Switching on Power Harmonic Filters

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Abstract

In modern industrial power supply systems, there is observed rapid growth of time varying nonlinear loads having low power factor. The most adequate engineering solution for reactive power compensation of the loads is using compensation units including multiple single tuned passive filters. The practice of operating multiple single tuned filter circuits in the power supply systems has shown that switching transients in the supply system can generate high overvoltages and overcurrents on the filter circuit components. Rated parameters of the filter capacitor and reactor are characterized by the certain manufacturing tolerances. So, filter tuning depends on the tolerances. The impact of the filter tuning on switching transient behaviour under harmonic filters energizing has been analysed in the study.

Keywords: industrial power supply system; filter circuit; filter tuning; switching transients; overvoltage; overcurrent.

1. Introduction

The increasing numbers of Industrial Disturbing Loads [1] which are characterized by time varying, asymmetrical and non sinusoidal currents significantly deteriorate power quality and increase active power losses in the supply systems. Most of them have nonlinear voltage-current characteristic, especially: electric arc furnaces (EAF), electrostatic precipitators, arc welders, rolling mills, adjustable speed motor drives have stochastic 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 system, which may result in penalties for exceeding reactive power consumption. Those effects require using modern equipment to voltage control, reactive power compensation and current and voltage harmonic filtering. Static VAR Compensator (SVC) is most often used for reactive power control in these power supply systems. This kind of units, compared to the other solutions, is distinguished by wide range of dynamic characteristics. It provides the opportunity to limit the effects of non sinusoidal and asymmetrical current fluctuations in supply system. Nowadays, there are some advanced power electronics systems and techniques such as: magnetic flux compensation, harmonic current injection to reduce harmonic distortion and reactive power compensation problems in industrial systems. However, these techniques are complex and cost too much, so they could not compete with currently used power capacitor banks and passive harmonic filters applications. In practice, the most commonly used are single tuned harmonic filters and C-type filters.

In most cases, for the power system supplying the powerful disturbing loads, multiple filter circuits are required. Often the harmonic current spectrum generated in power grid needs installing a number of single tuned filtering branches in the filter circuit to satisfy harmonic mitigation requirements. The most commonly used topology in industrial grids is passive harmonic filter.

In case of multiple harmonic filter units which are used in industrial power grids each of filter branches is tuned to required resonance frequency [2, 3, 4]. A significant role in the operation of the multiple filter circuits plays the proper sequences of switching on and switching off of the filter branches. The discussed issue has an essential role

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due to filter switching operation in power grid causing filter branch failure of the multiple filter circuit [4, 5]. Under technological switching on the operation should be realised from lower to higher harmonic filter units, for example: for 3rd and 5th harmonic units, the 3rd harmonic filter must be switched on before the 5th harmonic filter and switched off after 5th unit. Improper sequence, due to the high stored energy in filter elements can cause uncontrolled overvoltages which are characterised by high amplitude which may result in failure of filter elements and the other control and switching equipments. As it has been experienced [5, 6, 7, 8], selecting filter parameters and topology of the multiple filter circuits has to include not only full harmonic condition and reactive power compensation requirements, but the concern of the voltage and currents transients in the power supply system.

The paper presents the concern of switching transients in a multiple filter circuit (FC), operated within real industrial power supply system. Results of the presented study have been obtained from simulations of the possible switching events with consideration of the filter circuit capacitors and reactors manufacturing tolerances.

2. Concern of transients in power filters

Transient oscillations in industrial power supply systems and transmission network are caused by normal switching operation and can also be generated due to emergency situations, such as system faults or short circuits. In both cases the main reason behind that phenomenon are dynamic overvoltages and overcurrents generated due to a number of switching cycles, whose amplitudes significantly exceed the rated parameters of the compensation unit. The practice of operating multiple single tuned filters shows that frequent energizing unloaded transformers and FC switching in industrial power supply systems can cause damaging filter reactors and capacitor banks of the FC. Dynamic overcurrents and overvoltages during the switching operations can reach amplitudes that significantly exceed the rated parameters of the filter reactors and capacitor banks. The filters' failure caused by the switching transients has often been observed in the compensated power systems supplying EAFs. Due to high quality factor of the switching circuit the energizing unloaded furnace transformer or switching filters of the SVC cause long-lasting harmonic transients in the FC of the SVC in the supply system [6, 7, 13]. If this phenomenon occurs 25 to 50 times a day the filter capacitors and reactors may not be able to withstand these overvoltages for a long time. This could reduce capacitor and reactor lifetime and lead to eventual failures. It has been noted that duration of the transients and the number of occurrences is important the factor significantly influences the design of the FC.

