Optimization Methods for Current Harmonics Estimation

Kazimierz Mikołajuk, Sławomir Kwiczak

***Abstract* — The group harmonic compensation in electrical systems, especially compensation of scattered nonlinear loads needs a proper approach to acquisition of reference signals controlling compensators. Such signal cannot be worked out from the current of individual load. The reference signal should be obtained from voltage waveform. Presented method of compensation current estimation can be classified as an invasive method. The change of voltage waveform caused by compensator current is the source of information for proposed iterative algorithm. This algorithm allows to compute the current reducing voltage distortion. It has been shown that optimization algorithms available in MATLAB can be used for considered purpose. Numerical tests have been made for the example nonlinear circuit. The quasi-Newton algorithm was used in these tests.**

I. Introduction

During last decade it is possible to observe the spreading of power factor correctors application. In many countries rigor regulations concerning nonlinear devices connected to electrical systems have been introduced in many countries. Despite this the voltage distortion does not decrease. On the contrary in many European countries the increasing of voltage distortion is observable. The harmonic compensation of individual loads is presently dominating. It seems that in order to restraint voltage harmonic distortion the group compensation should supplement the individual compensation [2]. Such compensation methods actually are not sufficiently developed. Among numerous unsolved problems arising in the group compensation the problem of reference signals for such compensator control brings essential difficulties. Usually the reference signals for individual compensators are obtained from load current. Two approaches are most common for this purpose. The first method employs Fryze active current and the second is based on so called instantaneous reactive power. The conception of instantaneous reactive power is valid only for three-phase circuits. These both approaches need the load current to be available. When the group compensation is proposed the desired current injected to the electric grid should be worked out from the voltage waveform. The main purpose of the paper is to show how the reference signal can be worked out from voltage waveform with the use of iterative optimization algorithms.

Authors are with the Institute of the Theory of Electrical Engineering, Measurement and Information Systems, Warsaw University of Technology, ul. Koszykowa 75, 00-662 Warszawa, Poland, e-mail: *mik@iem.pw.edu.pl*

II. Formulation of the Optimization Problem

The problem of harmonic current estimation can be solved with the use of optimization algorithms. Because the estimation should be performed on-line the problem can be classified also as an optimal control problem. Unconstrained or constrained optimization methods can be used for this purpose. The paper presents only the unconstrained method.

Objective functions defined for the considered problem are smooth but practically it is impossible or difficult to compute the gradient vector of these functions. It follows from the fact that the function value is the result of complex processing of measurement or simulation data. It means that derivatives should be approximated by finite differences. This causes two kinds of errors: truncation error and condition (cancellation) error [3]. Truncation error is the linear function of finite difference interval h and condition error is a linear function of $(1/h)$. Hence, changes in h will tend to have opposite effects on these errors. Ideally, the finite-difference interval h would be chosen to yield the smallest error, i.e., to minimize the sum of the truncation and condition errors. Unfortunately, it is impossible in general to compute the value of h that yields the smallest error, since the quantities determining these two errors are not available.

The considered problem is specific in this, that objective function has its minimum equal to zero. Hence, the minimization problem is equivalent to finding a zero of the function. It means that algorithms for zero-finding also can be applied for the problem. Such algorithm using Newton's method was presented in the papers [4,5,6]. This simple algorithm may not be satisfactory when many harmonics are sought simultaneously.

The simulation results presented in the paper have been obtained with the use of MATLAB algorithms, namely the function *fminunc*. The function *fminunc* is based on quasi-Newton algorithm with curvature computation by Broyden-Fletcher-Goldfarb-Shanno method.

A choice of proper objective function is an important task and it depends on desired effects. The real and imaginary parts of voltage harmonic phasors are used as parameters of defined objective function. The parameter vector consists of the pairs representing each harmonic, since harmonics are described by their complex values.

In nonlinear circuits it is impossible to compensate each harmonic separately, since there is mutual influence between harmonics. The compensator reduces a finite set of harmonics and this harmonics should be computed in each algorithm step.

Total harmonic distortion (THD) is one of possible choice of optimization objective function. The other possibility is minimization of chosen set of voltage harmonic amplitudes. In the first case the minimization does not guarantees the complete reduction of harmonics generate by compensator but all harmonic spectrum is modified in such way that voltage THD is minimized. In the second case total reduction of chosen harmonics may be realized.

