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SIMULATION OF TRANSIENTS FOR DESIGNING MULTIPLE POWER FILTER CIRCUITS

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Abstract: The practice of operating multiple single-tuned filters in industrial power supply systems has shown that technological transformer capacitors in switching filters within the systems can cause the damage of filte rs. The most disturbing loads on the power supply systems are powerful AC arc furnaces. Static Var compensators used in the power supply systems contain multiple harmonic filters for harmonic mitigation and reactive power compensation. For examining the impact of the supply system and filter configuration on transient overvoltages and overcurrents in the reactor and capacitor bank of the filter during switching events, an arc furnace power supply system was chosen as an example. The transient analysis has been carried out by simulating transients within Matlab/Simulink software. In the research, the most typical switching events and harmonic impact on the transient overvoltages have been analysed. The paper focuses on the selection of ratings for capacitors and air-core reactors used in multiple single-tuned harmonic filter configurations based on the ANSI/IEEE Standards and the results of transient simulations. The comparison of reactor and capacitor bank ratings of the filter circuits selected on the base of steady state operation and transient requirements has been shown.

Key words: Simulation, transients, filter circuit, harmonics, capacitor, reactor, electrical arc furnace, static Var compensator.

1. Introduction

High voltage harmonic filters are widely applied in heavy and mining industry where power electronic and electric arcing devices essentially impact the supply system. In most cases, for the power system supplying the powerful industrial loads, the multiple filter circuits (FC) containing a number of single tuned filtering branches must satisfy harmonic mitigation requirements [1–5]. The topology most commonly used in industrial grids is a passive single branch harmonic filter.

Usually the most of the filter circuits are designed to limit the harmonic distortion to a specified level and provide the required reactive power output. The component ratings are often specified basing solely on steady state operation and on fundamental harmonic voltages and currents. While selecting capacitors and reactors of the filter circuit, the variations of their capacitance and inductance caused by the effect of environmental conditions and manufacturing tolerances are taken into account. In practice, it is assumed that a chosen filter resonance point h_r should be 2–10 % lower than the accurate resonant frequency h of the filter [3]. Although this may be applicable and satisfy stable loads, the discussed method is not adequate for the filter components installed to compensate the time varying powerful loads, where the technological process is accompanied by a lot of transient occurrences. In these applications, the filter circuit failures may occur during normal manufacture switching.

Nowadays arc furnaces are very essential in steel production companies for the production of high-quality steel being the most disturbing loads on power systems. Electrical arc furnaces (EAF) are classified as complex loads with nonlinear and time varying load characteristics, which can cause many problems with the power system quality, including voltage dips, harmonic distortion, unbalanced loads and flicker. The practice of operating EAF in industrial power supply systems has shown that equipment installed in the systems is affected by overvoltages and overcurrents during the normal operation of the arc furnace. The changes of electricity consumption during melting process depend mainly on the quality of the stock, accuracy of control circuits and thermal processes as well.

Each cycle of the EAF technological process is characterized by the active power changes and the number of switching required, with a trend towards the decrease and stabilization of processes in further cycles. The first period of metal formation is characterized by the highest power consumption, that is, 60–80 % of the total energy consumption of a whole technological cycle. In the following periods there are lower power fluctuations due to arc stabilization. In order to ensure the electromagnetic compatibility of the alternating current EAF with power supply systems, a lot of technical solutions exist. The most effective power quality improvement is based on using Static Var Compensators

(SVC). Controlled SVC thyristor-reactor series group allows carrying out time varying reactive power compensation, voltage and current phase balancing and reduction of voltage fluctuations. In addition, the harmonic filter as a capacitive power source of SVC unit is used for reducing voltage distortion in the supply network.

During practical operating the EAF involving SVC, filter failures are often observed caused by switching transients in the supply systems [2, 9]. The insulation of the filter capacitor and reactor may not be able to withstand these overvolatges. This reduces their lifetime and leads to eventual failures. It has been noted in [10], that the duration of the transients and the numbers of their occurrence are important factors significantly impacting the rating of the SVC filter circuit.

The paper presents an approach to selecting capacitor and reactor ratings for multiple single tuned filters operating in an arc-furnace supplying power system considering the impact of the transients under typical technological switching. The proposed method is based on existing IEEE Standards and simulation data.