Harmonic and transient overvoltage analyses and special design considerations for harmonic filters in EAF installations have been presented in [6, 7, 8, 9, 10]. Principles of filter selection and performance evaluation have been described in [5]. Reference [3] gives an optimal planning algorithm for large harmonic filters for high-voltage applications. Long-term overvoltages on industrial capacitor banks, which may lead to destructive effects due to the transformer energization inrush current, have been investigated in [7, 9]. The selection criteria for the voltage rating of shunt capacitors are given in [11, 12]. IEEE Standard [12] is a valuable guide to determining the transient overvoltage capability of capacitors and selecting their voltage ratings in view of harmonics and transformer inrush current components for EAF applications. Carefully designed passive shunt harmonic filters can successfully filter out harmonic current components produced by EAF installations except the 2nd harmonic component [7, 10]. The field data presented in [7] show that the common 2nd harmonic filter in commercial SVCs developed for EAF installations may even cause the amplification of 2nd harmonic current component. Therefore, a careful approach to the configuration of 2nd harmonic filter is needed to have a better filtering performance, as well as to prevent the filter circuit elements from destructive effects under switching inrush current harmonics in the long term.

A power capacitor switching creates transients that impact the utility system and remote locations. The transients are specified by inrush current of high magnitude and overvoltage reached theoretically up to 2 times the operating peak voltage. The magnitude of transient overvoltage generally is less than the mentioned value. It depends on the moment of energization and system damping characteristic. Transient frequency is specified by system short circuit capacity and switched capacitor size and typically falls in the range of 300-1000Hz [4]. The simplified estimation of the frequency can be carried out by equivalent values of the system inductance L and switched capacitance C:

$$f = \frac{1}{2\pi\sqrt{LC}}$$

(1)

Typical transient line-to-ground voltage waveforms during wye-ungrounded capacitor bank switching on 10 kV buses of utility 110/10 kV substation are depicted in Fig. 1.
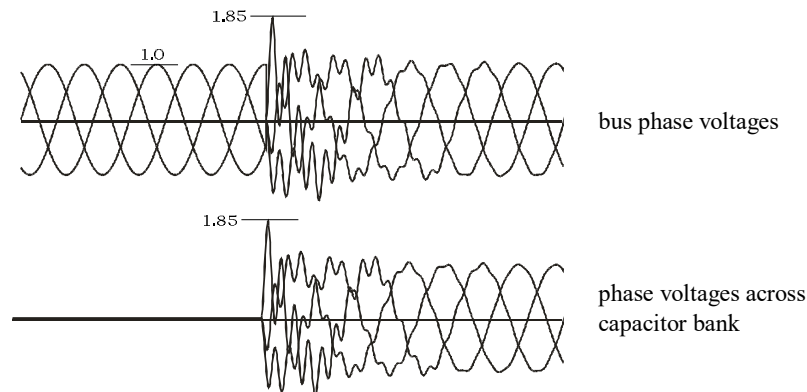
Fig. 1. Typical transient voltages during wye-ungrounded capacitor bank switching on.

Additional zeros in voltage waveforms can be caused by the oscillatory transient depending on the amount of the system damping. Overhead transmission lines or cables connected to the bus introduce additional damping to the transient and thus reduce the overvoltage magnitude. Other capacitor banks connected to the bus also reduce the equivalent system impedance resulting in lower overvoltage magnitude and moderate transient. However, during switching in the conditions (so called back-to-back switching) inrush current will increase between the capacitors. Most manufacturers suggest connecting small sized reactor to limit the transient stress. Therefore, these transients typically are not a concern for most applications because overvoltage magnitudes are below the level at which surge protective devices in the system will operate.

The capacitor switching on distribution substation bus can excite transient oscillations at remote power factor capacitors (typically in low voltage industrial systems). When the transient frequency of the switched capacitor is close to natural frequency of the circuit between the substation bus and placement of the power factor correction capacitors connection, the excited transient oscillation can be magnified due to the resonant conditions. As it has been pointed, this phenomenon can cause severe problems within customer system.

