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# Transients under energizing multiple power filter circuits

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The practice of operating reactive power compensation systems involving passive multiple filter circuits (FC) configured by single–tuned filters has shown, that it's energizing can cause damage of the filter components. Impact of feasible FC configurations, including FC with a C–type filter, on switching overvoltages and overcurrents under the harmonic filters energizing were analyzed. Influence of the filters tuning on transient behavior has been shown. The transient analysis has been carried out by simulating of the FC within Matlab/Simulink software.

KEYWORDS: capacitor, reactor, harmonic filter, C–type filter, Static Var Compensator, transient overcurrent, transient overvoltage, dynamic overcurrent, dynamic overvoltage, switching transients

## 1. Introduction

Industrial loads have become more complex. Most of them have nonlinear voltage–current characteristics, especially electric arc furnaces (EAF), arc welders, rolling mills, adjustable speed motor drives (ASD) have stochastically varying loads with significant reactive power consumption and have harmonic generation which includes unbalanced even and odd harmonics during normal operation. Moreover these loads also significantly increase the total power factor of power systems, which may result a penalties for exceeding reactive power consumption.

Nowadays, there are some advanced techniques such as: magnetic flux compensation, series shunt active filters, harmonic current injection to reduce harmonic distortion and reactive power compensation problems in industrial systems [1]. However, these techniques are complex and cost too much, so they could not compete with currently passive harmonic filters applications.

In practise the most commonly used are single–tuned harmonic filters and C–type filters. In several cases, capacitor and reactors used in these filter circuit arrangements have subsequently experienced insulation failures during switching operations. The main reason of that phenomenon are dynamic overvoltages and overcurrents generated due to a number of switching cycles whose amplitude significantly exceed the rated parameters of operated compensation unit.

The purpose of this paper is to study the transient overvoltages and overcurrents which occurred on the various filter banks during single filter or several filter energization within multiple filter circuit bank in a typical arc–furnace supplying power system. The comparative transient analysis has been carried out for the supply system whose filter circuit is equipped with: 1) three solely passive single tuned filters and 2) two single–tuned and $2^{nd}$ harmonic C–type filters. To analyze this phenomenon the Matlab/ Simulink software has been chosen because of there are known limitations in the field testing with respect to the circuit conditions and the number of times that the test can be carried out.

## 2. Switching surges phenomena in multiple filter branches

The common practise in filter design is to select a reactor and capacitor combination that limits the harmonic distortion to a specified level and delivers the proper reactive power output. It is achieved by appropriate component ratings for the series resonance and required harmonic frequencies which have to be filtered. It is assumed that proper filtering harmonic current spectrum at the bus in multiple filter branches is carried out from low to high order and to achieve a harmonic distortion level that will meet standardized requirements [1, 2, 3]. Moreover, to ensure the properly operation of each branches in multiple filter installations and provide required impedance characteristics of power system, each of filter circuits is properly design to adequate resonant frequency [2, 4].

In industrial applications the most popular harmonic circuits still represent single–tuned filters and broadband units. However power systems which supply nonlinear or disturbing loads (arc furnaces, traction loads etc.) are equipped with C–type filter with damping resistance but in several cases, there are possibilities to adopt other solutions, that may be favourable in terms of economic and technical indices. That applications is increasingly required a multiple FC which based on several single–branches passive filters tuned at different frequencies in order to achieve a harmonic distortion level that will meet the end customer’s requirement [2, 5, 6, 7]. Moreover, a multiple filter circuits comprising C–type filter have good suppression at tuned frequencies and more efficient damping the resonance that may occur.

An important point in complex filter units is a valid sequence of switching operation of single–tuned branches installed at power system. The proper sequence is carried out from low to high order harmonic filter and their incorrect switching events can cause transient overvoltages and severe stress on component insulation FC installations and fault system equipments.

Energizing a normal shunt capacitor bank and units cooperated with other capacitors under voltage can result in maximum transient crest voltage of twice the power frequency voltage per unit. Damping of the power system which in typically cases is a range 5 to 20 causes the transient to decay rapidly.

