FILTRATION OF HIGHER HARMONICS IN ELECTRICAL GRID IN DYNAMIC ENVIRONMENTS

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Issues associated with the harmonics filtration in electric mains have become more sensitive and vital with a progressive growth in application of electric power valve converters used under distorting loads.

Keywords: passive filters; active filters; amplitude and phase modulation.

High harmonics filtration in electric mains still remains one of the most complex issues

INTRODUCTION

Combinations of resonant LC-circuits have been applied so far to filter higher harmonics in electric mains. This raises the following dilemma. If the applied LC-circuit is of a high Q-factor, its residual resistance is small for an efficient bridging of the corresponding harmonics under stationary conditions. However, when the harmonic is characterized by variable amplitudes and phases under dynamic loads, resonant filtration circuits of high Q-factors do not improve filtration properties and can even make them worse. By reducing the Q-factor, we can limit negative effects of the dynamics. But at the same time we degrade filtration properties as the residual resistance increases. The pilot filter provides an opportunity to reduce the residual resistance by reducing wave impedance, but this is infeasible for power installations. A reduced wave impedance implies an increased rated capacity and cost of equipment, while a reduced Q-factor — an increased energy loss effect during operation.

Issues associated with the harmonics filtration in electric mains have become more sensitive and vital with a progressive growth in application of electric power valve converters used under distorting loads, such as:

- electric drives of hoisting mechanisms with frequency regulation options;
- thyristor rectifiers operating in a cyclic-pulse mode of energy consumption (for instance, in AC electric locomotives, high-energy electrophysical installations);
- electric arc DC furnaces.

However, converters has brought not only issues, but a solution as well. High-frequency tracking pulse-width modulated converters based on IGBT transistors can operate as wide-band amplifiers characterized by the absence of energy losses. Suitability for operation without ohmic power losses — non-dissipativity of such amplifiers make them applicable in the power sector. In addition to passive components (reactors, capacitors, resistors), power filters can also include an active component — a controllable voltage source in the form of a power amplifier.

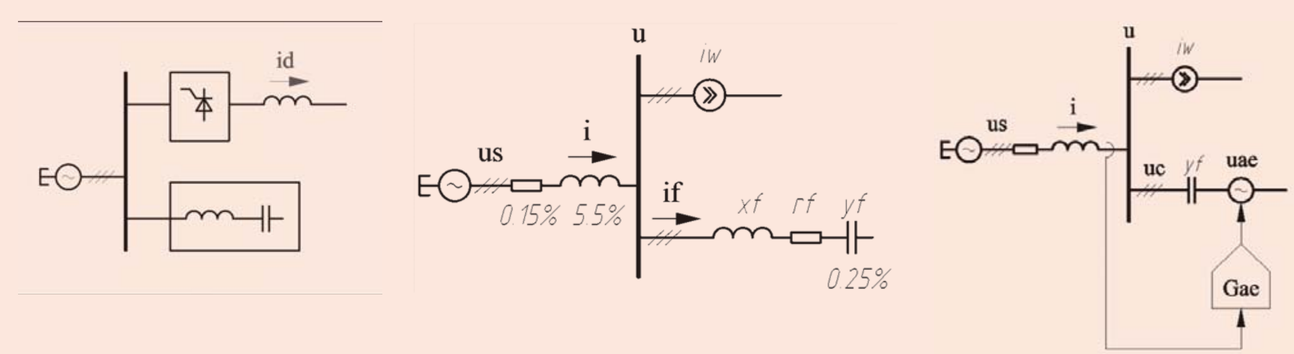
Active filters with operational amplifiers have been used for a long time in the analog signal processing. As to signal processing applications, such filters permitted to avoid a non-process component (electromagnetic reactor) and to reduce dimensions and cost of devices [1-3]. In power applications, active filters are able to deal with a fundamental problem of the efficient non-dissipative harmonics filtration in electric mains under dynamic conditions. Solutions based on IGBT-converters and their controllers became mature as regards to their functional capabilities, cost and reliability to be widely used in a vast range of applications, while active filters are already being incorporated in electric mains.