2. Description of power supply system

The simulation of the transients in the SVC filter circuit was carried out for the case of the EAF power supply system shown in the Fig.1. The medium voltage bus of 20 kV is supplied by high voltage network through the step-down transformer with capacity of 80 MVA.

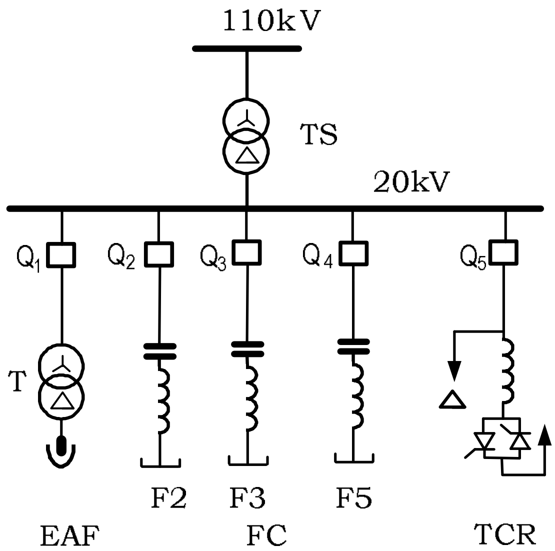


Fig. 1. EAF power supply system.

The arc furnace transformer of 50 MVA is connected to the 20 kV supply bus. A static VAR compensator (SVC) is a group including a Thyristor Controlled Reactor (TCR) and a multiple filter circuit (FC) consisting of passive harmonic filters. The FC and TCR are connected to the same 20 kV bus by the appropriate air blast circuit breakers. The FC of the SVC must be designed to achieve the required mitigation of harmonic distortion, generate the appropriate amounts of reactive power and ensure that all possible resonant conditions with the power grid are avoided.

The operating reactive power of the SVC is a sum of reactive power from the FC and TCR and its variation provided by the electronic control system of the TCR. Total installed reactive power of the 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. The arc furnace unit is supplied by an arc transformer T and is switched by air blast circuit breaker Q1. The 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.

In the analysed FC configuration, individual branches were modelled for the case of measured tuning of the filters as it is shown in the Table 1. The relative resonant frequency n for a single-tuned filter is determined by a following equation:

$$n = 1\Big/\left(2p\, f\sqrt{LC}\right), \quad (1)$$

where f is the power system frequency; L,C are reactor inductance and capacitor capacitance, considering their manufacturing tolerances.

The resistances of the FC branches have been calculated using the rating specifications of the reactors and capacitors.

Table 1

Parameters of the FC branches

FC branch	Rated power, MVA	Resistance, Ω	Tuning, n
F2	5.00	0.27	1.86
F3	22.00	0.07	2.79
F5	15.00	0.04	4.65

The purpose of the study was to determine the peak amplitudes of the transient currents and voltages on the FC capacitors and reactors for the different FC configurations in the power supply system during technological switchings. Filter tuning impact on the transient behaviour during switching has been studied as well. The next switching events in the examined supply system have been studied:

- switching on harmonic filters;
- switching off harmonic filters;
- switching on the arc furnace transformer

3. Modeling switching transients

Transient simulations presented in the study have been carried out by the developed models of the components of the power supply system, including transformers, capacitor banks, air-core reactors, SVC, which were created in Matlab/Simulink software environment. The method of transient simulations has been chosen because of known limitations on the field testing with respect to the circuit condition and the number of test repetitions. Moreover, the functions and algorithms available in the software allow for carrying out the observations and detailed analysis of single and complex transients, which are difficult to be observed 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. The parameters of the saturable transformer model are determined according to the implemented arc transformer rated data. The model takes into account the winding resistance, leakage inductance and magnetizing characteristic of the core.

