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Voltage harmonic damping with the framework based on Kalman approach

Abstract. *The paper presents the method of reference signal detection for shunt active power filter control. The signal is detected from voltage harmonics. The method uses the frequency state observer. The process needs a few iterative steps to obtain a compensator current reducing voltage harmonics. The virtual observer acting simultaneously with the system has kind of learning features.*

Streszczenie. *Podano metodę wyznaczania sygnału referencyjnego do sterowania aktywnego filtru energetycznego. Prądowy sygnał filtru jest obliczany na podstawie harmonicznych napięcia. W metodzie wykorzystywany jest obserwator działający w dziedzinie częstotliwości.. Proces wymaga kilku kroków iteracji do uzyskania prądu redukującego harmoniczne napięcia. Obserwator numeryczny działający równocześnie z systemem ma pewne cech uczenia się.* ***Tłumienie harmonicznych napięcia z wykorzystaniem struktury Kalmana***

Keywords: active power filters, detection of voltage harmonics, iteration algorithm.
Słowa kluczowe: energetyczne filtry aktywne, eliminacja harmonicznych napięcia, algorytm iteracyjny.

Introduction

Voltage distortion resulting from the harmonic currents produced by power electronic equipment has become a serious problem [1,2]. Generally, individual low-power and high-power consumers are responsible for limiting distortion at the end of line feeder, while electric utilities are responsible for limiting voltage distortion at the point of common coupling in distribution systems. Most of the previous works on harmonic compensation of individual loads are based on current-controlled methods [3,4,5]. The shunt active filters based on voltage detection at the points of compensator installation seem to be more flexible to the current-controlled compensators. The voltage-controlled method for a shunt active power filter is illustrated in Fig. 1. The symbol of current controlled source in this figure means a compensator. The system is divided into two subsystems, the active power filter is placed between two subsystems. The subsystems are composed of the sinusoidal voltage sources and linear RLC elements representing the transmission lines and nonlinear loads (Fig. 1).

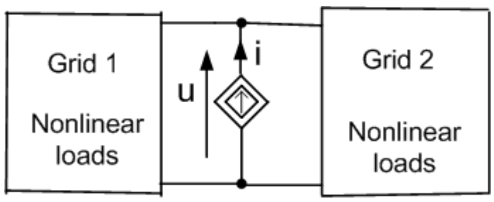

Fig. 1. General structure of voltage-controlled single-phase shunt active filter

The voltage-controlled method, which does not require the load current, detects reference signal from voltage waveform at the point of filter installation (PCC) , and then injects a compensating current.

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 as follows $i_c = G v_h$, where *G* is a control gain. The active filter behaves like resistor equal for all harmonic except the fundamental frequency. For fundamental harmonic it behaves as infinite resistance. Time and phase delay in active controller deteriorates harmonic damping and causes instability.

Iteration method of voltage harmonic detection is proposed in [6]. The method presented in [7] is based on the assumption, that all harmonics of compensator current should be shifted to voltage harmonics by 90°.

The optimization methods presented in papers [8,9] enable to find the optimal current waveform reducing voltage harmonics. This approach is very general but it needs many iteration steps to obtain satisfactory solution. Iteration algorithms based on electrical circuit properties and laws seems to be faster [8]. The method presented in this paper needs only a few iteration steps and still it has the merits of universality.

Iterative algorithm with learning attributes

The block diagram depicted the proposed method is shown in Fig. 2.