The purpose of this work is to demonstrate a simple test case confirming that active components can successfully solve a problem, which was unmanageable in applications with traditional passive resonant circuits.

TEST CIRCUIT

The test circuit includes a mains transformer, thyristor rectifier (distorter) and bridging filter (Fig. 1, a). For display purposes, we consider

TEST CIRCUIT (A); EQUIVALENT CIRCUIT FOR A RESONANT FILTER (B); EQUIVALENT CIRCUIT FOR AN ACTIVE COMPONENT AE (C)



a) b) c)

Fig. 1

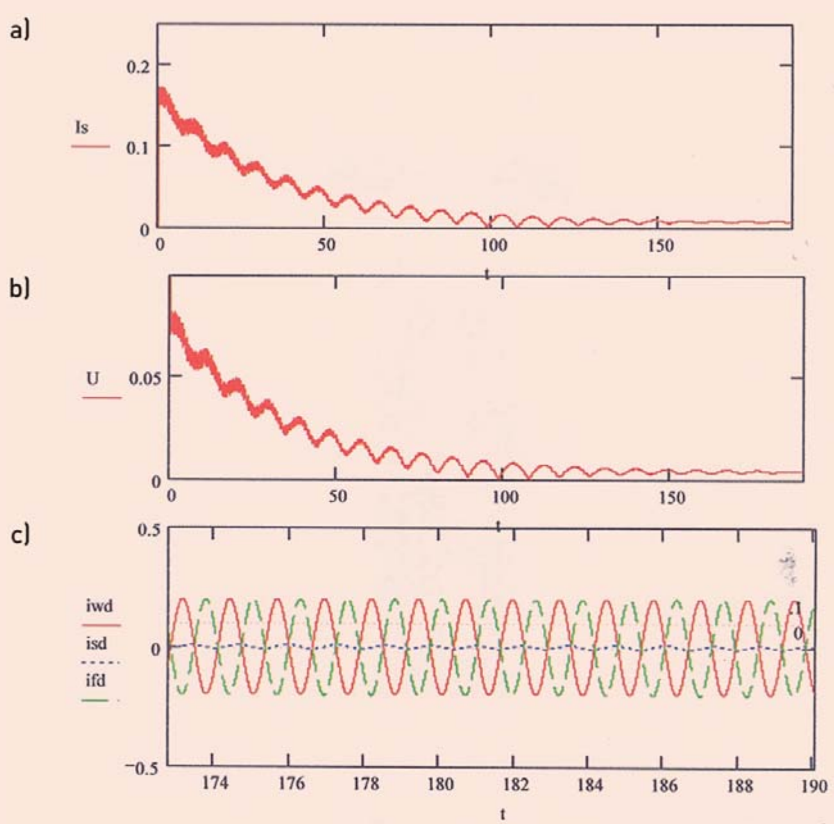
a simplest fifth harmonic filtration problem. The transformer power is assumed for testing as the doubled rectifier power, while the resonant circuit power as one fourth of the rectifier power. These parameters are adopted as per an actual operation case with a thyristor rectifier in a high-power electrophysical installation. Analysis is conducted in relative units, orthogonal axes (*d–q*). References are assumed as rated amplitudes of phase voltage and phase current and as rated cyclical frequency. In this case, the equivalent circuit (Fig. 1, b) is characterized by an inductive resistance and a capacitor bank conductivity amounting to *xs*=5,5%, *yf*=25%.

Fig. 1 uses the following codes: us — circuit voltage; *is* — circuit current; *iw* — distortion current; *if* — filter current; *uae* — active component voltage; *xf, rf, yf* — inductive resistance, filter active resistance and capacitor conductivity; *Gae* — active component transfer characteristic.

The circuit passive filter (see Fig. 1, b) is adjusted for the fifth harmonic, so

$xf=1/(25\cdot yf)$.