In application involving multiple single–tuned filters are observed a different character of transient and the values of current and voltages peaks. Energizing a single–tuned harmonic unit in multiple FC will also result in a voltage twice the voltage, which normally appears across the capacitor. Although, the nominal voltage across a filter capacitor, without harmonic being considered is greater than the bus voltage by the factor $k$:

$$k = \frac{h_r^2}{h_r^2 - 1}$$

where $h_r$ is the resonant frequency to which the filter unit is tuned. Therefore, the effect of the filter switching is to increase the amplitude of transient voltage on filter capacitor even twice than nominal at power system.

An important difference between energizing a shunt capacitor and a harmonic filter is frequency and duration of transient. The filter inductance is a large portion of the total circuit inductance in a low order FC. Therefore, the switching operations are characterized by lower transient frequency than switching transients in shunt capacitor bank. The phenomenon is as a result in difference between filter and system quality level. The X/ R ratio for FC is typically in a range of 100 – 150 compared to ratios of 5 to 20 for the power system as a whole. Therefore, the overall damping of the circuit is significantly reduced and the transient oscillations have shorter duration. Although it should be emphasized, that longer duration and lower frequency of transients can mean generate higher overvoltages and hence serious stress upon filter capacitor and reactor. As general analysis shows [8], 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.

## 3. Modeling the supply system

The examined industrial power system is shown in Figure 1. This arrangement is supply from 110 kV and is reasonable for a medium size arc furnace installation or other harmonic producing loads. The system involves a 20 kV industrial bus with a moderately strong source. The short circuit of the bus is 290 MVA. The step–down transformer TS supplying the bus is rated power from 80 to 160 MVA, wye–delta connected unit with the primary neutral solidly grounded. A 50 MVA arc transformer TP is connected to the 20 kV bus. Three single–tuned filters which represents the multiple Filter Circuit (FC) and Thyristor Controlled Reactor unit (TCR) are also connected the MV bus through a appropriate single air blast circuit breakers. The 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 unit consists of thyristor veristack made of anti–parallel and series connected thyristors with snubber circuits and provide fast reactive power and voltage regulation support. The snubber circuit is used for overvoltage protection of thyristors and to supply auxiliary power to thyristor electronic card.

Transients analysis during filter branches switching on, based on two power FC systems and is carried out for TS unit ratings from: 80 to 160 MVA.

System A – which involved all single–tuned passive harmonic filter, Fig. 1a.

System B – which based on 2nd C–type filter unit and 3rd and 5th single–tuned passive filters, Fig. 1b.

During energizing FC units, the TCR is running and provide the properly balance of reactive power on medium voltage bus.

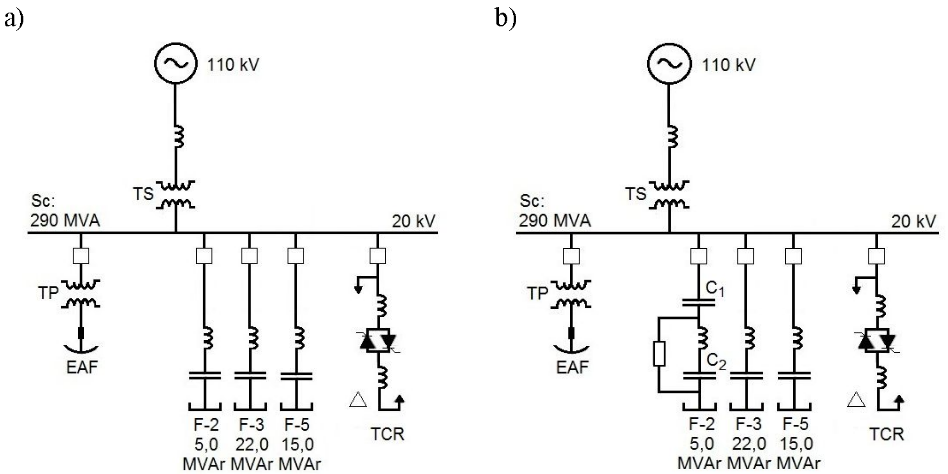


Fig. 1. Topology of AC–EAF industrial power supply system with TCR unit:
a) system A, b) system B

The individual filters are tuned to supply: 1.86, 2.79 and 4.65 MVAR for the second, third and fifth harmonic filters respectively. In the Table 1 and 2 are shown the FC harmonic filters parameters in consideration of their variations, for single branch passive filters and 2nd C–type filter respectively.

