in Figure 1. The installations involves 110 kV HV bus, which supply 20 kV MV industrial bus with a moderately strong source, by means of step down wye-delta connected transformer TS with rated power from 80 to 160 MVA, with the primary neutral solidly grounded. Arc furnace transformer TP of 50 MVA is connected to the 20 kV bus. The multiple Filter Circuits (FC) based on three single-tuned filters which similarly as Thyristor Controlled Reactor unit (TCR) are also connected to the MV bus through the appropriate air blast circuit breakers: Q2, Q3 and Q4. The individual filters are tuned to the: 2^{nd}, 3^{rd} and 5^{th} harmonics and provide a total capacitive reactive power to the bus of 42 MVAR. A TCR consists of thyristor veristack made of anti-parallel and series connected thyristors with snubber circuits. The snubber circuit is used for overvoltage protection of thyristors and to supply auxiliary power to thyristor electronic card.

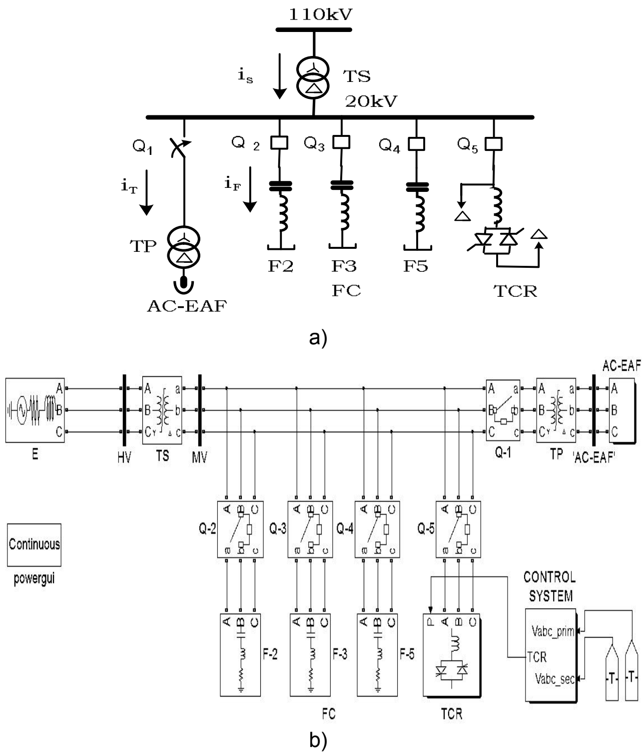

Fig. 1. Topology of AC-EAF industrial power supply system with SVC unit:
a) single phase diagram of the supply system, b) SIMULINK - model of the simulated system

The SVC unit is connected to the same bus from where AC-EAF is supplied, and it is used in parallel to provide fast reactive power and voltage regulation support. During energizing unloaded TP, the TCR is running and provide the properly balance of reactive power on medium voltage bus.

The FC unit consists of single-tuned filters tuned to supply: 1.86, 2.79 and 4.65 MVAR for the second, third and fifth harmonic filters respectively. 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
F-2	1,86	28,30	103,59	0,27	144
F-3	2,79	152,01	8,57	0,07	632
F-5	4,65	113,90	4,12	0,04	433

The harmonic current spectrum on which the filter design was based is shown in Table 2. An arc furnace application with thyristor controlled reactor may produce this type of harmonic currents.

Table 2. Harmonic current generation at the 20 kV bus

Harmonic number	I_h [A]
2,0	105
3,0	460
5,0	315

3. Transient and dynamic phenomena in multiple filter branches

At industrial applications, which configurations and electric parameters and utilities required multiple filter circuits, some of the types of switching events cause transient and dynamic overvolatages and overcurrents in industrial filter units. The special case of transient is energizing of transformers connected to the industrial power supply systems. During transformer energization, the magnitude of inrush current is high and the harmonic content could excite resonances, which extends the duration of transients [2]. This event is a result of voltages across the individual components of the filter that exceed the voltage at the bus. Hence with a number of arc transformer energizations between 20 to 40 times a day [3], that switching event cause the serious risk for filter circuits installed in industrial power systems. For these factors belongs as well: the main point of connections to supply grid and the bus short circuit determined by the apparent power of installed transformer. Generally, the high rated power of supplying transformer has an influence for the high magnitude of transient currents and increased their duration in filter circuits.

The inductance of filter is a large portion of the total circuit inductance. The X/R ratio for the dry-type air-core filter is typically in a range between 100 to 150 and for the power system is in range of 5 to 30. Therefore transient current, which oscillate between the lightly damped filters (X/R > 100) could be much higher than expected, and the overall damping of the power industrial system is mainly reduced from that of a capacitor banks circuit. So the typical overvoltage protection such as surge arresters installed at the medium voltage bus, may be inadequate unless the individual filter components are specially rated to handle the extra stress. That result is as well increased by duration of the transient and between events and the repetitive frequency of the occurrence.

Reference [1, 2, 3] describes, that harmonic filter tuning frequency and FC configuration have an influence for switching transients. In application involving multiple single-tuned filters are observed a different character of transient and the values of current and voltages peaks.

