Yuriy VARETSKY[1], Roman PAVLYSHYN[2], Michał GAJDZICA[1]

AGH University of Science and Technology (1), Lviv Polytechnic National University(2)

Harmonic current impact on transient overvoltages during filter switching-off

Streszczenie. *W artykule przedstawia sie charakterystyczne cechy wyłączenia filtrów mocy w sieciach zasilających zakłady przemysłowe. Przeprowadzono analizę przebiegu wyłączenia przy dużym udziale harmonicznych w prądach filtrów. W badaniach uwzględniono wpływ wartości prądów harmonicznych w przerywanym prądzie, rzędu strojenia filtru oraz warunków wyłączenia. Przedstawiono niektóre przebiegi symulacyjne charakteryzujące problem. (**Wpływ harmonicznych prądu na generowanie przepięć w chwili wyłączania filtrów**)*

Abstract. *This paper focuses on the features of power filter switching-off in industrial power supply systems. The filter switching-off behavior under a large amount of a harmonic current component has been analyzed. The effect of harmonic current content in interrupting current, filter order tuning and switching condition are considered in the analysis. Finally, several oscillograms of simulated cases are included to show main points of the investigation. (Harmonic current impact on transient overvoltages during filter switching-off)*

Słowa kluczowe: system zasilający, wyłącznik, filtr harmonicznych, przepięcie przejściowe, modelowanie.
Keywords: power supply system, circuit breaker, harmonic filter, transient overvoltage, simulation.

Introduction

Rapid growth of nonlinear loads such as static power converters, welders, arc furnaces, voltage controllers and frequency converters has led to many harmonic problems in power systems. So their solutions have become a major concern for present day engineers. The harmonic filtering is one of the solutions to prevent the troublesome harmonics from entering the supply system. Single tuned filter is the most commonly used filter. It supplies some or all of the fundamental frequency reactive power required for power factor correction. The filter components may be tuned to provide a low impedance shunt path to a specific frequency. The quality factor of the inductor determines the sharpness of tuning.

In many applications the filters are often switched (on a daily basis or performance requirements basis). As a consequence, the filter circuit switching causes transient overvoltage across the individual components of the filter that exceed the voltage at the bus.

Transient oscillation between the lightly damped filters can likewise be much higher then expected. Traditional surge arresters connected to the bus, may be inadequate overvoltage protection because of the filter components are subjected to extra stresses. Certain switching operation can also present potentially hazardous overvoltage conditions, not only to the filters, but to other substation equipment such as circuit breakers and transformers. As known from experience [1, 2, 3], switching transients in some industrial power systems inclusive filter circuits can result in damages of its components and circuit breakers. It has been noted in [3] that transient overvoltages caused by system faults or normal switching operations are well documented and accounted for in the design of adequate surge protection devices, but application of SVCs may increase the potential for excessive overvoltages. As it has been registered from field tests and simulation [4], the greater a harmonic content in the switching-off filter current, the higher residual filter voltage after interrupting will be.

The paper presents studies on switching-off the filter containing large portion of a harmonic current. The study has been carried out with typical arc furnace power supply system containing a set of single tuned harmonic filters. The investigated power supply system example includes many common features of other industrial power systems. Electromagnetic Transient Program [5] was used to simulating transient behaviors under filter circuit switching-off.

The studies have shown that harmonic content in the filter circuit current causes to grow recovery voltage between the circuit breaker contacts and residual voltage at the filter circuit. Increase in harmonic content of interrupting current tends to the higher overvoltage magnitudes and effects the possibility of circuit breaker restrike.

The authors are hoping that the results of these studies will be useful for harmonic filters application planning and improve its operation reliability.

Examined power supply system

The examined power supply system shown in the Fig.1 involves 220 kV bus supplying 35 kV bus by means of step down wye-delta connected transformer TS of 160 MVA with the primary neutral solidly grounded. Couple of 50 MVA electric arc furnace (EAF) units is connected to the 35 kV bus. The SVC circuit is assembled from four single-tuned filters and thyristor controlled reactor unit and connected to the bus through the appropriate circuit breakers. The individual filters are sized to supply 25, 30, 17 and 20 MVAr for the 2nd, 3rd, 4th, and 5th harmonic filters respectively. The filters are connected to the 35 kV bus through cables by air blast circuit breakers $Q_2 - Q_4$, which have become commonly used to switch filter circuits and capacitor banks. Damping circuits are connected to the switched cable ends for limiting fast transient overvoltages.