Table 1. Parameters of the single–tuned harmonic filters

| Filter | Tuning frequency | 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 |

Table 2. Parameters of the 2nd C–type harmonic filter

| Filter | Tuning frequency | Capacitance $C_1$, µF | Capacitance $C_2$, µF | Inductance $L_2$, mH | Resistance $R_T$ , Ω | $I_{nom}$, A |
|---|---|---|---|---|---|---|
| F–2 | 1.86 | 39.79 | 97.86 | 103.59 | 107.53 | 144 |

## 4. Switching surges on filter elements

The main purpose of simulation is determine the peaks of transient overcurrents 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 currents 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 tuning frequency on transients magnitude of voltages and currents, each of single–branch of FC circuits, during industrial harmonic filter or multiple filter branches 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 Switching

| FC topology | Switching event |
|---|---|
| FC I | Switch on single harmonic filter – F–2 or F–3 or F–5 |
| FC II | Switch on all harmonic filters – F–2 + F–3 + F–5 |
| FC III | Switch on single harmonic filter, under other units are supply to the bus.<br>Case 1. Switch on F–2, under F–3 and F–5 are operated<br>Case 2. Switch on F–3, under F–2 and F–5 are operated<br>Case 3. Switch on F–5, under F–2 and F–3 are operated |

### I. Transient overcurrents and overvoltages, system A

Figure 2 shows an example of transient currents and voltages for the most loaded phase in single–tuned 2nd harmonic filter, under FC energizing through 80 MVA power harmonic transformer in system. The results are shown for two different filters configurations of the system A.

