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Feedback control versus optimization method for voltage harmonic damping

Abstract. *Two methods of voltage harmonic elimination are compared - the feedback control method and optimisation approach. The first method has been presented in the literature, the second is proposed in the paper. The results of numerical experiments comparing the efficiency of both methods are presented and compared.*

Streszczenie. *Porównano dwie metody eliminacji harmonicznych napięcia w sieci elektrycznej – metodę sprzężenia zwrotnego i metodę optymalizacyjną. Pierwsza metoda jest opisana w literaturze druga jest proponowana w prezentowanej pracy. Przedstawiono wyniki eksperymentów numerycznych porównujących skuteczność redukcji wyższych harmonicznych przy użyciu obu metod.* ***(Porównanie metody sprzężenia zwrotnego i metody optymalizacyjnej eliminacji harmonicznych napięcia).***

Keywords: active power filters, detection of voltage harmonics, feedback loop damping, optimization method.
Słowa kluczowe: energetyczne filtry aktywne, eliminacja harmonicznych napięcia, sprzężenie zwrotne, optymalizacja.

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Introduction

Voltage distortion resulting from the harmonic currents produced by power electronic equipment has become a serious problem to be solved [1]. The fundamental change is caused by the power electronic based distributed generation [2,3]. Properly controlled distributed generation grid can improve the power quality. The converters interfacing wind or photovoltaic plants with the system can play a similar role as the active power filters. In general, individual low-power and high-power consumers are responsible for limiting distortion at the end of the line feeder, while electric utilities are responsible for limiting voltage distortion at the point of common coupling in the distribution systems. Most of the previous works concerning harmonic compensation of individual loads are based on the current-controlled method. The shunt active filter based on voltage detection at the point of compensator installation and the voltage-controlled method are more flexible in comparison to the current-controlled method. The typical structure of the power system composed of two grids and nonlinear load at application of the shunt active power filter in voltage-controlled method is illustrated in Fig. 1.

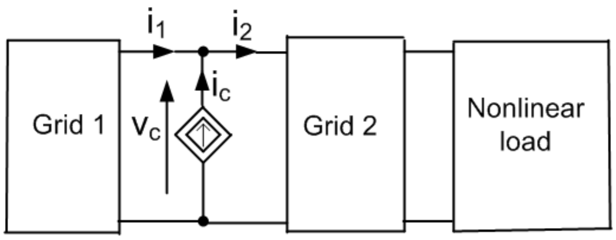

Fig. 1. General structure of connection of the voltage-controlled single-phase shunt active filter

In the voltage-controlled method we do not require a harmonic current reference. Instead we detect the voltage harmonics at the point of filter installation, and then inject a compensating current into the system.

Damping loop method

The voltage-controlled method proposed by Akagi [1] forms a feedback control loop. The filter detects voltage harmonics at the point of filter installation, and then injects a compensating current proportional to this harmonic. It can be described by the following relation

(1) $$i_c = G v_c$$

where *G* is a control gain.

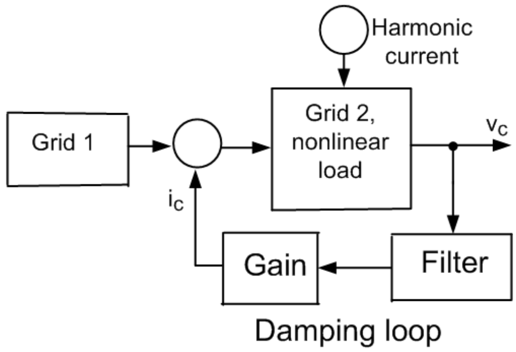

Fig. 2. Block diagram for Akagi damping method

The active filter behaves like resistor of equal resistance for all harmonics, except the fundamental frequency. For fundamental harmonic it behaves like an infinite resistance. The injected current is in a phase with the voltage for all harmonics; the phases of the injected current harmonics are not selected. Hence, this current does not reduce the voltage harmonics, it rather dumps the propagation of harmonics in the distribution system.

Optimization method

The other method of voltage control has been proposed in the papers [4,5,6,7]. This method is based on the optimization approach. The idea of it is illustrated in Fig. 3.

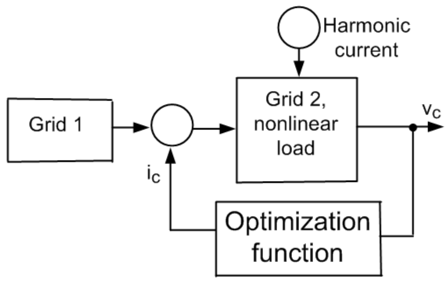

Fig. 3. Block diagram of the power system compensation using the optimization method

The total voltage harmonics distortion measured at the point of filter installation is chosen as the objective function which should be minimized in the process of optimization. Magnitudes and phases of the current harmonics that should be injected at the point of filter installation play the role of the optimized variables applied in the minimization process of the objective function (in practical computation they are substituted by the magnitudes of their sinusoidal and cosinusoidal components).