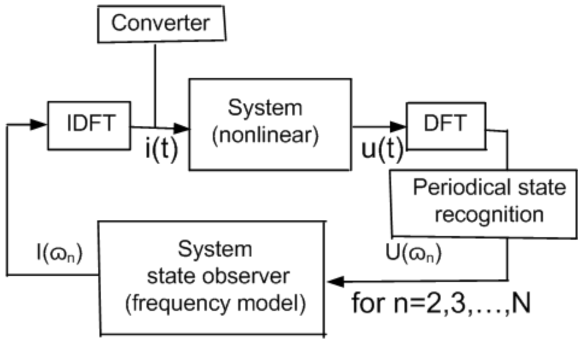

Fig. 2. Block diagram for searching of reference signal $i(t)$

In Fig. 2, the block named as *System (nonlinear)* denotes real electrical system and refers to the grids shown in Fig. 1. In the paper the real system is substituted for the simulation model (PLECS). The main interest is concentrated on the block named as *System state observer (frequency model)*, called in the text shortly model. This model can be treated as Kalman observer acting simultaneously to the real system [10,11]. The substantial difference between original Kalman concept and the presented here proposal follows from setting the model in frequency domain. The presented computations are concentrated on periodical state of the system under sinusoidal excitation. Time function of voltage $u(t)$ is transformed to the set of harmonics $U(\omega_n)$ for chosen harmonic ranks $n = 2,3,...,N$. The accuracy of harmonic computation is essential for the presented method. In order to obtain sufficient precision the window of samples for DFT [12,13] should be properly chosen also periodical state should be carefully estimated. This problem is marked in Fig. 2. During the iteration process, the system is stimulated with compensator current and satisfactory steady state must be reached and detected.

The essential for proposed method is the block named in Fig. 2 "*System state observer (frequency model)*". This model is composed of the set of *N* virtual circuits (F. 3).

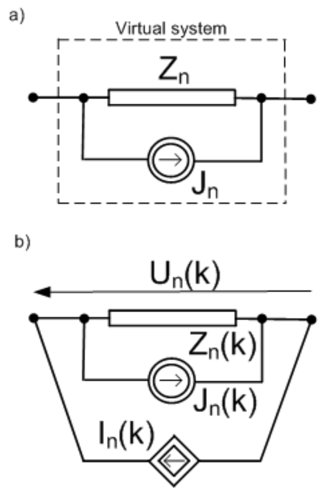

Fig. 3. State observer

Each *n*-th cell (component) is associated with *n*-th harmonic and it is responsible for generation of *n*th current harmonic $i_n(t)$. The parallel connection of two elements J_n and Z_n forms the circuit shown in Fig. 3. Current source J_n can be treated as the phasor representing current harmonic generated in *nonlinear system* (Fig. 2). Impedance Z_n means transfer function between compensator current as input and system voltage as output for *n*th harmonic. In *k*-th step, while the iteration process, this phasor and impedance take the complex values $J_n(k)$ and $Z_n(k)$. The pair J_n and Z_n can be interpreted as a describing function , known in control theory of nonlinear systems, originated by Krylov and Bogolubov in their averaging theory of nonlinear oscillatory systems.

Two measured signals, system voltage U_n and compensator current I_n, cooperate with the pair J_n and Z_n ,while iterative process is performed. At *k*-th iterative step, these four complex numbers are denoted as $U_n(k)$, $I_n(k)$, $Z_n(k)$, $J_n(k)$ as shown in Fig. 3b. The circuit shown in Fig. 3b leads to the set of equations having the unique solution. These equations and solutions constitute the base for the algorithm presented below.

Procedure for chosen *n*-th harmonic

Step 1.

The virtual system parameters $Z_n(1)$, $J_n(1)$ and compensator current $I_n(2)$ for step 2 are computed.

Measure voltage $U_n(0)$ for zero compensator current $I_n(0) = 0$.

For circuit in Fig. 3b

(1) $$U_n(0) = -Z_n(1)J_n(1)$$

Measure the voltage $U_n(1)$ for optional chosen nonzero compensator current $I_n(1)$.