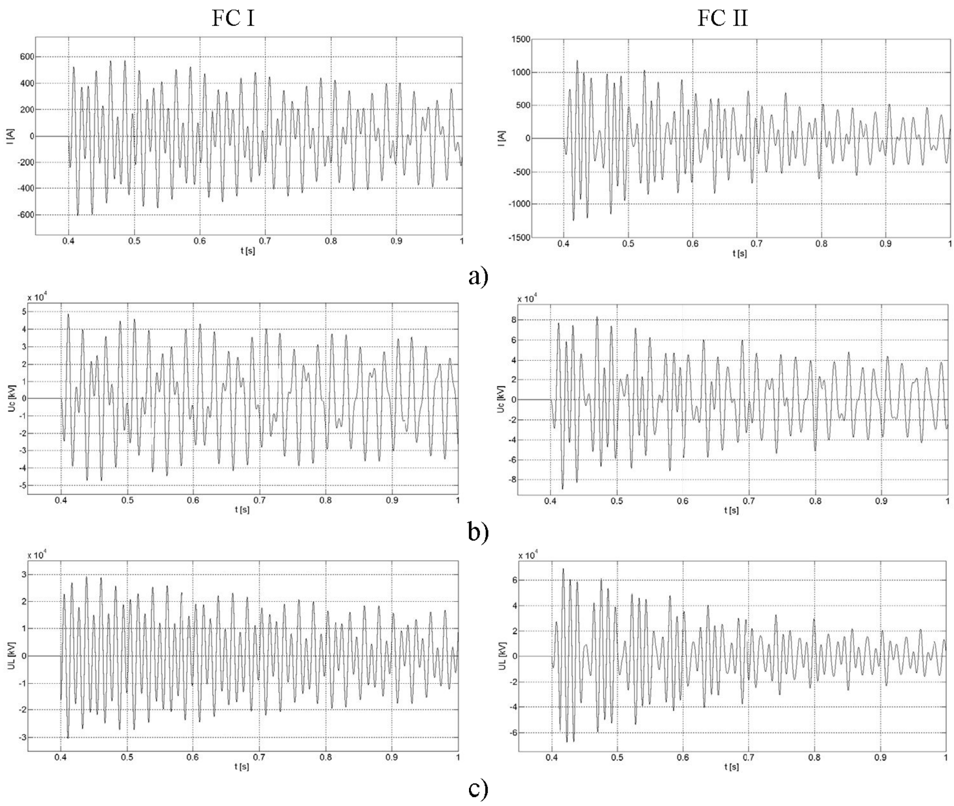


Fig. 2. Transient currents (a) and voltages across 2nd harmonic filter capacitor (b) and reactor (c) tuned to $h_r = 1.86$, during FC unit switching on, system A

As one can see, the harmonic filter energization causes high voltage and current distortion in filter circuit at second harmonic. The effect of that phenomenon has increased during all filters switching in FC units, where it can be observed the higher amplitude and the longer duration of transient in filters circuit. The results presented in that case, with high magnitude and damping transients, causes a significant effect of FC units on the other filters resonance sensitivity during filter energization. The nature of switching transients are the effect of filter current variation, but the ratio between capacitor and reactor strictly depends on the value and relative tuning frequency of the filter in application.

Furthermore, transient analysis at 2nd harmonic filter circuit, in the implemented industrial power system supplied by power transformers with power ratings from 80 to 160 MVA does not indicate for a significant changes of impedance frequency characteristic of the filter circuit. Presented situation indicates low impact of system inductance on occurring transients.

Table 4 shows the magnitude of the transient overvoltages and overcurrents obtained during energizing one (FC I) and all (FC II) single–tuned harmonic filters to power system.

Table 4. Peak transient currents and voltages in FC units comprising single–tuned filters

| Design tuning, below resonant frequency | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Rating of TS, MVA | | 80 | 160 | | 80 | 160 | 80 | 160 |
| Filter | Current peak | | | | Voltage peak | | | |
| | | | | | Capacitor | | Reactor | |
| F–2 | kA | 1.26 | 1.21 | kV | 89.59 | 81.11 | 69.14 | 66.55 |
| | p.u. (*) | 6.20 | 5.95 | p.u. (*) | 3.91 | 3.54 | 10.43 | 10.03 |
| F–3 | kA | 3.39 | 3.65 | kV | 43.85 | 43.93 | 16.47 | 18.14 |
| | p.u. (*) | 3.81 | 4.10 | p.u. (*) | 2.34 | 2.35 | 6.86 | 7.55 |
| F–5 | kA | 1.98 | 2.09 | kV | 40.23 | 38.57 | 6.70 | 7.59 |
| | p.u. (*) | 3.24 | 3.42 | p.u. (*) | 2.35 | 2.25 | 8.48 | 9.61 |
| Fine tuning to resonant frequency | | | | | | | | |
| Rating of TS, MVA | | 80 | 160 | | 80 | 160 | 80 | 160 |
| Filter | Current peak | | | | Voltage peak | | | |
| | | | | | Capacitor | | Reactor | |
| F–2 | kA | 1.34 | 1.30 | kV | 82.13 | 83.12 | 63.04 | 65.39 |
| | p.u. (*) | 6.59 | 6.39 | p.u. (*) | 3.58 | 3.62 | 9.51 | 9.86 |
| F–3 | kA | 3.35 | 3.68 | kV | 45.29 | 42.32 | 14.89 | 16.63 |
| | p.u. (*) | 3.76 | 4.13 | p.u. (*) | 2.42 | 2.26 | 6.20 | 6.92 |
| F–5 | kA | 2.06 | 2.24 | kV | 40.17 | 38.85 | 6.00 | 6.92 |
| | p.u. (*) | 3.37 | 3.66 | p.u. (*) | 2.34 | 2.27 | 7.59 | 8.76 |

(*) base value – rated filter current and voltages for capacitors and reactors

Analysis of the transient current peaks presents, that for case with all harmonic filters in FC unit there are observed the maximum amplitudes after a certain time from the harmonic filter energization. Furthermore, the damping transients are longer and slower achievement of steady state values during all single–tuned filters are switched. This fact is due to the properties of systems, at the appropriate frequencies during transients. In the examined power system there was proved, that relatively higher peaks of transient currents in filter units are observed at circuits supplied by transformer with lower inductance and for precise filter tuning, accurate to resonant frequency $h_r$.