HIGH-Q RESONANT FILTER AT A NON-MODULATED RECTIFIER CURRENT



a) Is — mains current; b) U — bus voltage; c) is — mains current; iw — distortion current; if — filter current

Fig. 2

The fifth harmonic amplitude of the current rectifier is about 1⁄5 of the main harmonic *Iw1*:

$Iw5(\cdot)\approx 0,2\cdot Iw1(\cdot)$,
$\overrightarrow{Iw5}(\theta)=Iw5(\theta)\cdot exp(-j\cdot 5(\theta-a))$.

Where θ = ωt; α — rectifier control angle; j = √−1.

(the 5th harmonic rotates in the reverse direction, i.e. its degree of order is 5.) Due to the rectifier operation the current *iw5(·)* is modulated by an amplitude and phase (when the control angle changes), i.e. generally becomes a variable modulated both in amplitude and phase [4]. Amplitude and phase modulations of such load shall be analyzed separately as to their effect on the filtration efficiency by a resonant filter and an active component as shown below:

- amplitude modulation — when the rectifier current alters as per a bell-shaped curve with a period Te = 55 ms = 17.28 p.u., while the phase remains unchanged;
- phase modulation — when the current amplitude is maintained unchanged, while the phase alters as per a saw-tooth curve with the same period of Tc = 55 ms.

The distortion duration is also adopted as per an actual operation case with a thyristor rectifier in a high-power electrophysical installation. We subsequently consider effects appearing due to the use of a traditional resonant filter (see Fig. 1, b) and an active component, being a more advanced technical solution (see Fig. 1, c).

RESONANT FILTER EFFECTS

We start considering parameters of the resonant circuit under non-modulated conditions

$A_{iw}(\cdot)\equiv 0,2$;

$cos((a(\cdot))\equiv 0,54$,

where A_{iw} — distorter current module. Resonant circuit Q-factor D_{of} = 80.

Fig. 2 (a, b) demonstrates the resonant circuit in a transient mode; Fig. 2 demonstrates it in a stable mode.

As for the stable conditions, the resonant circuit copes with the task: bus bar voltage module A_u reaches a stable low level of 0.45%, while the fifth harmonic current module A_{is} appearing in the module is lowered from 20.00 to 0.83% (based on the superimposing principle applicable to the considered line system, we can consider effects of current harmonics *iw(·)* separately; Fig. 2 shows diagrams with the only active harmonic –5; while the rest are neglected). The transient mode is of some length (Fig. 2, a, b) as the filter Q-factor is rather high (D_{of} = 80). Diagrams of the transient mode *Is(·), U(·)* demonstrate some beat-frequency interference. It is caused by an admittance function zero shift from 5, amounting to 0.5(5−*fn*), where:

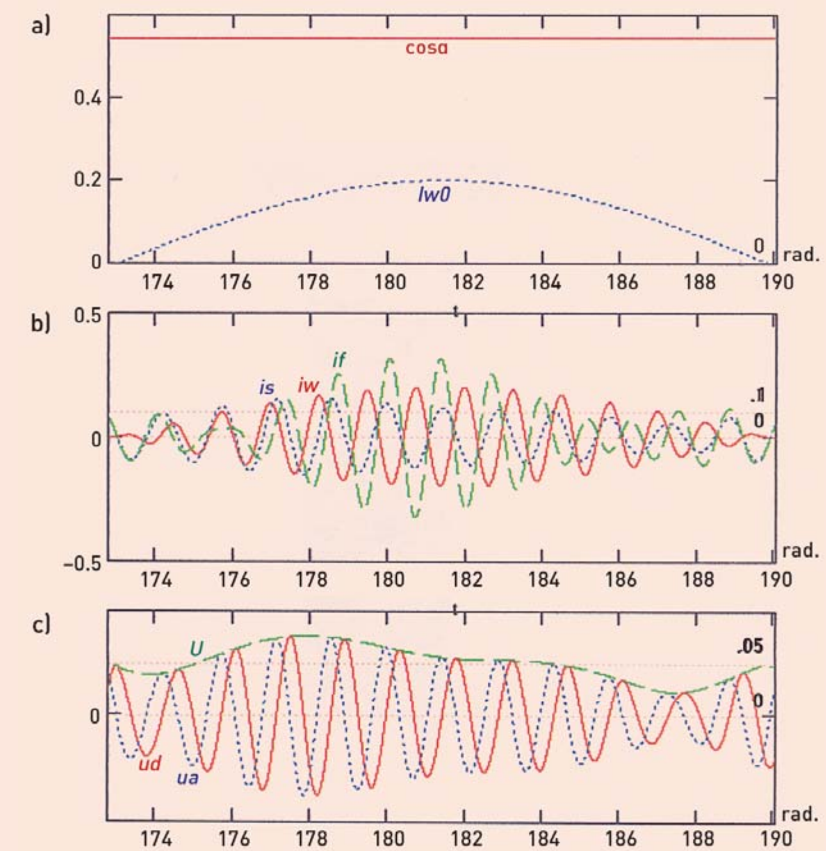
$f_n=1/\sqrt{((xs+xf)\cdot yf)}$.