III. Simulation examples

Let us consider the circuit shown in Fig. 1 [7]. The nonlinear inductance is supplied from sinusoidal source $e = E_m \sin(\omega t + \varphi)$. The inductance current is nonsinusoidal and as a effect voltage u becomes non-sinusoidal. The compensator represented by current source should generate such current i_K that distortion of voltage u is reduced to zero. We assume that inductance current cannot be measured, only voltage waveform u and compensator current i_K is available.

Błąd! Nie podano tematu. Fig. 1. The circuit with nonlinear inductance and compensator i_K

Such aim can be reached by minimization of the objective function properly chosen. In presented example as the objective function the voltage total harmonic distortion coefficient (THD) is chosen

$$F = \frac{\sqrt{\sum_{h=2}^{\infty} (U^{(h)})^2}}{U^{(1)}} \quad (1)$$

The task described above has been solved with the use of *fminunc* function from MATLAB program [1]. The Fourier transform of voltage u and compensator current i_K waveforms are computed in each iteration step. The harmonics are represented by their real and imaginary parts, which are changed within optimization process. The objective function (1) is computed in each iteration step from simulation of the circuit shown in Fig. 1 with the use of NAP program. In the performed test the compensator current i_K was chosen consisting only three harmonics as given below

$$i_K = I_K^{(3)} \sin(3\omega t + \varphi^{(3)}) + I_K^{(5)} \sin(5\omega t + \varphi^{(5)}) + I_K^{(7)} \sin(7\omega t + \varphi^{(7)}) \quad (2)$$

The problem described above has been solved for the following circuit resistances $R = 5\Omega$, $R_0 = 10\Omega$, source voltage $e = 340\sin(314t)$ and nonlinear inductance is defined by the given in Table I. In this table Ψ means inductor magnetic flux given in webers and i inductor current in amperes.

Table I

The Nonlinear Inductor Characteristics

i	A	0	0.45	0.98	1.37	2.00	2.52
Ψ	Wb	0	0.07	0.15	0.18	0.22	0.25
3.33	4.33	6.07	8.33	13.3	21.7	33.3	40
0.27	0.28	0.31	0.32	0.32	0.38	0.39	0.4

For magnetic flux depending on current as given in table 1 it is possible to determine dynamic inductance as the function of inductor current. Such characteristics are shown in Fig. 2.

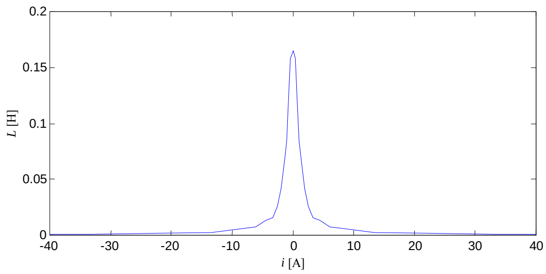


Fig. 2. The inductance as the function of inductor current

The optimization process is illustrated in Fig. 3. After about 100 steps objective function (THD) is stabilized on the quite low level.

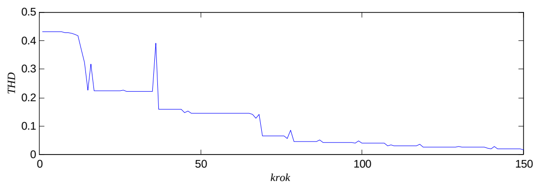
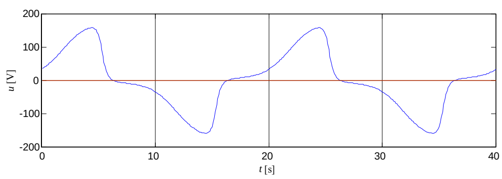


Fig. 3. THD as a function of the optimization process

The computation starts from arbitrarily chosen small compensator current i_K. For such current voltage u is computed using NAP program. The results of NAP simulation are further processed by MATLAB [1]. The voltage u FFT transform and objective function (1) is computed. Then *fminunc* function is employed and new current harmonics and it yields new compensator current.

The results of the optimization are shown in Fig. 4 and 5 and in Table 2. Upper drawing in Fig. 4 shows the voltage waveform u before compensation and lower drawing shows this voltage after compensation.