For circuit in Fig. 3b

(2) $$U_n(1) = -Z_n(1)J_n(1) + Z_n(1)I_n(1)$$

From (1) and (2) is obtained

(3) $$Z_n(1) = \frac{U_n(1) - U_n(0)}{I_n(1)}$$

and

(4) $$J_n(1) = -\frac{U_n(0)}{Z_n(1)}$$

For step 2

(5) $$I_n(2) = J_n(1)$$

Equation (5) can be explained as follows. The desired voltage in the next step should be zero, $U_n(2) = 0$. For estimated system parameters (3) and (4) , it means that the following equation should be fulfilled

(6) $$0 = -Z_n(1)J_n(1) + Z_n(1)I_n(2)$$

Hence, equation (5) is proposed.

Step 2.

The virtual system parameters $Z_n(2)$, $J_n(2)$ and compensator current $I_n(3)$ for step 3 are computed.

Measure voltage $U_n(2)$ for compensator current $I_n(2)$ given in (5). As it can be expected $U_n(2) \neq 0$ and the next iteration step is necessary.

Taking in consideration (5), for circuit in Fig. 3b we obtain

(7) $$U_n(2) = -Z_n(2)J_n(2) + Z_n(2)J_n(1)$$

Two unknowns $Z_n(2)$ and $J_n(2)$ are seen in (7). Modified equation (1) is applied as the additional equation. New value $Z_n(2)$ instead of $Z_n(1)$ is put to (1) . Thus, we have

(8) $$U_n(0) = -Z_n(2)J_n(2)$$

From (7) and (8) is

(9) $$Z_n(2) = \frac{U_n(2) - U_n(0)}{J_n(1)}$$

(10) $$J_n(2) = -\frac{U_n(0)}{Z_n(2)}$$

(11) $$I_n(3) = J_n(2)$$

Formulae (9) and (10) can be generalized for *k*-th step.

(12) $$Z_n(k) = \frac{U_n(k) - U_n(0)}{J_n(k-1)}$$

(13) $$J_n(k) = -\frac{U_n(0)}{Z_n(k)}$$

(14) $$I_n(k+1) = J_n(k)$$

The algorithm should be executed for *k=1,…,K*, where index *K* should be chosen in the proper stop criterion, for example taking $|U_n(K)| < U_{\max}$, for *n*=2,…,*N.*

The algorithm given in equations (1)-(15) for single harmonic can be simultaneously performed for all chosen harmonics.

The algorithm contented in equations (1)-(14) can be illustrated for real numbers. Let the circuit in Fig. 3b be substituted for dc resistive circuit with the same topology and $Z(k) = R(k)$. For such dc circuit the following equation, similar to (2), can be written

(16) $$U(k) = R(k)I(k) - R(k)J(k)$$

Equation (16) describes the family of straight lines $U = f(I)$ for k=1,2,3,..,K . These lines are shown in Fig. 4.

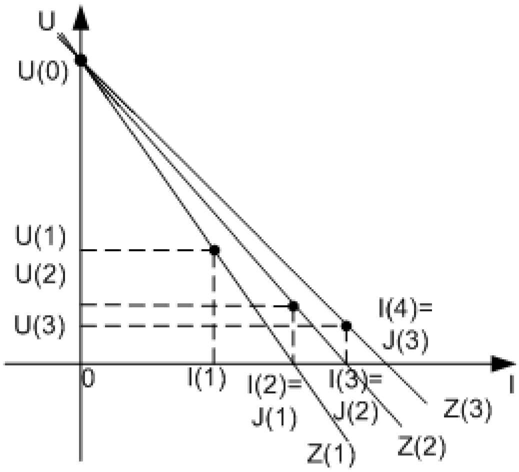

Fig. 4. Graphical illustration of the proposed algorithm

The pencil of lines illustrating the sequence of iterations can be also drawn for the next iteration sequence. For the next sequence the pencil of lines is similar as shown in Fig. 4, but the point $U(0)$ should be moved to new place on *y* axes with coordinate equal $U(0)_r + U_n(0)_p$.