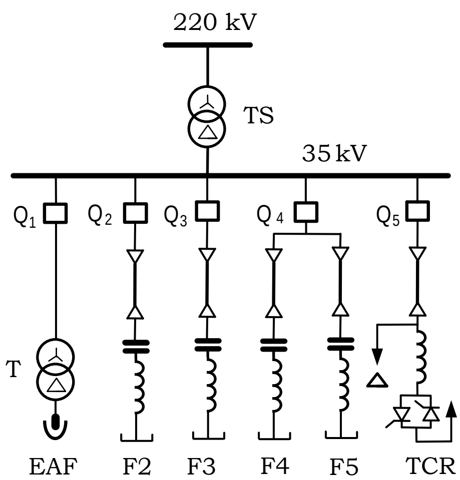

Fig. 1. Single-phase diagram of the EAF supply system

As it have been shown in [6], switching-on ungrounded wye filters in the investigated power system results in transient overvoltage magnitudes approaching 1.5...1.7 p.u. on the substation bus.

In general, however, the overvoltages, associated with normal filters energizing in the presented system, are do not dangerous for the filter equipment and do not usually endanger substation equipment at the bus location. The peak currents in the filters are a few times higher than steady-state levels. The energizing of a filter generates steep fronted voltage waves on filter reactor which can result in high local overvoltages along reactor winding length. As a consequence of this phenomenon the adequate measures to prevent the reactor insulation dielectric failure must be provided.

If under filter switching-off there is successful interruption of the capacitor current at zero crossing and the switching device withstands the transient recovery voltage there are no significant transients on clearing a filter. The occurrence of reignitions during circuit breaker poles opening tends to cause adverse transient recovery voltage conditions.

To investigate switching-off transient overvoltages in the presented scheme the equivalent circuit shown in Fig.2 was constructed for the Electromagnetic Transient Program. The every source voltage u_A, u_B, u_C was adjusted as a set of the system frequency and a harmonic frequency voltages to modeling required harmonic content in interrupting current. Circuit breaker Q in the equivalent circuit was modeled by typical air blast breaker voltage-second characteristic for switching-off load currents. Current distorted wave for each phase was interrupted by crossing zero, so after first interrupted phase current interruption in second and third phase occurs simultaneously in the presented system.

For example, Fig.3 shows voltages and current when circuit breaker interrupts the 3rd filter currents (without harmonic presence) following one and two restrikings. As it was noted, restriking of switching breaker under interrupting currents produces sufficiently higher overvoltage magnitudes in comparison with no breaker restriking.

The transient voltages include oscillation in accordance with system natural frequency. Application of damping circuit C_D, R_D allows to limit magnitude and rate of rise of the transient recovery voltage across the opening breaker contacts.

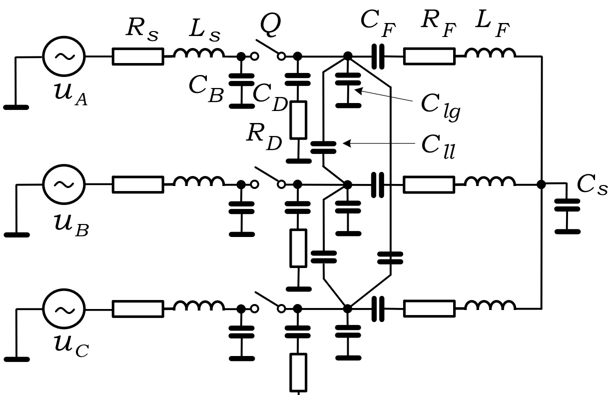

Fig. 2. Equivalent circuit of the supply system: u_A, u_B, u_C – distortedd voltage waves; R_S , L_S – power supply system;$_F$, C_F , L_F – filter circuit; R_D , C_D – damping circuit; C_{ll}, C_{lg} – cable capacitances; C_B – equivalent bus capacitance; C_S – equivalent stray capacitance.

As it can be observed from the oscillograms, current reigniting between circuit breaker contacts will produce transient voltages and currents significantly high in magnitude than those occurring during closing. Since restrikes can occur when there is a charge remaining on the filter capacitor bank it is possible for restrikes to generate transient overvoltages that are much higher in magnitude than on closing. The transient voltages on a filter and recovery voltages across a switching device can be reduced during restrikes by installing arresters on the filter side of the switching device.