Under stable conditions, this interference is damped within some time and the filter starts bridging the distorting harmonic of the rectifier current upon completion of the transient mode.

Diagrams of Fig. 3 show the process in the same system with a bridging circuit of a high Q-factor under conditions when the rectified current alters cyclically so that the rectifier circuit current becomes amplitude-modulated.

The rectified control angle cosine is maintained constant $cosa(\cdot)\equiv 0,54$,

AMPLITUDE-MODULATED CURRENT IN THE CIRCUIT WITH A HIGH-Q RESONANT CIRCUIT: DISTORTIONS IN THE VOLTAGE AND CURRENT OF THE NETWORK ARE UNACCEPTABLY HIGH (A_U=7,6%,A_{IS}≈15,5%)



a) distortion current amplitude — Iw0 and delay angle cosine; b) is — mains current; iw — distortion current; if — filter current; c) U-bus voltage; ud, uq — bus voltage in axis d, q

Fig. 3

while the current amplitude *Iwo(·)* alters as per a bell-shaped curve (Fig. 3, a). The calculated process indicators show that the high-Q filter is absolutely inefficient under such conditions. The fifth harmonic voltage amplitude has unacceptable value A_u=7,57%. The circuit current module A_{is}=15,5% shows that the resonant circuit has practically no effect on the rectifier distorted current appearing in the circuit. Diagrams of Fig. 3, b illustrate this phenomenon. Current build-ups/falls in the high-Q resonant circuit *if(·)* lag behind rectifier current build-ups/

falls *iw(·)* so that the fifth harmonic of the circuit current *is(·)* remains high.

Fig. 4 shows process indicators and diagrams for conditions when the rectified current remains constant A_{iw}≡0,2, while the rectified control angle cosine cosα alters as per a saw-tooth curve in the range of 0.254–0.54 (Fig. 4, a). Under these conditions, the rectifier current is phase-modulated. According to expectations, effects of the high-Q resonant filter are not quite satisfactory under these conditions either.

Voltage distortions exceed 10% — A_u≈ 10,5%, while the current harmonic of the circuit exceeds even the rectifier current harmonic. A_{is}=21,4%, A_{iw}=20%.