Comparative to the capacitor without series reactor, switching single tuned filters combined with capacitors and inductors will result in a voltage more than twice the voltage which normally appears across the capacitor as it will be shown in the described study.

It must be pointed, that switching events is characterised by permissible derating factors of voltages and currents which refer to the selecting filter air-core reactors and capacitor banks. The derating factors are based on the existing Standards [5, 11, 12] and appropriate time duration of the transient condition - significantly dependent upon duration of transient in the power supply system. The derating factors presented in Table. 1 are "a rule of thumb" for selecting filter equipments considering transient voltage and current amplitudes, duration of oscillations and their numbers of occurrence. Comparing together respectively ratings of RMS values of transient and steady state condition the more rating values have to be selected for reactor and capacitor specifications among the two.

Table 1. Typical derating factors for filter reactor and capacitor bank under switching events.

Switching operation	Filter air-core reactor		Filter capacitor bank
	Overcurrent	Overvoltage	Overvoltage
Transformer energizing (occurs between 1000 to 30.000 times/year)	3.0	1.5	2.5
Harmonic filter switching (occurs between 10 to 1000 times/year)	2.0	2.0	1.4
Restrike transient (occurs < or = 10 times/year)	1.5	2.0	3.0

That has to be emphasized, that the actual permissible voltages and thus the derating factors are dependent on the transient duration. However, the transient duration for different applications may be varying significantly and the transients conditions need to be considered in determining the equipment ratings.

3. The power supply system description

Simulation of the transients under switching on filter circuits was carried out for the case of an EAF power supply system shown in the Fig.2. The medium voltage bus 20 kV is supplied by high voltage network through the step-down transformer with capacity of 80 MVA with the primary neutral solidly grounded.
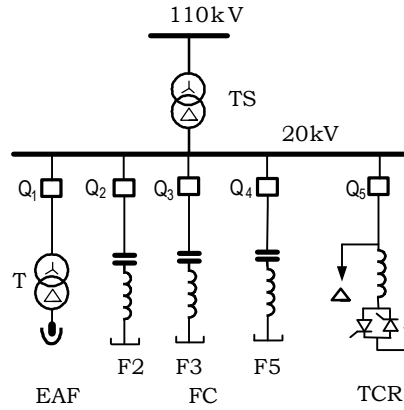
Fig.2. Topology of the examined power supply system.

The arc furnace transformer of 50 MVA is connected to the 20 kV bus. Static VAR Compensator (SVC) consists of multiple Filter Circuit (FC) based on passive harmonic filters and Thyristor Controlled Reactor (TCR). The FC and TCR are connected to the same 20 kV buses by the appropriate air blast circuit breakers.

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 the thyristors. The FC of the SVC must be designed to achieve the required harmonic distortion mitigation, generate the appropriate amounts of reactive power, and ensure that all possible resonant conditions with the power grid are avoided.

Operating reactive power of the SVC is a sum of reactive power from FC and TCR and its variation provides by electronic control system of the TCR. Total installed reactive power of implemented FC is a sum of installed reactive power of the passive single-tuned filters which parameters are selected taking into account the harmonic current spectrum of the EAF and TCR unit. The arc furnace unit is supply by arc transformer T and is switched by air blast circuit breaker Q1. Examined FC consists of single-tuned passive harmonic filters F2, F3 and F5. The FC based on three single-tuned filters is also connected to the MV bus through appropriate air blast circuit breakers Q_2- Q_4.

The relative design resonant frequency n_D for a single-tuned filter is determined by following equation:

$$n_D = \frac{1}{2\pi f \sqrt{LC}} , \qquad (2)$$

where f is the power system frequency; L,C - filter inductance and capacitance.

Equation (2) shows that the filter relative resonant frequency n_D depends on the power system frequency as well as filter inductance and capacitance. Any variation of these parameters causes deviation of the resonant frequency. So, the possible deviation from the fine resonant value can be obtained by the following equation:

$$\frac{n_F}{(1+\Delta f_*)\sqrt{(1+\Delta L_*)(1+\Delta C_*)}} \le n_D \le \frac{n_F}{(1-\Delta f_*)\sqrt{(1-\Delta L_*)(1-\Delta C_*)}} , \qquad (3)$$

where Δf_* - power system frequency variation, p.u.; $\Delta L_*, \Delta C_*$ - inductance and capacitance variations, p.u.; n_F - fine relative filter resonant frequency (n_F = 2, 3, 5).