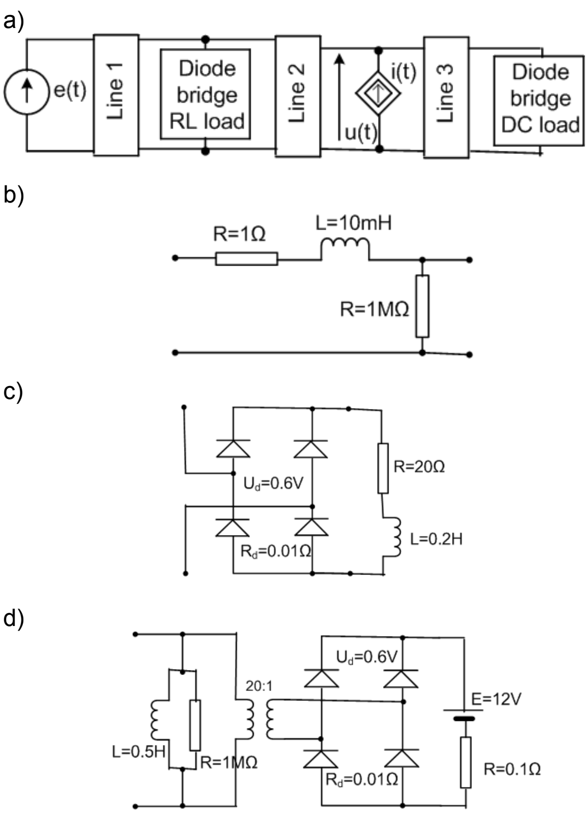

Fig. 5. Simulated circuit , a) structure, b) lines, c) load 1, d) load 2

Simulation results

The single phase circuit shown in Fig. 4 is chosen for computer simulation. The system is fed by sinusoidal voltage $e = E\sin(\omega t + \psi)$, with $E = 400V$, $\omega = 2\pi 50 \frac{rad}{s}$, $\psi = \frac{\pi}{2}$. Three sections of transmission lines (Fig. 4b) are connected to two nonlinear loads containing diode bridges (Fig. 4c and d) . The compensator, denoted as the controlled current source, is connected between line 2 an line 3 (Fig. 4a). Voltage $u(t)$ is detected, current $i(t)$ is searched ad injected to the system in order to reduce harmonics of voltage $u(t)$.

The circuit shown in Fig. 5 is simulated with the use of program MATLAB+PLECS and verified with LTspice. The procedure presented above is applied starting from *step 1* . The obtained results are shown in Figs. 6 to 8 and in Table1. Fig. 6 shows the voltage amplitudes for harmonics 3,5,7 obtained in the preceding iteration steps from 0 to 8.

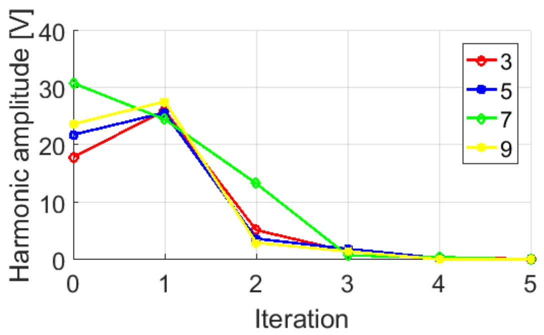

Fig. 6. Voltage harmonic amplitudes during iteration process

Table 1.System describing parameters, compensator currents and system resulting voltages

Iter	Z3 [Ω]	J3 [A]	I3 [A]	U3 [V]
0	--------- ---------	------- ---------	0.000 0.000i	23.209 4.977i
1	14.305 -3.155i	-1.474 -0.673i	0.200 0.200i	26.701 7.207i
2	14.179 -4.996i	-1.346 -0.825i	-1.474 -0.673i	-1.052 2.799i
3	14.963 -5.496i	-1.259 -0.795i	-1.346 -0.825i	-1.468 0.026i
4	14.909 -5.513i	-1.261 -0.800i	-1.259 -0.795i	0.054 0.064i
5	14.883 -5.459i	-1.266 -0.799i	-1.261 -0.800i	0.076 -0.048i