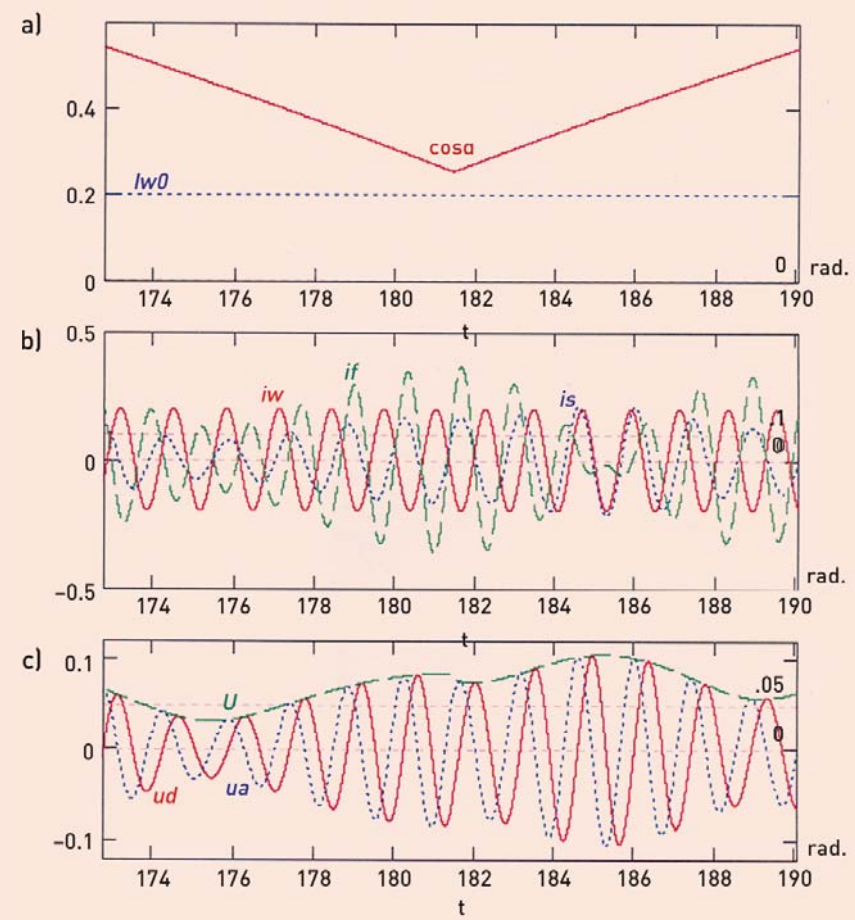
As demonstrated by diagrams (Fig. 4, b, c), the current of the high-Q resonant circuit becomes both phase- and amplitude-modulated with some delay as to *iw(·)* and corresponding consequences.

Thus, the high-Q resonant circuit remains absolutely inefficient for both amplitude and phase modulations of distorted currents. This can be slightly changed by reducing the Q-factor of the resonant circuit, i.e. by increasing energy losses in the circuit. Effects due to a reduced Q-factor are shown by diagrams in Fig. 5.

The diagrams demonstrate voltage distortion A_u and circuit current distortion A_i by changing the Q-factor in a wide range D_0∈0,1–1000. Upper diagrams refer to the phase modulation (Fig. 5, a) and lower — to the amplitude modulation (Fig. 5, b). The left end of diagrams at D_0=0,1 corresponds to conditions when the resonant circuit is practically out of operation. In this case, the total rectifier current flows into the circuit A_{is}=A_{iw}=20%, while voltage distortions due to the fifth harmonic amount to A_u≈11%.When moving to the right, i.e. gradually improving the Q-factor, all four curves trend downward achieving their minimum at the same area at the Q-factor of D_0≈8-12.

Any further improvement of the Q-factor leads to increased distortions which is illustrated above. Achievable minimum voltage distortion values: for voltage — min A_u≈5,6 and 6,0%, and for the current — min A_{is}≈10,7 and 11,9%. these indicators are anything but satisfactory. The resonant filter is inefficient under dynamic loads, even if its Q-factor is reduced by increasing energy losses in the circuit.

PHASE-MODULATED DISTORTING CURRENT IN THE HIGH-Q RESONANT CIRCUIT: VOLTAGE AND CURRENT DISTORTIONS ARE UNACCEPTABLY HIGH (A_U=10,5%, A_{IS}≈21,4%)



a) distortion current amplitude — Iw0 and delay angle cosine; b) is — mains current; iw — distortion current; if — filter current; c) U-bus voltage; ud, uq — bus voltage in axis d, q

Fig. 4

ACTIVE FILTER OPERATION

Fig. 1, c shows an active component of a hybrid filter with a condenser bank *yf* preserved. Its value remains unchanged *yf*=0,25. Due to this fact the required active component capacity is small which impacts expenses significantly. We can assume that the active component just replaces the throttle *Lf* in the initial circuit.

The considered scheme of the hybrid filter an active element can operate for the purpose of damping circuit current distortions *is(·)* or for damping bus bar voltage distortions *u(·)* by a circuit current feedback or a bus bar voltage feedback. Results of one or the other function are generally quite similar. The selection of one of the function variants is based on surrounding circumstances which are irrelevant for this article. We will further consider an option with the circuit current feedback as shown in Fig. 1, c.