Multidimensional unconstrained nonlinear optimization process attempts to find the local minimum of the defined objective function. In this method not only magnitudes of the current harmonics but also their phases are selected.

Simulation results

Two methods: feedback damping control and an optimization approach are illustrated and compared for the simplified equivalent single phase circuit shown in Fig. 4.

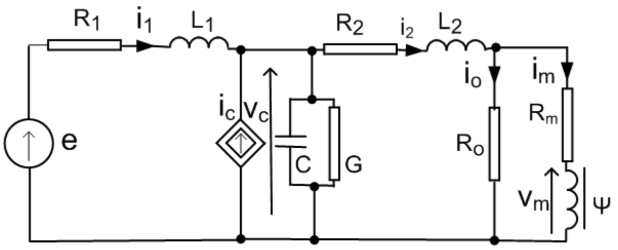

Fig. 4. Simulated circuit

The nonlinear load composed of resistance R_m and nonlinear inductor Ψ is supplied by a sinusoidal voltage $e = E_m \sin(\omega t + \psi)$. The magnetic curve is approximated by the polynomial of 9th order, $i_m = k_1\psi + k_9\psi^9$, where i_m and ψ are inductor current and magnetic flux, respectively. Due to the nonlinear inductance the voltage waveform v_c contains harmonics. The current controlled source i_c represents compensator and its current is controlled by the voltage v_c. We assume that currents i_m and i_2 are not available at measurements.

Two approaches to the problem are compared. The first, called a damping method (Fig. 2) assumes, that the compensator current is proportional to the voltage v_C with the extracted fundamental harmonic

$$i_c = G(v_c - v_1) \tag{2}$$

where v_1 represents first harmonic of voltage v_C and G is the compensator feedback gain.

The second proposed approach, called an optimisation method, assumes that reference current i_C is computed in such way that total harmonic distortion THD of the voltage v_C is minimized. The magnitudes and phases of the compensator current harmonics play the role of the searched variables.

The numerical results have been obtained for the following values of the circuit parameters: $E_m = 700V$, $\omega = 314\frac{rad}{s}$, $L_1 = 11mH$, $R_1 = 0.13\Omega$, $L_2 = 11mH$, $R_2 = 32\Omega$, $R_o = 10\Omega$, $R_m = 0.1\Omega$, $C = 0.1\mu F$, $G = 0.001S$ and magnetic curve coefficients $k_1 = 9$, $k_9 = 10$.

When the damping method is applied the compensator current is controlled according to the feedback loop of Fig. 1 which is presented in detail in Fig. 5 [1]. This branch contains two transfer functions $G_1(s)$, $G_2(s)$ and the additional gain G. In the considered numerical example the transfer function

$$G_1(s) = \frac{(314/\sqrt{2})s}{s^2 + (314/\sqrt{2})s + 314^2}$$

is realized as the second order filter, while the inertial element is characterized by the lowpass function

$$G_2(s) = \frac{5000}{s + 5000}$$

realizing the additional correction of the control dynamics.

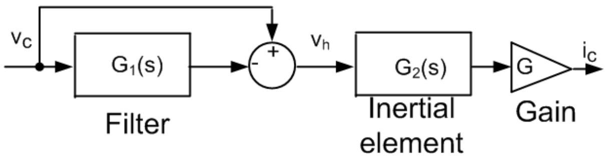

Fig. 5. Block diagram of feedback loop

The numerical experiments have shown that the system without additional inertial element looses stability in the case, when the gain $G > 0.015$. The lowpass filter improves dynamics of the system and enables application of the control with an optimal gain equal $G = 0.05$. The numerical verification of the Akagi method applied to the circuit of Fig. 4 has been conducted using Matlab.