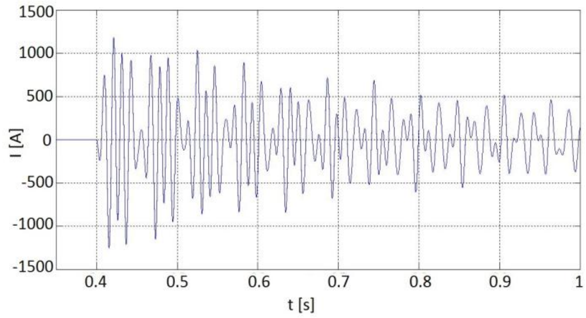
The SVC model used in the research is completed with the TCR and FC program modules. The TCR unit was implemented in delta connection and consists of fixed reactors in series with a bi-directional thyristor valves. Current in the reactor is phase-controlled by varying the firing angle of the thyristor 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 current harmonics, the three-phase circuit breaker model was used. The unit was chosen from Matlab/Simulink library and provided the required switching procedures in the selected time moments. Modelling the circuit breaker under switching off has to take into account the behaviour of the current just after the contact breaking. Just after the interruption of the current the recovery voltage across the terminals of the circuit breaker reaches the network voltage which is at its maximum at this moment for reactive circuits. The transient current does not stop flowing due to the stray capacitances of the network. During the transient the high frequency voltage oscillations are added to the power system voltage. This voltage, called transient recovery voltage (TRV), depends on the power grid characteristics and the rate of increase (*dv/dt*) of this voltage. Considerable rate of the overvoltage between the contacts of the circuit breaker can lead to phenomenon called reignition. Generally speaking, reignition is a typical phenomenon for short arcing periods, since the distance between contacts is not sufficient to withstand the appeared overvoltage. This happens each time an arc appears just before the current drops to natural zero.

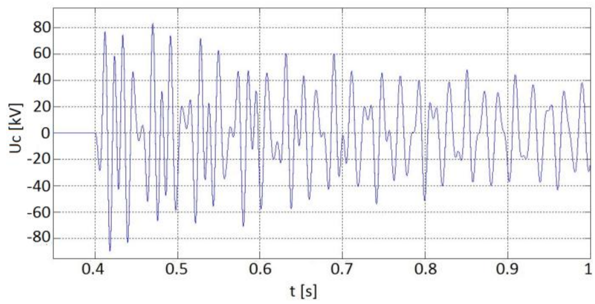
The implemented model of the circuit breaker includes the additional parallel R_{on} contact resistance branch for taking into account the stray snubber resistance R_p and snubber capacitance C_p of an open contact gap. The following values of these branch parameters have been adopted: R_{on} = 10 mΩ, R_p = 80 kΩ and C_p = 1010 pF. To control the TRV behaviour on the contact gap the volt-versus-second characteristic of the implemented air blast circuit breaker has been modelled.

4. Results of the transient simulations

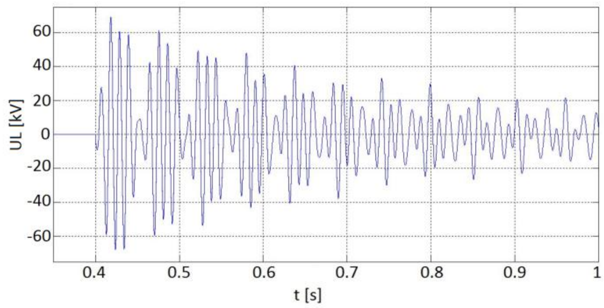
During the simulations the peak amplitudes of the transient currents and voltages across FC capacitors and reactors due to typical switchings in the supply system have been determined. Each switching event causes the transient characterized by certain voltage and current values and duration. For example, in Fig. 2 there are the waveforms of the transient currents and voltages across F2 capacitor bank and F2 reactor under FC switching.



filter current



capacitor bank voltage

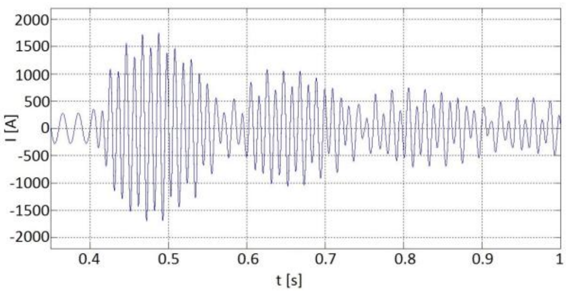


filter reactor voltage

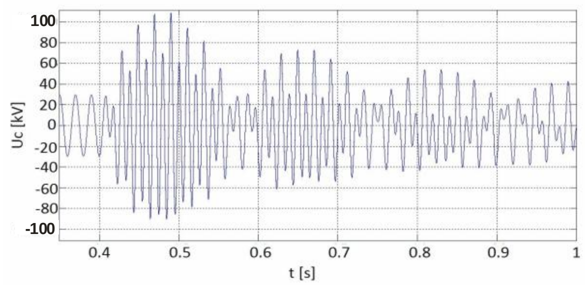
Fig. 2. Transient in the 2nd harmonic filter under FC switching on.