Iter	Z5	J5	I5	U5
0	--------- ---------	-------- --------	0.000 0.000i	-30.499 4.779i
1	18.441-14.518i	1.147 0.644i	0.200 0.200i	-23.907 5.564i
2	24.258 -6.206i	1.227 0.117i	1.147 0.644i	1.320 13.279i
3	24.119 -6.806i	1.223 0.147i	1.227 0.117i	-0.100 -0.753i
4	23.904 -7.106i	1.227 0.165i	1.223 0.147i	-0.220 -0.398i
5	23.865 -7.095i	1.229 0.165i	1.227 0.165i	-0.050 0.007i

Iter	Z7	J7	I7	U7
0	--------- ---------	-------- --------	0.000 0.000i	13.320-17.329i
1	24.349-13.116i	-0.721 0.323i	0.200 0.200i	20.813-15.083i
2	28.198-10.460i	-0.616 0.386i	-0.721 0.323i	-3.634 -0.671i
3	30.793-10.601i	-0.560 0.370i	-0.616 0.386i	-1.543 1.089i
4	31.214-10.558i	-0.551 0.369i	-0.560 0.370i	-0.251 0.131i
5	31.186-10.598i	-0.552 0.368i	-0.551 0.369i	0.030 0.012i

Iter	Z9	J9	I9	U9
0	--------- ---------	--------- --------	0.000 0.000i	7.691 16.212i
1	31.919-12.104i	-0.042 -0.524i	0.200 0.200i	16.496 20.175i
2	34.490-21.644i	0.052 -0.438i	-0.042 -0.524i	-5.107 -0.943i
3	31.261-21.453i	0.075 -0.467i	0.052 -0.438i	-0.083 1.423i
4	31.467-20.821i	0.067 -0.471i	0.075 -0.467i	0.311 -0.049i
5	31.736-21.052i	0.067 -0.466i	0.067 -0.471i	-0.091 -0.142i

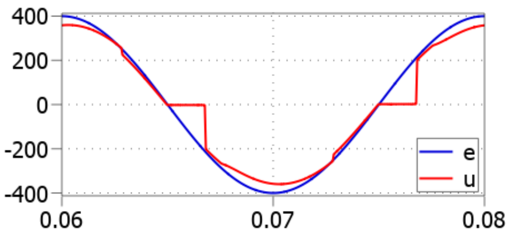

Fig. 7. Voltage waveform of the generator and voltage at the compensator location before compensation

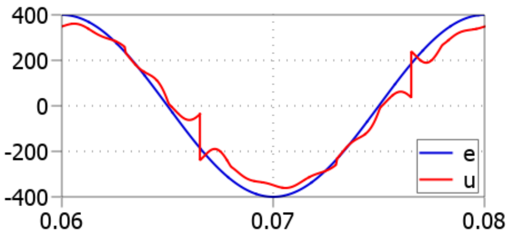

Fig. 8. Voltage waveform of the generator and voltage at the compensator location after compensation

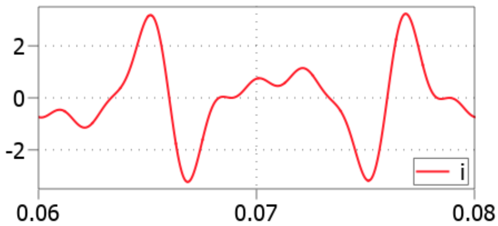

Fig. 9. Compensator current achieved

The numerical results obtained for four harmonics while iteration process are presented in Table 1. This table contains complex numbers obtained in preceding iteration steps. The first two columns include parameters describing virtual model of the real system, namely, its describing impedance Z_n and describing current source J_n.