Switching on the filters draws the more lasting transients, than in the case of transformer energization [6, 7].

Analysis of the transient voltage peaks on filters reactor and capacitor has shown similar results to the overvoltages generated on filter component during transformer energization [6, 7]. Switch on single and all harmonic filters tuned to resonant frequency causes a higher transient voltage peaks than FC’s design and tuned below resonant frequency. In the first case, harmonic filters supplied by power transformer with power ratings 160 MVA, switching transients have longer duration and frequency variation dies out more slowly.

The examination of switching events within filter system A topologies has shown, that solely energization of 5$^{th}$ harmonic filter under operated the rest of FC units causes higher transient overvoltages and overcurrents, than maximum peaks of voltages and currents obtained during switching 5$^{th}$ harmonic filter in the I$^{st}$ and II$^{nd}$ FC topology. The magnitudes of transients peaks recorded from the simulation are shown in Table 5.

Table 5. Peak transient currents and voltages in FC III topology for fine tuned filters, case 3

| Rating of TS, MVA | | 80 | 160 | | 80 | 160 | 80 | 160 |
|---|---|---|---|---|---|---|---|---|
| Filter | Current peak | | | | Voltage peak | | | |
| | | | | | Capacitor | | Reactor | |
| F–2 | kA | 0.66 | 0.65 | kV | 51.92 | 51.16 | 29.95 | 29.48 |
| | p.u. $^{(*)}$ | 3.25 | 3.20 | p.u. $^{(*)}$ | 2.26 | 2.23 | 4.52 | 4.44 |
| F–3 | kA | 3.14 | 3.12 | kV | 43.56 | 41.69 | 17.79 | 16.99 |
| | p.u. $^{(*)}$ | 3.53 | 3.50 | p.u. $^{(*)}$ | 2.33 | 2.23 | 7.40 | 7.07 |
| F–5 | kA | 2.93 | 2.99 | kV | 42.70 | 41.05 | 11.91 | 12.08 |
| | p.u. $^{(*)}$ | 4.79 | 4.89 | p.u. $^{(*)}$ | 2.49 | 2.40 | 15.07 | 15.29 |

$^{(*)}$ base value – rated filter current and voltages for capacitors and reactors

A special case is energization of 3$^{rd}$ harmonic filter, under the rest FC units is connected to the bus – Table 3, case 2. The Table shows, that transient overvoltages and overcurrents on filter reactor significantly exceed the surges magnitude which was calculated for cases FC I and FC II. Moreover, in all presented cases at FC III configuration, the shorter duration and lower frequency can mean decreased stress upon the capacitor and reactor units.

## II. Transient overcurrent and overvoltages, system B

Figure 3 shows the comparison of transient voltages and currents for the most loaded phase in 2$^{nd}$ damped harmonic filter, resulting from simulation, under FC energizing through 80 MVA power transformer in system. The results are shown for two different filters configurations FC I and FC II of the system B, comprising C–type filter. Relative tuning frequency of the 2$^{nd}$ damped filter in the experiment has taken to be: 1.86 and 2.0. The analysis of current peaks on FC circuit components during C–type filter energization has shown, that additional damping resistance $R_T$ good suppress tuned frequency and more effectively damps the resonance which occur. Besides, in comparison with system A, in the case when the switching occurs, the transient faster achieves of steady state value.