4. Result of simulations

The main purpose of simulation is determine the peaks of transient overcurrent and overvoltages in filter circuits which are operated in a different FC configuration and power supply systems. In analysis there are examined the influence of: configuration of single-tuned filters, short circuit of power supply systems and harmonic filter tuning frequency for variations of voltages and current in FC.

In the examined arc supply system there are different topologies of the TCR-FC circuit. In order to verify the impact of the examined filter circuit configurations and the harmonic filter tuning frequency on transients magnitude of voltages and currents each of single-branch of FC circuits, during arc furnace transformer switching the simulations has been considered. The studies have been carried out 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 2 shows an example of transient currents and voltages for the most loaded phase in 2nd harmonic filter, under arc furnace transformer energizing through 80 MVA power transformer in system. The results are shown for two different FC configurations.

As one can see, the transformer energization excites the system causing high voltage and current distortion in the filter circuit at second harmonic. The effect of that phenomenon has increased and the duration of transient is longer during all filter switching in FC circuits. That case which results in very high magnitude and damping transients causes more resonance sensitivity of circuit on the 2nd harmonic frequency. The nature of switching transients are the affects of filter current variation, but the ratio between the capacitor and reactor voltage strictly depends on the value and relative tuning frequency of the filter in the experiment. Hence the conclusions, the higher frequencies of transient currents generate higher magnitude of dynamic overvoltages across the isolation of filter reactors than on capacitor banks.

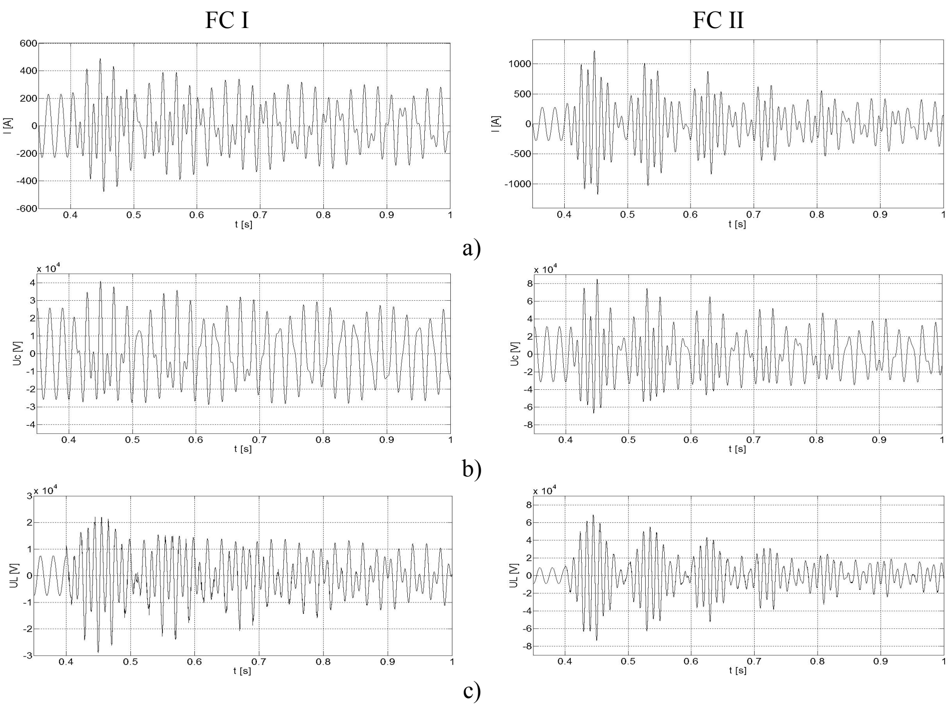

Fig. 2. Transient currents (a) and voltages across 2nd harmonic filter capacitor (b) and reactor (c) tuned to h_r = 1,86, during transformer energization in the supply system with FC circuit

Furthermore the transient analysis at second harmonic filter circuit, in the industrial system supplied by power transformers with power ratings from 80 to 160 MVA does not indicate for a significant changes of impedance frequency characteristics of the FC circuit. That situation indicates low impact of system inductance on occurring transients.

Analysis of the transient current peaks shows, that for all harmonic filters in FC circuit there are observed the maximum amplitudes after a certain time from the arc transformer energization. This fact is due to the properties of systems at the appropriate frequencies during transients.

In the examined power system there was proved, that variation of filters parameters have no direct impact on the value of TS and TP transformer inrush currents. This is mainly observed in FC as transient current fluctuation and its duration. Changing the nature of transient based on relevant variation of frequency parameters of supply installation. The result will not be generalized for application to other systems, but will only be used to determine the electrical switching stress on the filter components of this system. In another cases, we can expect a completely different relations. Even so, the dynamic overvoltages and overcurrent phenomena exhibited here are common to many others.

5. Selection of dry type air-core filter reactor and filter capacitor ratings

In accordance with selecting procedure for dry type air-core filter reactor [8] and filter capacitor banks [9] in the considered supply system the next rating criteria are calculated, Table 4.