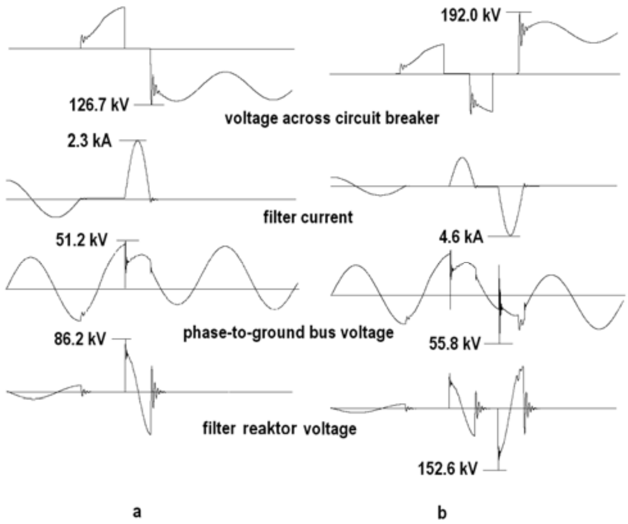

Fig. 3. Voltages and current for phase A (interrupted as the first) under one (a) and two (b) 3rd filter breaker restrikings

Arresters connected phase-to-ground will limit the recovery voltage but do not necessarily limit the voltage trapped on filter capacitors during restrikes. Arresters are sometimes connected from phase to neutral to limit the trapped voltages to lower levels, thus reducing switch recovery voltage and minimizing the possibility of multiply restrikes [8].

Harmonics affect overvoltages

If the circuit breaker is applied to filter circuit loaded a large amount of a harmonic, the behavior of the transient voltages will be different from described above. As it has been noted above, harmonic content in the interrupting current will influence on the transient behavior. Such a case can be observed in the power supply system described in the Fig.1. EAF generate significant harmonic currents that flow in SVC filter circuits. The harmonic currents vary randomly during EAF operating cycle. Magnitudes of individual harmonic currents may reach sufficient values. During EAF operating it is possible that a specific filter branch may be out of service. In the circumstances the filters in service will be overloaded due to possible resonances in supply system. It provokes activation of the filter overload protection and switching-off the filter.

Energizing arc furnace transformer in EAF supply system is a powerful harmonic disturbance. In the examined supply system arc furnace transformer (T) energizing occurs several times a day. When the transformer is energized, inrush current can be high in magnitude. The transformer inrush current consisting high harmonic content can be long duration (lasting several seconds). The harmonic content causes resonance in the filter circuit that extends the duration of the inrush transient and resonance. The resonance in the filter may cause the filter relay undesirable operation. So, the filter circuit breaker will be switched-off under high harmonic presence, increasing possibility of overvoltages.

As example let us consider for comparison the oscillograms shown in the Fig.4.

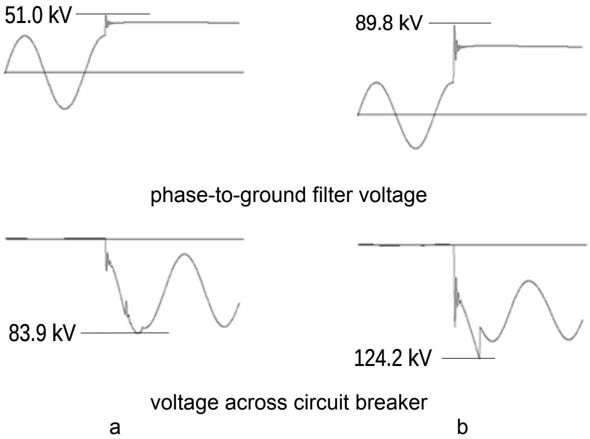

Fig. 4. Voltages for 2nd filter breaker switching-off without restrikes: a – no second harmonic presence; b – second harmonic is equal to fundamental.

If the interrupted current contains harmonic component, the maximum recovery voltage between filter circuit breaker contacts increases giving rise to the possibility of restriking. When compared with the interruption of the current having no harmonic component the presence of harmonic current will also result in greater overvoltage magnitudes. Fig. 5 shows residual voltages on 2nd filter phases versus harmonic content in interrupted currents (phase *A* is first interrupted). Base voltage is crest value of nominal phase-to-ground voltage.

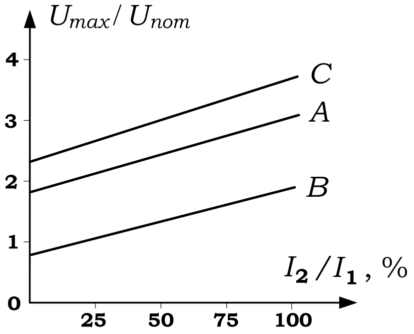

Fig. 5. Residual voltages on 2nd filter phases vs 2nd harmonic content.