According to the notes, the possible filter inductance and capacitance variations have been included in the transient analysis. In the analysed configuration FC the individual branches were modelled for cases of design and

fine tunings as it is shown in the Table 2. Resistances of the FC branches have been calculated from rating specifications of the reactors and capacitors.

Table.2. Parameters of the FC branches.

FC branch	Rated power, MVA	Resistance, Ω	Design tuning, n_D	Fine tuning, n_F
F2	5.00	0.27	1.86	2.0
F3	22.00	0.07	2.79	3.0
F5	15.00	0.04	4.65	5.0

The examined supply system allows verifying the impact of the implemented FC configuration and the harmonic filter tuning on transient voltages and currents of the FC capacitors and reactors during filter branches switching.

The purpose of the study was to determine the peak amplitudes of the transient currents and voltages on the FC capacitors and reactors during harmonic filters switching on in the different FC configurations in the power supply system. Impact the filter tuning of the FC filters on the transient behaviours under switching on has been studied as well.

The next switching events for the examined FC configuration have been studied:
- switching on single harmonic filter – F2 or F3 or F5;
- switching on all harmonic filters – F2 and F3 and F5;
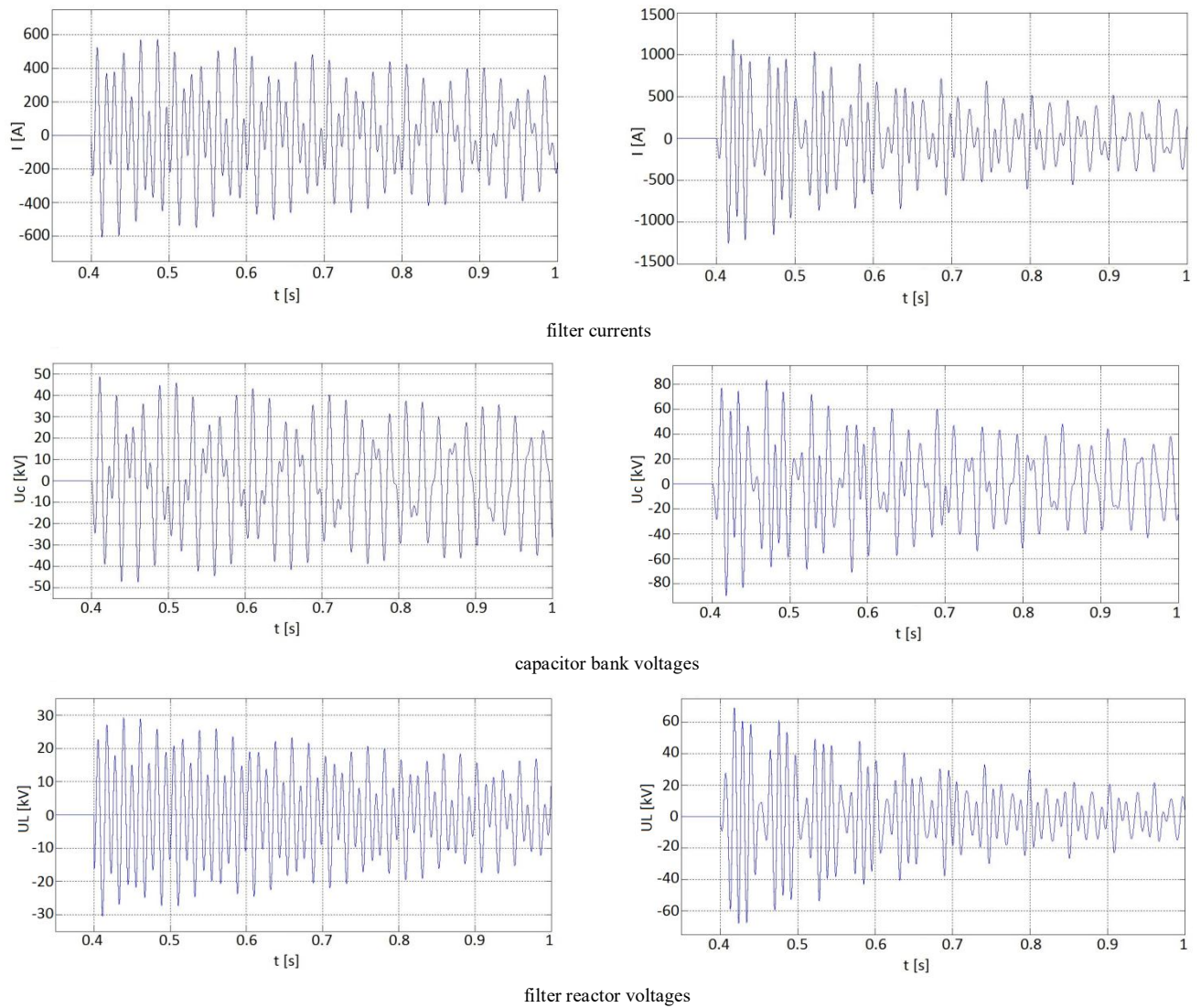- switching on single harmonic filter, when the two other is operated.