The active filtration predetermines that the circuit resistance function synthesis is replaced by the transfer characteristic synthesis Gab(p) for the active component control unit. The class of transfer functions is much wider than the one of the resistance functions which drastically expands opportunities of filtration removing previous limitations [5, 6]. Another feature shall also be noted. The transfer function *Gab(·)* is implemented as a signal processor program as distinct from the resistance function implemented by power components L, C, R. This shift makes it possible to apply any improving function complications to achieve inaccessible previously flexible properties.

The transfer characteristic *Gab(p)* synthesis is implemented based on a heuristic method of the transfer characteristic synthesis for the electric mains active filtration — DSB-algorithm elaborated in [7]. The method is based on distinguishing the following three functions:

- damping (D);
- selective harmonics filtration (S);
- energy balance (B);

and valid for PWM-converters of any topology with any PWM pattern formation.

The active component does not dissipate or absorb energy, but at the same time dampens transient vibrations as is the case with a resistor. The combination of non-dissipativity and damping properties becomes possible due to an energy storage capacitor incorporated in the active component, variables averaging and frequency conversion. In this case, the active component transfer function indicates not only functional tasks of damping (D) or selective suppression (S), but also an auxiliary task of energy balancing (B) for the storage capacitor.

RELATION BETWEEN DISTORTIONS OF VOLTAGE AU( ) AND CURRENT AIS( ) AND Q-FACTOR OF THE BRIDGING RESONANT CIRCUIT D0 FOR PHASE (A) AND AMPLITUDE (B) MODULATIONS OF THE DISTORTING CURRENT