As it can be observed from the transient behaviour, under switching on harmonic filters, the per unit values of the peak amplitudes of filter reactor voltage significantly exceed per unit values of the peak amplitudes of filter capacitor voltage. Furthermore, under switching on individual filter or all filters of the FC topology, the higher peak amplitudes of the transient voltages were observed when tuning filters close to an exact resonant value.

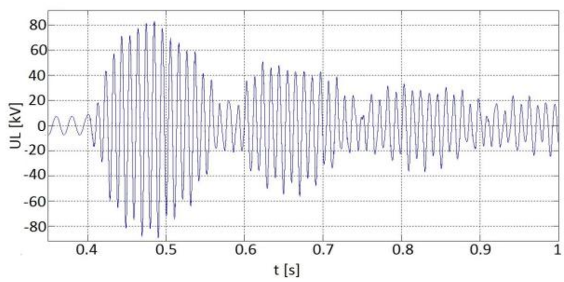
Arc transformer inrush current is characterized by a rich spectrum of harmonic currents whose amplitudes vary during the transients [6]. The transformer energization excites the transient oscillation of the resonant harmonic in the FC. Fig. 3 shows an example of transient current and voltages in the most loaded phase of the 2-nd harmonic filter during energizing the arc furnace transformer.



filter current



capacitor bank voltage

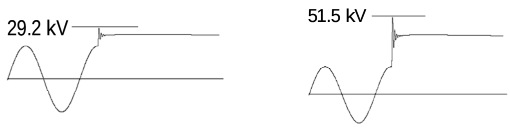


filter reactor voltage

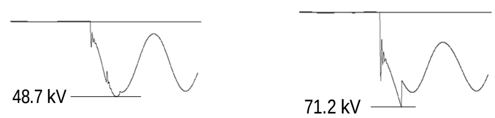
Fig. 3. Transient currents and voltages across 2nd harmonic filter capacitor and reactor during arc transformer energization.

As the analysis of the transient waveforms shows, the variations of FC parameters change the transient behaviour. Exact tuning of harmonic filters to the resonant frequency causes higher transient current and voltage amplitudes on the FC components.

During the normal operation of the supply system, the FC branches may be switched off for the protection of device operation or exploitative requirements. As a consequence, the FC switching causes transient overvoltage across the individual components of the filter exceeding the voltage at the bus. As experience shows [4, 5], switching transients in some inclusive FC of industrial power systems can result in damages of its components and circuit breakers. As it has been registered during field tests and simulations [7], the greater a harmonic content in the switched off filter current is, the higher residual filter voltage after interrupting will be. As an example, in Fig. 4 the transient voltages during switching off the 2nd harmonic filter without reignition of the circuit breaker contact gaps are shown. The influence of the current of the 2nd harmonic flowing in the filter on peaks of the transient voltage can be observed.



phase-to-ground filter voltage



voltage between cirguit breaker contacts

no 2nd harmonic presence *2nd and 1st harmonics are equal*

Fig. 4. Transient voltages during switching off 2nd harmonic filter without restrikes.

When compared with the current interruption without harmonic component, the presence of harmonic current will result in greater overvoltage magnitudes. The overvoltage magnitude depends on the tuning of the switched filter and the phase shift of harmonic current. As it has been observed during the experiments, the most dangerous rise of the overvoltage magnitude versus harmonic takes place for the 2nd harmonic filter. A close examination of the overvoltage magnitudes during reigniting current of the circuit breaker was conducted by the means of simulation. The greatest transient voltage peaks were produced when restriking coincides with the recovery voltage maximum. Under the certain circumstances, the peak transient overvoltages may exceed maximum impulse voltage allowable for substation insulation. A general analysis shows that the presence of harmonic content of the interrupted filter current raises both recovery voltages across the contacts of the circuit breaker and filter residual voltage. The bigger harmonic content, the higher the overvoltage magnitudes, the higher the possibility of arc restrikes between the contacts of the circuit breaker is.