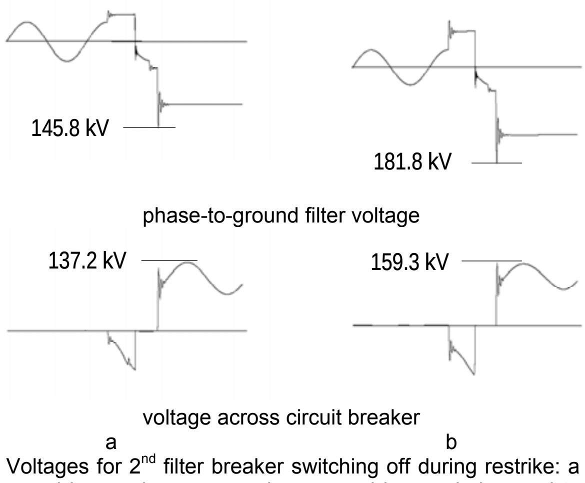

Fig. 6. Voltages for 2nd filter breaker switching off during restrike: a – no second harmonic presence; b – second harmonic is equal to fundamental.

A close examination was conducted on the overvoltage magnitudes during reigniting circuit breaker current by Electromagnetic Transient Program simulating. The overvoltage magnitude depends on the order of the switching filter and harmonic current phase shift. As it has been observed from the experiments the most dangerous rise of the overvoltage magnitude versus harmonic takes place for the 2nd filter.

Let us consider transient behavior under restriking between a filter circuit breaker contacts. Fig.6 shows transient voltages during 2nd filter circuit breaker current reigniting.

The next investigation have been carried out is examination of the conditions where the maximum overvoltage magnitudes occur. If restriking occurs at the maximum recovery voltage, the great peaks are produced in other phases. In the certain circumstances the peak transient overvoltages may exceed withstand impulse voltage for substantion insulation. The maximum values of transient voltage magnitudes on filters under restriking are shown in Table 1.

Table 1. Maximum filter overvoltages under restriking

Harmonic content, %	Order of filter		
	F2	F3	F5
0	5.08	4.51	4.28
25	5.34	4.63	4.32
50	5.71	4.82	4.39
100	6.38	5.18	4.56

Note: Base is the crest value of phase-to-ground voltage

As it can be observed from the Table 1 the restriking surges depend on the order of the filter and the value of harmonic current. When compared with the switching-off filter having no harmonic component it has been noted that presence of harmonic results not only higher recovery voltage in the first interrupted phase but also higher residual voltages of the second and third interrupted phases. Since overvoltage magnitudes under circuit breaker restriking is great it is necessary to evaluate its relationship to withstand impulse voltages. Therefore, if the restriking is observed for the filter circuit breaker, it should be necessary to evaluate possibility installing the surge protective devices.

A special case of transients which must be considered in the examined power supply system is analysis of the phenomenon under arc furnace transformer energizing. As it noted above inrush currents contain full range of harmonics beside their fundamental and dc components. Furthermore the inrush phenomenon can last many cycles and activate overvoltage and overload relays of SVC filter circuit causing trip a filter breaker under inrush condition. So, protection coordination studies should be implemented to remain SVC in service over the range of normal and transient conditions.

Conclusions

The paper presents the results of filter breaker switching-off phenomenon at an example of industrial power supply system consisting on EAF and SVC.

A general analysis shows that presence of harmonic content in the interrupting filter current increases both recovery voltages across the circuit breaker contacts and filter residual voltage. The greater harmonic content, the higher the voltage magnitudes, the more possibility of arc restrikes between the circuit breaker contacts.

Special considerations must be carried out for arc furnace power supply systems because of possible presence of great harmonic magnitudes in filter circuits and necessity of prevention of the filter protection misoperation.

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***Authors**: prof. dr hab. inż. Yuriy VARETSKY, AGH - University of Science and Technology, Faculty of Energy and Fuels, Department of Fundamental Research in Energy in Energy Engineering, 30 Mickiewicza Ave,30-059 Krakow, Poland, E-mail: jwarecki@agh.edu.pl; mgr inż. Roman PAVLYSHYN, Lviv Polytechnic National University, Institute of Energy Engineering and Control Systems, Department of Power Systems and Grids, E-mail: pavlyshyn@gmail.com; mgr inż. Michał GAJDZICA, AGH - University of Science and Technology, Faculty of Energy and Fuels, Department of Fundamental Research in Energy in Energy Engineering,30 Mickiewicza Ave,30-059 Krakow, Poland, E-mail: michal.gajdzica@wp.pl.*