4. Transients under energizing multiple power filters

Transient's simulations which are presented in the study have been carried out based on developed models of nonlinear components in the power supply system, including transformers, capacitor banks, air-core reactors, SVC, which were implemented in Matlab/Simulink Software. The program has been chosen because of there are known limitations on the filled testing with respect to the circuit condition and the number of times that the test can be carried out. Moreover, the functions and algorithms available in the software allow for carrying out detailed analyses and observations of single and complex transients, which are difficult to observe during experimental tests in power supply systems

Especial attention on the modelling switching transients was paid to the models of the arc transformer, SVC and circuit breakers. The two-winding, three-phase saturable transformer model was chosen from the SimPowerSystems library. Parameters of the saturable transformer model are defined by the implemented arc transformer rated data. The model takes into account the winding resistance and the leakage inductance as well as the magnetizing characteristic of the core. The SVC used in the research is made of the TCR and FC modules. FC includes several harmonic filters of capacitive nature. The first one, TCR unit was in triangle implemented in the modelled system and consists of fixed air-core reactors in series with a bi-directional thyristor valves. The current in the reactor is phase-controlled by varying the firing angle of the thyristor valve. In that way, the reactive power output is continuously variable over a range of the MVAr rating of the reactor. For the transient studies in the analysed power supply system with numerous of current harmonics the three-phase circuit breaker model was used. The unit was chosen from Matlab/Simulink's library and provides the three phase contacts closing in the selected time moments.

Analysis of the current and voltage peaks on the FC branches informs that configuration of the FC under switching on has the significant impact on the transient behaviours. The higher peak amplitudes for two tuning types are observed in all FC branches under switching on the all harmonic filters. For example in the Fig. 3 there are shown the waveforms of the transient currents and voltages across F2 capacitor bank and F2 reactor under energizing from the system transformer in case of design filter tuning. That trend of oscillations is not observed for 3rd and 5th harmonic filters.

Analysis of the transients shows that in all branches of FC, unlike switching on a capacitor without series reactor, there is observed the rise of maximum amplitudes after a certain time from the moment of the switching. It obvious from the study that the parameters' deviation of the capacitor bank and reactor as well as variations of the supply system frequency characteristics affecting the nature of the filter transient.

filter currents

capacitor bank voltages

filter reactor voltages

Switching on 2nd harmonic filter   Switching on all harmonic filters

Fig. 3. Transient in the 2nd harmonic filter, design tuning.

Tables 3 - 5 present the transient current and voltage peak amplitudes which were obtained when switching on single filters or all filters to the power system. With regard to the rated values of the reactors and capacitor banks the appropriate per unit values are determined.

Table 3. Peak transient current amplitudes in FC branches.

Filter		Switching on single harmonic filter		Switching on all harmonic filters	
		Design tuning	Fine tuning	Design tuning	Fine tuning
F2	kA	0.61	0.62	1.21	1.30
	p.u. (*)	3.00	3.05	5.95	6.39
F3	kA	3.17	3.30	3.65	3.68
	p.u. (*)	3.56	3.71	4.10	4.13
F5	kA	2.84	2.91	2.09	2.24
	p.u. (*)	4.65	4.76	3.42	3.66

(*) base value – rated filter current

Table 4. Peak transient voltage amplitudes on the filter capacitor banks of the FC.