When optimization method is applied the controlled current source produces the current composed of chosen harmonic set. In the presented numerical experiments this current was assumed in the form of four odd harmonics

$$i_c = I_3 \sin(3\omega t + \psi_3) + I_5 \sin(5\omega t + \psi_5) + $$
$$+ I_7 \sin(7\omega t + \psi_7) + I_9 \sin(9\omega t + \psi_9).$$

The magnitudes I_3, I_5, I_7, I_9 and corresponding phases ψ_3, ψ_5, ψ_7, ψ_9 are computed with the use of an optimization method. The total harmonic distortion of the voltage v_C is chosen as an objective function to be minimized. In the presented simulation two optimization functions of Matlab optimization toolbox have been used: *fminsearch* and *fminunc.*

The results of application of Akagi method and optimization approach are shown in Fig. 6. It presents the magnitudes of different harmonics of the voltage measured at the point of compensation. The lower image presents the results in a reduced scale to emphasize the details of higher harmonics relations before and after compensation.

The exact values of the voltage harmonic magnitudes obtained using both compensation methods are shown in Table 1.

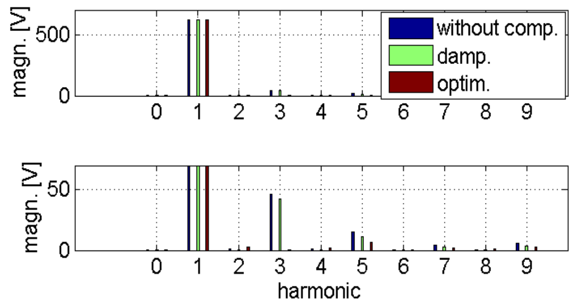

Fig. 6. Voltage harmonic magnitudes before and after compensation (the bottom figure presents the results in a reduced scale)

Table 1. Voltage harmonic magnitudes

Voltage harmonic	Without compensation	Damping Akagi method	Optimization method.
0	0.0263	0.0571	0.2350
1	617.7898	617.6387	617.3885
2	1.4097	0.2464	2.7062
3	46.0001	42.5123	0.7603
4	1.1058	0.1674	1.9150
5	16.5184	11.2148	6.3950
6	0.5047	0.0125	0.6131
7	4.0635	3.0918	2.0936
8	0.5612	0.0902	1.1734
9	5.8978	3.4565	2.3929

The resulting values of the voltage total harmonic distortion (THDV) before and after compensation using both methods are shown in Table 2.

Table 2. THDV for the two compensation methods

	Without compensator	Damping method	Optimization method
THDV	7.94%	7.16%	1.16%

The contents of the voltage harmonics presented in Fig. 6 and Table 1 are the effect of application of two different compensation methods and the resulting compensating currents injected into the power system. Table 3 presents the values of harmonics of compensator currents for the damping method with gain *G*=0.05 S and the optimization method after application of *fminsearch* Matlab function.

Table 3. Compensator currents in two compensating methods

Current harmonic	Damping method		Optimization method	
	Magnitude	Phase	Magnitude	Phase
	A	radians	A	radians
0	0.8589	0	0	0
1	1.7157	3.0700	0	0
2	1.7124	3.0570	0	0
3	1.0266	-1.6113	5.3068	-0.2685
4	1.7008	2.9637	0	0
5	1.6477	-3.0402	0.4096	-1.1955
6	1.6645	2.8712	0	0
7	1.7825	2.8075	0.2516	0.2516
8	1.6184	2.7850	0	0
9	1.6169	2.6491	0.2516	2.6114

Conclusions

The paper has compared the effectiveness of two methods of compensating current identification for a shunt active filter based on voltage detection. The filter based on the first approach, called in the paper the damping method, behaves like resistor for all voltage harmonics except the fundamental one. The active filter based on the first method forms a feedback control loop between the detected harmonic voltage and the compensating current. For the fundamental frequency it behaves as an infinite resistance. Time and phase delay in active controller might cause instability or deteriorate harmonic damping.

The second approach discussed in the paper, called the optimization method, identifies the compensating current also on the basis of the voltage measurement. However, the feedback loop formed in this method is based on the optimization algorithm. The computed values of the harmonics determine the magnitudes an phases of the compensator current harmonics. The system constitutes the feedforward control. Therefore, the system is less susceptible to the instability. The optimization process needs the additional time for computation and system may not follow the quick changes occurring in electrical system.

The comparison of these two discussed methods was done on the example for the circuit shown in Fig. 4. Therefore the conclusions following from this particular example cannot be treated as general. However, they show some particular features of the considered methods. It is seen in Table 3 that the compensating currents in these two methods are different. The dominating odd harmonics: 3 and 5, observed in a voltage waveform, are present and dominate in the compensator current when the optimization control is applied. Such correlation is not noticed in the damping method. The damping method needs precise adjustment of the parameters of the compensator. The parameters of the feedback gain and filter have to be adopted very precisely. Moreover, the phases of filtered voltage harmonics are important in the damping method. The second parameter, the feedback gain is also crucial, since its improper value may result in the loss of stability.

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