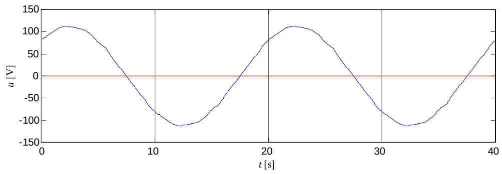


Fig. 4. Voltage waveforms before and after compensation

The harmonic amplitudes of voltage waveforms shown in Fig. 4 are presented in Fig. 5. All harmonics are reduced as a effect of compensation.

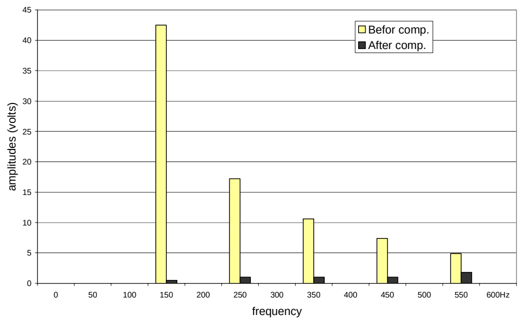


Fig. 5. Voltage harmonic amplitudes before and after compensation

The voltage total harmonic distortion (THD) before compensation is equal 0,43. This coefficient after compensation is reduced to 0.01. The compensator current harmonics computed by optimization process are presented in Table 2.

TABLE II

COMPENSATOR CURRENT HARMONICS

Harmonic rank *h*	$I_K^{(h)}$ [A]	THD
3	$-15.2\exp(j1.01)$	
5	$6.61\exp(-j0.38)$	0.01
7	$1.91\exp(-j1.40)$	

We can observe in Fig. 5 that as a effect of compensation harmonics 9^{th} and 11^{th} are reduced as well, although compensator generates only harmonics 3^{rd} , 5^{th} and 7^{th}. As a result of circuit nonlinearity there is influence of one harmonic on the other. But such effect not always is positive. Such negative influence can be noticed in the next example.

Fig. 6 illustrates the simple network with two linear loads R_{L1}, R_{L2} and one nonlinear load – rectifier bridge supplying series connection or resistor R_{L3} and inductor L_{L3}. Remaining resistances R_S and inductances L_S represent parameters of supplying lines. The current source i_K represents compensator. The problem is to compute such compensator current i_K which minimize the voltage distortion across the load R_{L2}.

Błąd! Nie podano tematu.

Fig. 6. The circuit with diode bridge and compensator i_K

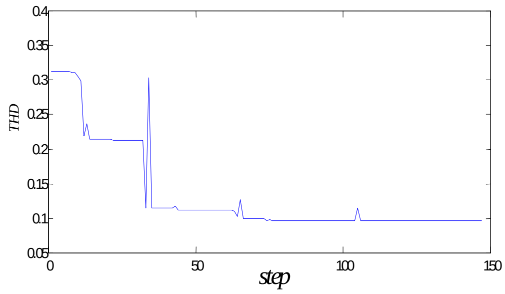
We assume that compensator generates the current containing three odd harmonics as given in (2).

Each harmonic should be properly chosen to minimize the objective function. In the present example the objective function is defined by (1), so it is the same as in the previous example.

Numerical tests have been done for the following values of the circuit parameters: $e_1 = 220\sqrt{2}\sin(\omega t)V$, $R_{L1} = 30\Omega$, $R_{L2} = 30\Omega$, $R_{L3} = 3\Omega$, $L_{L3} = 100mH$, $L_{S1} = 10mH$, $L_{S2} = 10mH$, $L_{S3} = 10mH$, $R_{S1} = 3\Omega$, $R_{S2} = 3\Omega$, $R_{S3} = 3\Omega$.

Fig. 2 shows how the objective function is changing with the progress of optimization process. It is seen that during the first tens of iterative steps the changing of the objective function has the staircase form.

Voltage THD before compensation is equal to 0.31, after 146 steps of optimization process THD has been reduced to the value 0.09. The voltage harmonic amplitudes before and after compensation are shown in Fig. 4.