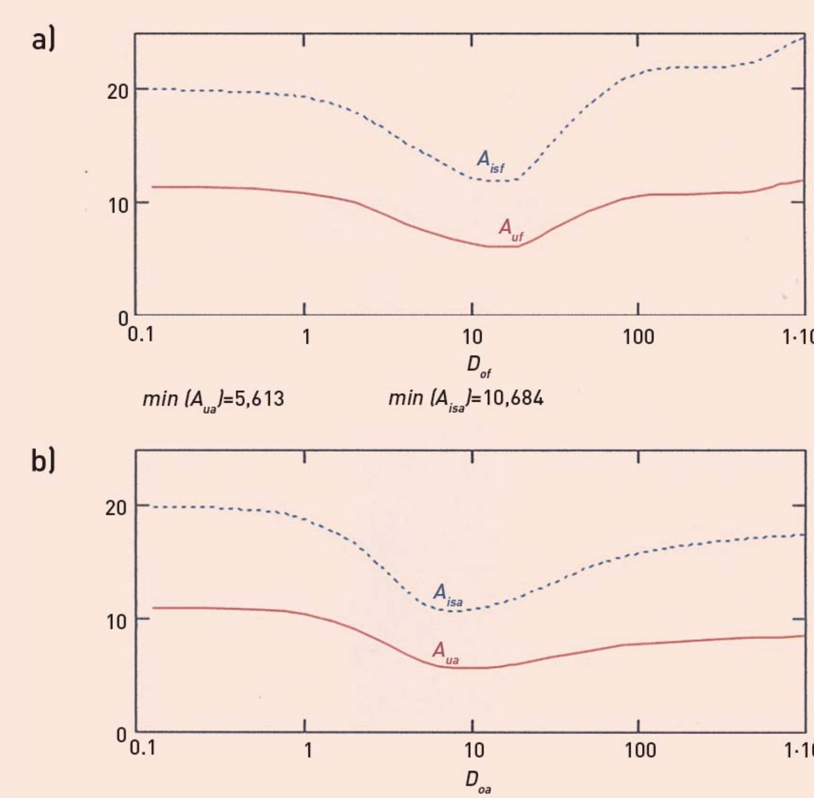


Fig. 5

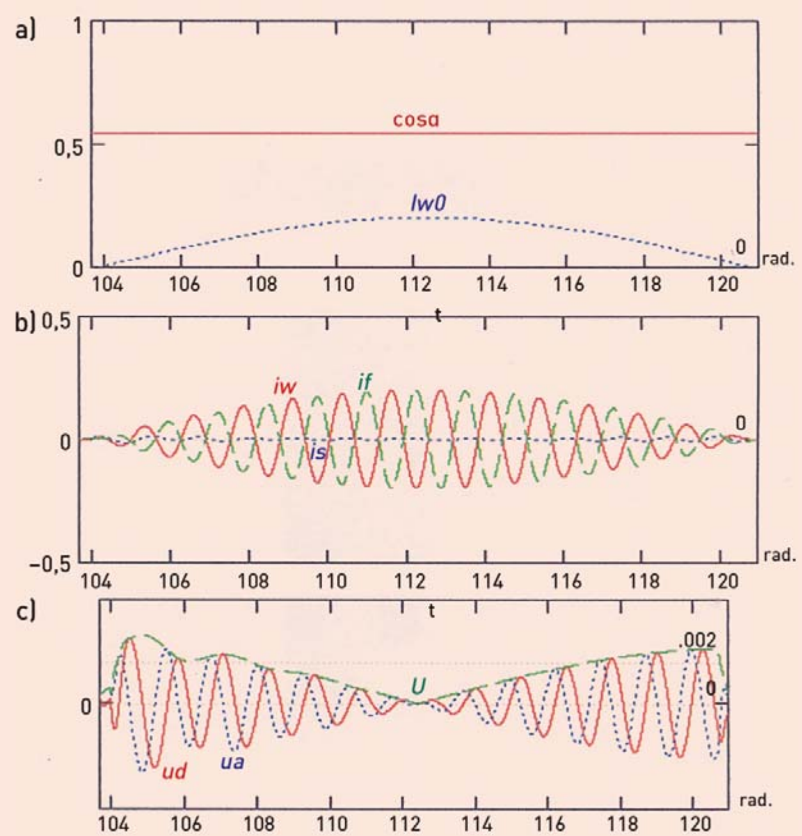
Results of calculations shown below are applicable to a scheme incorporating an active component (Fig. 1) with an active component control unit being synthesized by the DSB-algorithm. Operating conditions are the same as assumed above.

Fig. 6 shows active filter operating indicators and diagrams at the amplitude-modulated rectifier current. Parameters *xs, yf* remain unchanged. The rectifier current amplitude *Iw(·)* alters as per a bell-shaped curve, while the control angle cosine *cosa(·)* (see Fig. 6, a). The measured amplitude of bus bar voltage distortions amounts to A_u≈0,33%, while the amplitude of the current penetrating in the circuit is A_{is}≈1,5%.

Fig. 6, b shows rectifier currents *iw(·)*, of the filter *if(·)* and the circuit *is(·)* at the modulation step. It is evident that the filter current practically corresponds to the rectifier current in the reverse phase. Thus, the circuit current *is(·)* is vanishingly small and almost cannot be seen in the figure. Fig. 6 shows voltage diagrams *u(·)* by axes *d, q*. The ordinate scale here is substantially reduced as compared with Fig. 3 and 4; the pulsation amplitude hardly amounts to some fractions of one percent. The current curve valley *iw(·)* shows that pulsations are dampened up to zero and appear only at curve peaks *iw(·)*.

Fig. 7 shows active filter operating indicators and diagrams at the phase-modulated rectifier current. Voltage and current distortions under these conditions are efficiently dampened up to A_u≈0,345 %, A_{is}≈1,67 %.

ACTIVE FILTRATION OF AMPLITUDE-MODULATED CURRENT



a) distortion current amplitude — Iw0 and delay angle cosine; b) is — mains current; iw — distortion current; if — filter current; c) U-bus voltage; ud, uq — bus voltage in axis d, q

Fig. 6

CONCLUSION

The considered simple case clearly demonstrates that:

- high-Q resonant filters have no positive impacts under dynamic circuit loads and can even make filtration properties worse;
- a reduced Q-factor of applicable resonant circuits implying also energy losses has a very limited effect not permitting to achieve high filtration properties at dynamic circuit loads;
- high-frequency pulse-width modulated IGBT-converters can function in circuits as an active component — non-dissipative capacity amplifier which can synthesize, together with passive ohmic L, C-components, filters for the efficient absorption of circuit harmonics even at dynamic circuit loads when the harmonics appear to be modulated both by phase and amplitude.