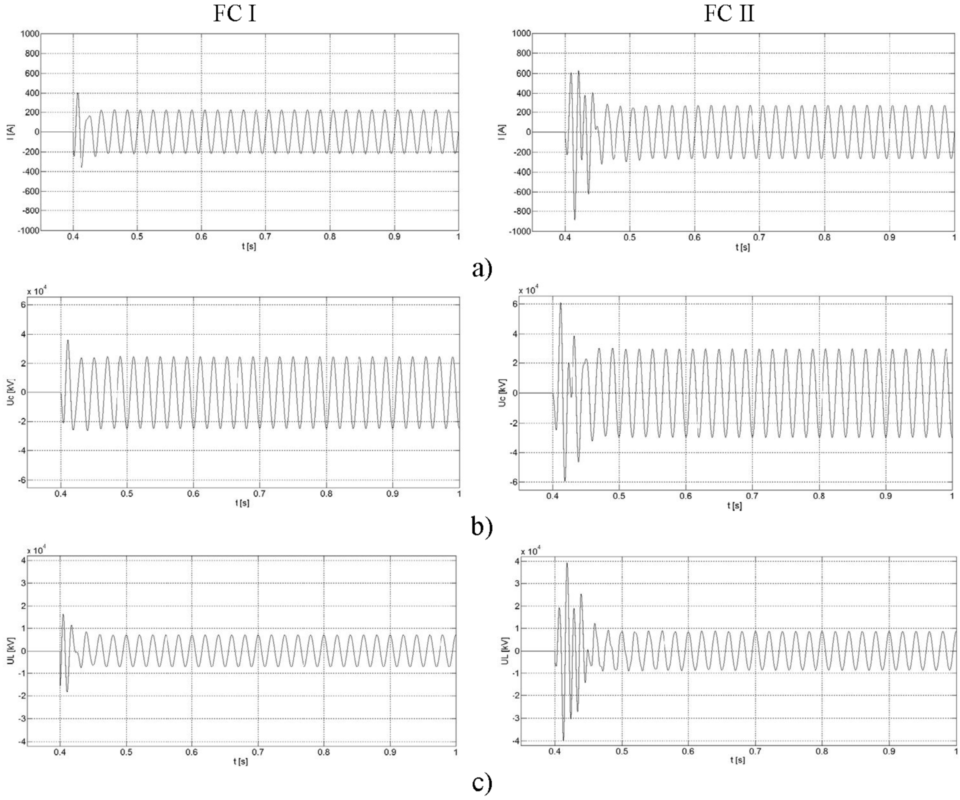


Fig. 3. Transient currents (a) and voltages across 2nd harmonic C–type filter capacitor $C_1$ and $C_2$ (b) and reactor (c) tuned to $h_r$ =1.86, during FC unit switching on, system B

The results of all transient magnitudes of currents and voltages, across the filters for system B within in FC I and FC II switching topologies, comprising 2nd damped filter are presented in Table 6.

The experiment shows, that similarly to the cases from FC system A, the same levels of voltage and current surges on filters insulation components, during FC units energization are observed at the supply system equipped with 160 MVA power transformer and harmonic filter circuits tuned to resonance frequency $h_r$.

Changing the nature of transient based on relevant variation of frequency parameters of supply installation. The result will not be generalized for applications to other systems, but will only be used to determine the electrical switching stress on the filter components of that system. In another cases, we can expect completely different relations. Even so, the dynamic overvoltages and overcurrents phenomena exhibited here are common to many others.

Table 6. Peak transient currents and voltages in FC units comprising 2nd damped filter