In Table 2 the maximum values of the voltage and current amplitudes for the components of the 2nd harmonic filter obtained from the simulations of the examined power supply system during energizing the arc transformer, switching on and switching off the harmonic filters are presented.

Table 2

Transient current and voltage peaks on the 2nd harmonic filter

Switching operation	Filter current, p.u. (*)	Voltages, p.u. (*)	
		Capacitor bank	Air-core reactor
Transformer energizing	7.02	2.91	8.14
Filters switching on	5.20	2.40	6.37
Filters switching off	-	2.79	6.06

(*) base values – rated current and voltages of the filter component

Similar data referring to maximum peaks of the transient voltages and currents have been obtained for the 3rd and 5th harmonic filters of the examined power supply system. These values are the base for correcting the sizing of the filter circuit branches of analysed power supply system considering transient events.

5. Impact of the transients on the filter sizing

The ratings of the FC components considering the harmonic content are based on steady states and include all criteria concerning voltages and currents from existing IEEE Standards. The common practice in the design of air-core filter reactor advises the use of the following values [8]:

– RMS voltage across the reactor for steady state operating conditions. It represents the permissible voltages across insulation of the air-core filter reactor:

$$U_R = \sqrt{\sum_{h=1}^{\infty} U_h^2}\ , \qquad (2)$$

– RMS current value in the filter reactor under steady state conditions. It represents the permissible currents in the air-core filter reactor:

$$I_R = \sqrt{\sum_{h=1}^{\infty} I_h^2}\ , \qquad (3)$$

– RMS symmetrical short circuit in the filter reactor under steady state conditions. It represents the permissible overload of the air-core filter reactor due to short circuits in FC units:

$$I_{SC} = U_{LL} \Big/ \left(X_L \cdot \sqrt{3} \right), \qquad (4)$$

where U_{LL} is the operating RMS line-to-line voltage at the supply system bus, X_L is filter reactor reactance.

Requirements for shunt capacitors [9] are determined by following design values:

– RMS voltage value across the filter capacitor banks for steady state conditions. It represents the permissible voltages across the insulation of the filter capacitor:

$$U_C \geq \sum_{h=1}^{\infty} U_h\ , \qquad (5)$$

– RMS current value in filter capacitor banks under steady state conditions. It represents the permissible currents in the filter capacitor:

$$I_C = \sqrt{\sum_{h=1}^{\infty} I_h^2}\ , \qquad (6)$$

Transient current peak amplitudes lead to high electrodynamic forces on the filter reactor winding and increase the criteria of reactor selection. Furthermore, overvoltage peaks cause degradation of the reactor insulation that can result in its failure.

Selected voltage ratings of filter capacitor banks strictly depend on the maximum amplitudes and duration of transient voltages generated in power systems. These events can lead to the fault of the internal insulation of the capacitor. Thus, the determination of the ratings of harmonic filters is carried out by the appropriate existing IEEE Standards considering typical transients in the supply system. It is based on the calculations of RMS currents and voltages, which are equivalents of their peak values observed under repetitive transient conditions. This method requires calculating the following values:

– RMS voltage across the reactor for transient conditions considering the repeatability of the transients for typical operating switchings:

$$U_R = U_{pk} \Big/ \left(a \cdot \sqrt{2} \right), \qquad (7)$$

– RMS symmetrical short circuit of the filter reactor under transient conditions. It represents the permissible overload current in the air-core filter reactor considering the repeatability of the transients for typical switching events:

$$I_{SC} = b \cdot I_{pk} \Big/ \sqrt{2}\ , \qquad (8)$$

– RMS voltage across the capacitor bank for transient conditions considering the repeatability of the transients of the typical operation switching:

$$U_C = U_{pk} \Big/ \left(d \cdot \sqrt{2}\right), \qquad (9)$$

where U_{pk}, I_{pk} are transient voltage and current peak amplitudes, a, b, d are the voltage and current derating factors for typical switching events according to [3].

Similar to steady states, under transient conditions these values determine the power rating of the filter capacitor bank:

$$S_C = 3 \cdot U_C \cdot I_C, \qquad (10)$$

Therefore, the selection of FC components in the examined power supply system of the arc furnace has to be carried out with considering steady state and transient conditions.