In recent years, the presence of high harmonics in circuits has become an issue of concern. International (IEC, SIGRE) and Russian companies (GOSSTANDART, PJSC FGC UES, part of PJSC Rosseti Group of Companies, PJSC Rosseti) prepare new regulations on quality and filtration (for instance, [9], [10]). Under such conditions, active filters are recommended for designed facilities subject to dynamic loads.

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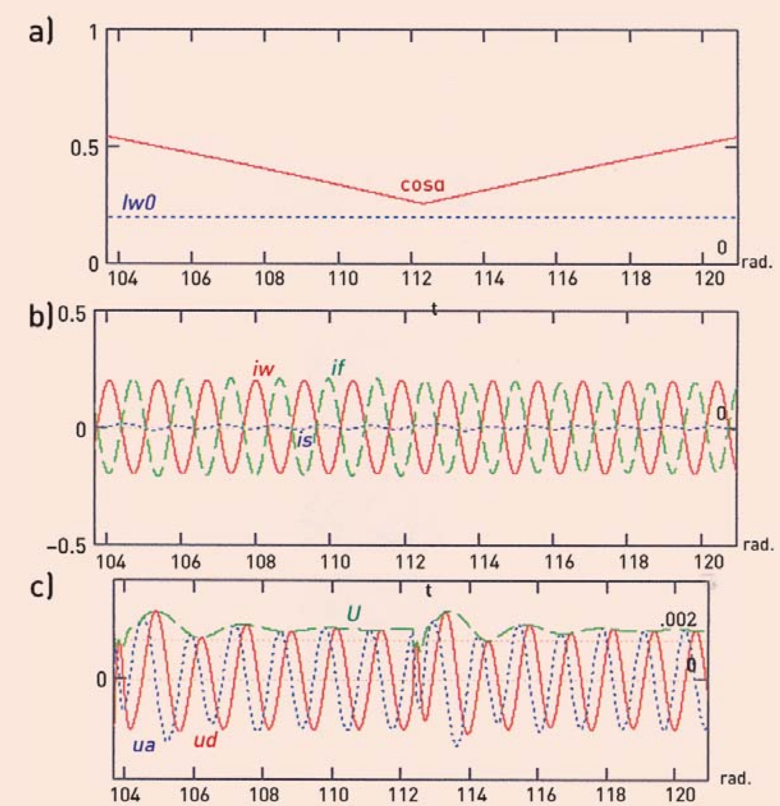
ACTIVE FILTRATION OF THE PHASE-MODULATED CURRENT



a) distortion current amplitude — Iw0 and delay angle cosine; b) is — mains current; iw — distortion current; if — filter current; c) U-bus voltage; ud, uq — bus voltage in axis d, q

Fig. 7

INFORMATION

ACTIVE FILTERS

Passive filters based on inductive reactors and capacitor banks have until recently been the main type of devices for filtering harmonics in an electrical network.

Disadvantages of passive filters on the basis of inductive reactors and capacitor batteries appear in two cases:

- when the requirement of qualitative filtration is combined with the need to adjust the reactive power;
- when the reactive power required for the system is less than the one obtained by filtration conditions.

Modern conditions of backbone electrical networks operation require increase in flexibility of electricity transmission, the use of sequential compensation controlled by thyristors and valve converters of power transmission and DC inserts.

Thereby, there is assumed wider application of the active filters, by which the filtration tasks are solved more efficiently.

Improvement of power transistors (increase in unit capacity, reduction of dynamic and static losses), as well as improvement of the signal processors (rapidity growth, increase in digit capacity) are additional factors in favor of the use of the active filters.

The use of active filters is most justified in systems that are organic sources of harmonics — thyristor converters of inserts and DC transmissions.