The second two columns contain current injected to the system I_n and resulting harmonic voltage U_3. It can be seen that the components of column J_3 are equal to the delayed components of I_3. The current initiated the procedure was chosen freely, as it can be seen in Table 1, this value is equal 0.2+0.2i for every harmonic.

The time waveforms of the generator voltage and the voltage at the compensator location, before and after compensation, are shown in Figs. 7 and 8. Fig. 9 shows the waveform of compensator current computed while iteration procedure is injected to the system.

Conclusions

The method uses the state observer acting in frequency domain. The computations concern periodical state of system under sinusoidal excitation. The time function of voltage is transformed to the set of chosen harmonics. The accuracy of harmonic computation is essential for the presented method. In order to obtain sufficient precision the window of samples for DFT should be chosen close to voltage period. During the iteration process, the system is stimulated with compensator current, the satisfactory steady state must be reached and detected. Within the compensating process the system parameters are continuously estimated . This estimated parameters can be applied within the process.

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REFERENCES

[1] H. Akagi, Control Strategy and Side Selection of a Shunt Active Filter for Damping of Harmonic Propagation in Power Distribution Systems , *IEEE Tarans. Power Delivwery*, Vol. 12, January 1997, pp. 354-362

[2] J. Tlusty, P. Santarius, V. Valouch, J. Skramlik, Optimal control of shunt active power filters in multibus industrial power systems for harmonic voltage mitigation, *Mathematics and Computers in Simulation*, 2006, t. 71, z.4 p. 369

[3] R. Strzelecki, H. Supronowicz: Współczynnik mocy w systemach zasilania prądu przemiennego I metody jego poprawy. Oficyna Wydawnicza Politechniki Warszawskiej, 2000

[4] H. Akagi, E. H. Watanabe, M. Aredes, Instantaneous Power Theory and Applications to Power Conditioning, John Wiley & Sons, 2007

[5] T. Adrikowski, D. Buła, M. Pasko, „Simulation of active Power filter with prediction control In MATLAB and CAD enviroments with using SLPS interface," *Przegląd Elektrotechniczny*, vol. 87, No. 5, 2011, pp. 1-5.

[6] D. Menniti, A. Burgio, N. Sorrentino, A. Pinnarelli, Implementation of the shunt harmonic compensation approach, *ELSEVIER Electric Power Systems Research* 81 (2011) 798-804

[7] C. Mingfeng, Lei Wanjun, N. Cheng, W. Huajia, W. Yue, A novel contrl algprithm of shunt active power filter based on voltage detection, 2016 China Int. Conf. on Electricity Distribution, Xi'an, 10- 13 Aug., 2016

[8] K. Mikołajuk, S. Osowski, A. Toboła, Feedback control versus optimizatiom metod for voltage harmonic damping. *Przegląd Elektrotechniczny*, vol. 90, No. 4, 2014, pp. 239-241

[9] K. Mikołajuk, A. Toboła, Multiobjective Optimization Approach to the Active Power Filter Control. CPEE 16, Sandomierz, September, 2016

[10] J. Barros, E. Perez, An Adaptive Method for Detrmining The reference Compensating Current in Single-Pfase Shunt Active Power Filters, IEEE Trans. on *Power Delivery*, Vol. 18, No. 4, October 2003

[11] J. Ye, Z. Zhang, A. Shen, J. Xu, F. Wu, Kalman Filter Based Grid Impedance Estimating for Harmonic Order Scheduling Method of Active Power Filter with Output LCL Filter, Int. Symposium on Power Electronics, Electrical Drives, Automation and Motion, IEEE 2016

[12] E. Jacobsen, R. Lyons, The Sliding DFT, *Signal Processing Magazine*, IEEE, Vol. 20, No 2, March 2003, pp. 74-80

[13] K. P. Sozański, Harmonic Compensation Using the Sliding DFT Algorithm for Three-phase Active Power Filter, Power Electronics Specialists Conf. 2004, PESC 04.2004 IEEE