To calculate RMS ratings meeting the requirements of the FC steady state operation in the power supply system, the average values of harmonic currents generated by the examined EAF and SVC have been adopted.

Calculating RMS ratings ensuring requirements of the FC reliable operation under transient conditions has been carried out considering voltage and current peak magnitudes obtained from simulating all switching events in the analysed system. The value of the RMS rating for each of these magnitudes was taken into consideration through the appropriate derating factor according to the existing IEEE Standards for filter capacitor banks and air-core reactors [8, 9].

According to completed research the capacitor and reactor parameters have been calculated considering steady state and transient conditions for all filters of the analysed FC as it is shown in Table 3 and Table 4.

Table 3

Comparison of parameters for FC reactors

Filter	Operating Condition	I_r, kA	I_{sc}, kA	U_r, kV
F2	Steady state	0.17	0.39	1.11
	Transient	**0.17**	**3.86**	**43.06**
F3	Steady State	**0.74**	**5.57**	1.57
	Transient	0.74	4.75	**6.59**
F5	Steady State	**0.50**	**11.44**	0.89
	Transient	0.50	4.69	**3.51**

To select the design rating of capacitor and reactor of the filter the higher of the two comparable RMS values has to be adopted considering steady state and transient conditions. These parameters are noted in the tables by numbers in bold.

Table 4

Comparison of parameters for FC capacitor banks

Filter	Operating Condition	U_c^*, kV	I_c, kA	S_c, MVA
F2	Steady state	21.12	0.17	10.77
	Transient	**31.36**	**0.17**	**15.99**
F3	Steady State	**17.58**	**0.74**	**39.03**
	Transient	9.84	0.74	21.85
F5	Steady State	**12.90**	**0.50**	**19.35**
	Transient	7.29	0.50	10.93

6. Conclusions

Operating experience shows that transient phenomena in power filter circuits due to various technological switchings in industrial power supply systems can lead to the failures of filters or degradation of their insulation. Therefore, during the design of filter circuits, the switching transient phenomena have to be taken into account.

Modelling is the most acceptable approach to studying the transients in compensation devices due to the variety of their topologies and features in operating conditions of industrial power supply systems and known limitations of their field testing.

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МОДЕЛЮВАННЯ ПЕРЕХІДНИХ ПРОЦЕСІВ ДЛЯ ДЛЯ ВИБОРУ КОМБІНОВАНИХ ЕНЕРГЕТИЧНИХ ФІЛЬТРОВИХ КІЛ

Юрій Варецький

Практика роботи комбінацій одноналаштованих фільтрів у промислових системах електропостачання показала, що технологічні комутації фільтрів, трансформаторів, конденсаторів у межах цих систем можуть спричинити пошкодження фільтрів. Найбільш збурювальними навантаженнями у електропостальних системах є потужні електродугові печі змінного струму. Статичні компенсатори реактивної потужності, які використовують у цих системах електропостачання, містять комбінації гармонічних фільтрів для зниження гармонік та компенсації реактивної потужності. Для вивчення впливу системи електропостачання та конфігурації фільтрів на перехідні перенапруги та надструми реактора та конденсаторної батареї фільтра під час комутацій вибрано приклад певної системи електропостачання дугової печі. Аналіз перехідних процесів проводився шляхом моделювання перехідних процесів у програмному середовищі Matlab / Simulink. У цьому дослідженні проаналізовано найтиповіші комутаційні події та вплив гармонік на перехідні перенапруги. У пропонованій статті зосереджено увагу на виборі номінальних параметрів конденсаторів та реакторів без феромагнітного осердя, які використовують у конфігураціях з комбінаціями одноналаштованих гармонічних фільтрів, на основі стандартів ANSI/IEEE та результатах моделювання перехідних процесів. Показано порівняння номінальних параметрів реакторів та конденсаторних батарей фільтрових кіл, вибраних на основі усталених режимів роботи та вимог перехідних процесів.

Prof. Yuriy Varetsky – Ph. D. and D. Sc. in Power Engineering awarded by Lviv Polytechnic National University, Ukraine, in 1982 and 1999. respectively. Presently, he works as Professor of the Department of Energy and Fuels at the AGH University of Science and Technology, Poland.

Scientific interests: power quality and power systems analysis.