Fi

Fig. 7. Optimization process: voltage THD as a function of iterative step number

This result was obtained for compensator current consisting only three harmonics given by (2). It is seen that dominated 5^{th} and 9^{th} harmonics are reduced. The remaining harmonics after compensation are bigger than before compensation. Despite this, the objective function (1) equivalent to THD coefficient is reduced from 0.31 to 0.9. The 2^{nd}, 3^{rd} and 7^{th} harmonic appeared although those were absent before compensation. It can be explained by the need of reduction of 9^{th} harmonic which was one of two dominated before compensation and absent in compensator current. It could be done only with the assistance of 3rd and 7th harmonic, as compensator does not generate 9th harmonic.

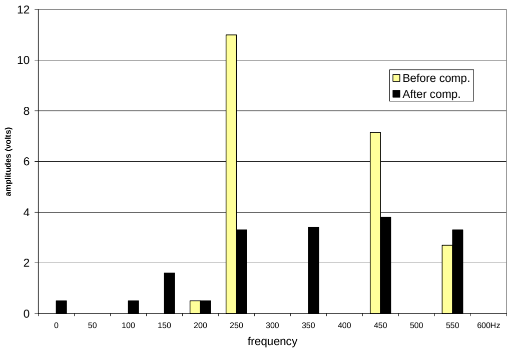


Fig. 8. Voltage harmonc amplitudes before and after optimization process

The 3rd harmonic is the biggest in computed compensator current although it was not observable in voltage waveform before compensation.

TABLE III

COMPENSATOR CURRENT HARMONICS

Harmonic rank h	$I_K^{(h)}$ [A]	THD
3	$-7.61\exp(j1.01)$	
5	$3.83\exp(-j1.39)$	0.09
7	$1.83\exp(-j0.64)$	

IV. CONCLUSIONS

Depending on desired goal the electronic parallel compensator should develop the proper current. If nonlinear load is connected to the grid with sinusoidal voltage, then the current drown by the load is non-sinusoidal. The voltage across this load remained almost sinusoidal, provided that load current is small comparing with short circuit current of the supplying system. With such simplification it can be assumed that the compensator's role is to reduce all harmonics contained in the load current. Hence, the compensator should generate the current opposite to the difference between actual load current and its fundamental harmonic. If the supplying system is not stiff enough, then such assumption leads to considerable errors. The compensator connected to the weak network causes the voltage waveform distortion. The problem of the compensator current choice should be solved by iterative procedure. The problem can be solved using Optimization methods bring tools proper for this purpose. Such method has been employed in the presented paper.

The optimization method applied in the presented examples issues from MATLAB. Even such non-specialized algorithm brings interesting results. The presented examples illustrate phenomenon of the frequencies mixing. The compensator connected causes appearance of new harmonics non-observed in original voltage.

The compensator from its nature can generate only limited band of frequencies. However a proper choice of the developed spectrum is important.

In the first example the compensator generating only three harmonics reduces whole harmonic spectrum very efficiently. In the second example these three harmonics are not satisfactory. Probably supplementing the compensator current with 9th harmonic could bring considering improvement. The optimization approach to compensation problems is not satisfactory developed, but the first trials are quite promising.

REFERENCES

[1] Coleman T.,Branch M. A., Grace A., Optimization Toolbox User Guide, MathWorks, 1999

[2] Dai X., Gretsch R. Optimal Compensator Currents for the Reduction of the Harmonic Distortion Networks, ETEP Vol. 4, 1994, pp. 301-313

[3] Gill P. E ., Murray W., Wright M. H., Practical Optimization, Academic Press, London, 1981

[4] Mikołajuk K., Toboła A., A New Method for Reduction of Currents and Voltage Harmonic Distortion In Power Systems, Eur. Trans. On Electr. Power, no. 1, 1993, pp. 85-90

[5] Mikołajuk K. Kwiczak S. K., Staroszczyk Z., Measurement aspects of the voltage distortion compensation; European Trans. El. Power Eng. vol.4 No.5 (1994), pp.403-410

[6] Mikołajuk K., Staroszczyk Z., Kwiczak S., Three Phase System Harmonics Identification for Compensation Purposes, Fifth International Workshop on Power Definition and Measurements under Nonsinusoidal Conditions, Milano, 2000

[7] Kwiczak S. K., Estymacja wyższych harmonicznych prądu w oparciu o pomiary napięcia, Doctoral Thesis, Warsaw University of Technoogy, 2003