| Design tuning, below resonant frequency | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Rating of TS, MVA | | 80 | 160 | | 80 | 160 | 80 | 160 |
| Filter | Current peak | | | | Voltage peak | | | |
| | | | | | Capacitor | | Reactor | |
| F–2 | kA | 0.89 | 0.85 | kV | 60.92 | 58.12 | 39.91 | 38.94 |
| | p.u. (*) | 4.38 | 4.18 | p.u. (*) | 2.66 | 2.53 | 6.02 | 5.87 |
| F–3 | kA | 3.42 | 3.69 | kV | 45.32 | 45.20 | 16.44 | 18.14 |
| | p.u. (*) | 3.84 | 4.14 | p.u. (*) | 2.42 | 2.40 | 6.84 | 7.55 |
| F–5 | kA | 2.03 | 2.14 | kV | 41.15 | 39.33 | 6.72 | 7.26 |
| | p.u. (*) | 3.32 | 3.50 | p.u. (*) | 2.40 | 2.29 | 8.51 | 9.19 |
| Fine tuning to resonant frequency | | | | | | | | |
| Rating of TS, MVA | | 80 | 160 | | 80 | 160 | 80 | 160 |
| Filter | Current peak | | | | Voltage peak | | | |
| | | | | | Capacitor | | Reactor | |
| F–2 | kA | 0.92 | 0.87 | kV | 61.45 | 58.75 | 37.60 | 37.36 |
| | p.u. (*) | 4.52 | 4.28 | p.u. (*) | 2.68 | 2.56 | 5.67 | 5.63 |
| F–3 | kA | 3.38 | 3.71 | kV | 41.62 | 42.66 | 14.80 | 16.63 |
| | p.u. (*) | 3.80 | 4.17 | p.u. (*) | 2.22 | 2.28 | 6.16 | 6.92 |
| F–5 | kA | 1.93 | 1.97 | kV | 41.25 | 39.79 | 6.03 | 6.70 |
| | p.u. (*) | 3.16 | 3.22 | p.u. (*) | 2.41 | 2.32 | 7.63 | 8.48 |

(*) base value – rated filter current and voltages for capacitors and reactors

The study on filters from the system B in the FC III switching configuration has shown, similarly to system A, transients for 5th harmonic filter under all the rest filters are connected to the bus (case 3). For all simulated cases of FC, comprised 2nd C–type filter, one can observe a shorter duration of transients, than in the system without damping filter. Table 7 is presented the magnitude of transient overvoltages and overcurents recorded from the simulation.

Table 7. Peak transient currents and voltages in FC III topology for fine tuned filters, case 3

| Rating of TS, MVA | | 80 | 160 | | 80 | 160 | 80 | 160 |
|---|---|---|---|---|---|---|---|---|
| Filter | Current peak | | | | Voltage peak | | | |
| | | | | | Capacitor | | Reactor | |
| F–2 | kA | 0.48 | 0.47 | kV | 38.52 | 37.89 | 22.24 | 21.18 |
| | p.u. (*) | 2.36 | 2.31 | p.u. (*) | 1.68 | 1.65 | 3.35 | 3.19 |
| F–3 | kA | 2.63 | 2.71 | kV | 43.08 | 41.21 | 16.96 | 16.87 |
| | p.u. (*) | 2.95 | 3.04 | p.u. (*) | 2.30 | 2.20 | 7.06 | 7.02 |
| F–5 | kA | 2.80 | 2.88 | kV | 42.05 | 40.48 | 14.68 | 14.75 |
| | p.u. (*) | 4.58 | 4.71 | p.u. (*) | 2.45 | 2.36 | 18.58 | 18.67 |

(*) base value – rated filter current and voltages for capacitors and reactors

In the considered circuit, the maximum peaks of the transient voltages and currents on $5^{th}$ harmonic filter components are higher magnitude, than values from cases FC I and FC II during third harmonic filter energization.

## 5. Conclusions

General analysis of a sample industrial power system comprising multiple filter circuit has allowed drawing the next finding.

The effect of the all filters switching within multiple filter circuit is to increase the maximum peaks of voltages and currents on filter reactor and capacitor, in all analyzed systems. The transients decay more slowly, comparatively to separate switching on each filter.

The study on system B comprising C–type filter has shown lower transient overvoltages on the C–type filter components, operated in all analyzed cases. The examination confirms, that the damping resistance has no effect on maximum peaks of overvoltages on the third and filth harmonic filter capacitors. At the same time, the bypassed resistor effectively damps the transient oscillations and therefore reduces their duration on the other filters.

Results of the investigation shows, that power system capacity in the point of filter circuit connection and accuracy of filters tuning, have no significant effect on the transient overvoltages during energizing single filter or group of filters.

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