Filter		Switching on single harmonic filter		Switching on all harmonic filters	
		Design tuning	Fine tuning	Design tuning	Fine tuning
F2	kV	48.89	47.25	81.11	83.12
	p.u. (*)	2.13	2.06	3.54	3.62
F3	kV	41.79	40.17	43.93	42.32
	p.u. (*)	2.23	2.15	2.35	2.26
F5	kV	32.44	33.86	38.57	38.85
	p.u. (*)	1.89	1.98	2.25	2.27

(*)base value – rated voltages for capacitors banks

Table 5. Peak transient voltage amplitudes on the filter reactors of the FC.

Filter		Switching on single harmonic filter		Switching on all harmonic filters	
		Design tuning	Fine tuning	Design tuning	Fine tuning
F2	kV	30.75	28.37	66.55	65.39
	p.u. (*)	4.64	4.28	10.03	9.86
F3	kV	16.31	14.74	18.14	16.63
	p.u. (*)	6.79	6.13	7.55	6.92
F5	kV	9.46	8.75	7.59	6.92
	p.u. (*)	11.97	11.07	9.61	8.76

(*)base value – rated voltages for reactors

Analysis of the transients which were obtained for switching on a harmonic filter, when the two other are operated, has shown that current and voltage peaks on the FC capacitors and reactors are higher than under single filter switching on and close to the transients under all filters switching on.

It can be noted from the study that simultaneous switching on all the harmonic filters results in longer duration of the transients than switching on a single filter. Comparative analysis in the FC energized from system transformers of higher capacities (up to 160 MVA) does not indicate a significant difference in the nature of the transients.. That shows a small effect of the power system impedance for the transients.

The examination confirms that due to normal energizing of the FC branches to the system bus there are observed relatively higher transient current peak amplitudes and longer duration of transient oscillations in branches than in the case of arc transformer energizing [8, 9, 10, 13]. Quality factor of the switching circuits is the main reason for this difference.

As it can be observed from the transient behaviours under switching on the harmonic filters in all switching events, the per unit values of the filter reactor voltage peak amplitudes significantly exceed per unit values of the filter capacitor voltage peak amplitudes. Furthermore, under energizing individual or all filters of the FC topology higher peak amplitudes of the transient voltages were observed in the case of fine filters tuning.

5. Conclusion

Results of the study show that to define the effect of typical switching events which occurred in power systems on compensator units and indicate which of these operations is the most dangerous, simulation study has to be carried out. The analysis has shown that peak amplitudes of the transient currents and voltages across FC components due to filters switching on are characterized by high values and long duration and have to be involved in the procedure of sizing the capacitors and reactors.

Capacitor bank and reactor parameter deviations of the filter as well as variations of the supply system frequency characteristics impact the nature of the filter transient. The numerical results obtained from the case study cannot be generalized to application for other systems, but only have to be used to determine the electrical switching stress on the filter components of this system. In another cases, we can expect completely different relations. Even so, the nature of dynamic overvoltages and overcurrents exhibited here is common to many others applications.

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Увімкнення силових фільтрів гармонік

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Анотація

У сучасних системах промислового електропостачання спостерігається бурхливе зростання кількості різноманітних нелінійних навантажень, що мають низький коефіцієнт потужності. Найбільш адекватним технічним рішенням для компенсації реактивної потужності таких навантажень є використання пристроїв компенсації, які мають у своєму складі кілька одно налаштованих пасивних фільтрів. Практика експлуатації схем кількох одно налаштованих пасивних фільтрів у вказаних системах електропостачання показала, що перехідні процеси під час комутацій у системі електропостачання можуть спричинити високі перенапруги та надструми на компонентах схеми фільтра. Номінальні параметри конденсаторів та реакторів характеризуються певними допусками під час їх виробництва. Тому частота налаштування фільтра залежить від цих допусків. В дослідженні було проаналізовано вплив частоти настроювання фільтрів на характер перехідних процесів під час увімкнення гармонічних фільтрів.

Ключові слова: промислова система електропостачання; фільтрове коло; налаштування фільтра; комутаційний перехідний процес; перенапруга; надструм.