Table 4. Typical Filter Reactor and Capacitor bank Rating Criteria

Filter Reactors	Steady state	- Root square sum of the harmonic voltage drops across the reactor	$U_R = \sqrt{\sum_{h=1}^{\infty} U_h^2}$
		- Root square sum of the harmonic currents seen by the reactor	$I_R = \sqrt{\sum_{h=1}^{\infty} I_h^2}$
		- RMS symmetrical short circuit rating	$I_{SC} = \frac{U_{LL}}{X_L \sqrt{3}}$
	Transient	- Energizing transient	$U_R = \frac{U_{pk}}{1,5\sqrt{2}}$
		- RMS symmetrical short circuit rating	$I_{SC} = \frac{I_{pk}}{\sqrt{2}} \cdot 3$
Filter Capacitor Banks	Steady state	- Linear sum of harmonic voltages	$U_c \geq \sum_{h=1}^{\infty} U_h$
		- Root square sum of the harmonic currents seen by the capacitor	$I_C = \sqrt{\sum_{h=1}^{\infty} I_h^2}$
	Transient	- Energizing transient	$U_c = \frac{U_{pk}}{2,5\sqrt{2}}$

Definition of symbols: U_h, I_h – RMS harmonic voltage drop and current at "H" harmonic, U_{LL} – voltage at the supply system bus ($U_{LL} = c \cdot U_n$, c = 1,1), U_{pk}, I_{pk} – peak overvoltage and peak overcurrent, X_L – filter reactance of the fundamental frequency.

These expressions are a reasonable for selecting filter equipment considering transient voltages and current magnitudes, transient duration and its number of occurrence. Compared together respectively rating of RMS values for transient and steady state condition, the more rating value among itself have to be selected for reactor and capacitor specification.

Considering the transient in selecting the filter parameters could increase the electrical rating of the reactor and capacitor equipment, but it will also assure long term proper performance of the equipment. Table 5 and 6 compares the ratings for steady state operation and transient for reactor and capacitor bank respectively.

As one can see the calculated values has shown, that the selecting ratings for filter reactors and capacitors in application involving multiple single-tuned filters based solely on the steady state conditions and are not sufficient to ensure the compensation unit operation without failures. The peaks of current and voltages strictly depends on the frequency characteristics from whole power supply industrial system.

Table 5. Comparison of filter reactor ratings for FC

Rating of TS, MVA		80				160			
Filter	Operation condition	Filter Circuit	I_R [kA]	I_{SC} [kA]	U_R* [kV]	Filter Circuit	I_R [kA]	I_{SC} [kA]	U_R* [kV]
F-2	Steady state	-	0,17	0,39	1,11	-	0,17	0,39	1,11
	Transient	I	0,17	1,04	13,66	I	0,17	1,03	13,26
		II	**0,17**	**2,59**	**34,68**	II	**0,17**	**2,23**	**29,02**
F-3	Steady state	-	**0,74**	**4,47**	1,57	-	**0,74**	**4,72**	1,57
	Transient	I	0,74	4,48	4,92	I	0,74	3,82	4,52
		II	0,74	4,58	**6,58**	II	0,74	4,58	**6,58**
F-5	Steady state	-	**0,50**	**9,85**	0,89	-	**0,50**	**9,85**	0,89
	Transient	I	0,50	4,14	3,97	I	0,50	3,05	**3,50**
		II	0,50	4,18	**4,05**	II	0,50	4,01	3,49

(*) phase values

Table 6. Comparison of filter capacitor bank ratings for FC

Rating of TS, MVA		80				160			
Filter	Operation condition	Filter Circuit	Uc* [kV]	Ic [kA]	Sc [MVA]	Filter Circuit	Uc* [kV]	Ic [kA]	Sc [MVA]
F-2	Steady state	-	17,20	0,17	8,68	-	21,12	0,17	10,77
	Transient	I	11,55	0,17	5,89	I	11,53	0,17	5,88
		II	**21,12**	**0,17**	**10,66**	II	**21,14**	**0,17**	**10,78**
F-3	Steady state	-	**14,80**	**0,74**	**32,78**	-	**17,58**	**0,74**	**39,03**
	Transient	I	8,57	0,74	19,02	I	8,13	0,74	18,05
		II	9,77	0,74	21,64	II	9,77	0,74	21,69
F-5	Steady state	-	**14,30**	**0,50**	**21,40**	-	**12,90**	**0,50**	**19,35**
	Transient	I	6,15	0,50	9,23	I	5,68	0,50	8,52
		II	7,96	0,50	11,94	II	7,26	0,50	10,92

(*) phase values

6. Conclusions

A general analysis shows that transformer switching with harmonic filter has an influence for the magnitude and variation of transient currents and voltages in filter circuit. Switching surge characteristic (magnitude and duration) and the values of parameters can be determined using transient analysis based on computer simulation. That fact justify the adopt of modeling during the rating procedure of filter reactors and capacitor banks. The examination confirms that the parameters calculated for steady state are not sufficient to ensure faultless operations of filter circuit involving multiple single-branch filters in the industrial power supply systems.

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