Non-linear Loads Identification Using Voltage Source with Second Harmonic Injection

Marko Dimitrijević, Vančo Litovski

Abstract - The existence of the higher harmonics in the current spectrum are well known and studied phenomena. Their negative effects on power grid and connected devices are of particular importance and subject of an extensive research. Nevertheless, higher harmonics in current spectrum can be utilized for identifying nonlinear loads connected to the power grid. The method of identification can be based on some type of machine learning or deep learning algorithm, where current harmonics are used as input parameters.

At most nonlinear loads, the harmonic amplitude decreases monotonically as the harmonic order increases, and current spectrum consists of odd harmonic only. This can reduce the number of input parameters and impair performance of an algorithm.

In this paper, we are proposing the method of voltage source second harmonic injection that can overcame identified problems.

Keywords – current harmonics, nonlinear loads identification.

I. INTRODUCTION

In the last 30 years, the way electricity has been used has changed significantly [1]. Increase in the number of consumer electronic devices had enormous influence on world economy and to our lifestyle. In addition, raising awareness of climate changing forces automotive industry to switch from internal combustion engines to electric ones. As a consequence, electronic devices immensely change the structure of total power consumption. With the increase in electric power consumption, load identification and monitoring became important.

Today, electronic systems are synonym for nonlinear load. They represent a circuit consisting of semiconductor devices, which require direct current for operation. However, electric energy is supplied in the form of alternating current, which cannot be directly used for electronic device operation. Hence, all electronic devices must have some kind of power converter.

The power converter can be modelled as two-port network with nonlinear input impedance connected to power grid. Hence, the characterization of the electronic device can be performed by characterization of the power converter. This characterization can be done by determining the current spectrum or other quantities that can be used as unique fingerprint of that device. The higher harmonic components in the current spectrum cause losses and disturbance in the power grid. Favourably, they can be regarded as specific signature of a nonlinear load, therefore providing the means for classifying nonlinear loads connected to the power grid [2].

The identification and classification methods of nonlinear loads can be direct – using harmonic components of current spectrum, or indirect – using some of the parameters that depend on harmonics. In our previous research, an indirect method for classification of nonlinear loads using artificial neural networks (ANNs), based on active, reactive and distortion power was investigated [3, 4].

The direct method, using current spectrum is elaborated in [2]. In this research, amplitudes of current harmonics as inputs for classification of nonlinear loads were used. The presented method fits into NILM category – one measuring device for various combinations of devices were used. The method consists of three phases: signal acquisition, current harmonic extraction and device identification and classification using ANNs. The acquisition and harmonic extraction are performed using system for nonlinear load analysis [5]. The extracted parameters, i.e., amplitudes of current harmonics are used for ANN training. Finally, the trained ANN was employed for identification of similar nonlinear loads and unknown combinations of loads connected to the power grid.

For most nonlinear loads, the harmonic amplitude decreases monotonically as the harmonic order increases, and current spectrum consists of odd harmonic only. This reduces number of input parameters and impairs performance of an algorithm. In this paper, the issues of identification and classification based on current harmonics are discussed and the method of voltage second harmonic injection is proposed, that can overcome identified problems.

The paper is organized as follows: in the second section the classification of nonlinear loads using current spectrum is discussed. In third section, the method of second voltage injection is proposed and discussed. The measured results with nonlinear loads are presented. Forth section concludes the paper.

II. CLASSIFICATION OF NONLINEAR LOADS USING CURRENT SPECTRUM

A. Harmonic analysis

The first step in recognizing and classifying nonlinear consumers is harmonic analysis. It will provide parameters

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for ANN training. Harmonic analysis is performed using system for nonlinear load analysis, in order to measure current and to determine the current spectrum, i.e., higher harmonics using Fourier analysis. The system is based on acquisition modules for A/D conversion, computer interface and software component for harmonic analysis, described in great detail in [5].

Having in mind that power grid impedance is low, the voltage waveform can be regarded as constant and independent on current at the point of common connection (PCC). The mains can be approximated with ideal voltage generator (Fig 1).

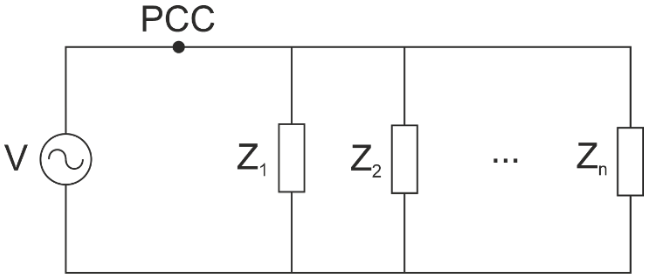

Fig. 1. The mains is approximated with ideal voltage generator V, suppling various loads Z_1, ..., Z_n.

The total current flowing through PCC is equal to the sum of all currents flowing through loads Z_n.

The current can be represented using Fourier series:

$$i(t) = A_0 + \sum_{k=1}^{\infty}\left(A_k \cdot \cos(k\omega t) + B_k \cdot \sin(k\omega t)\right)$$
$$i(t) = I_0 + \sum_{k=1}^{\infty} I_k \cdot \cos(k\omega t + \varphi_k) \qquad (1)$$

where $I_0 = A_0$ represents DC current, $I_k = \sqrt{A_k^2 + B_k^2}$ amplitude and $\varphi_k = \arctan\frac{A_k}{B_k}$ phase of the k^{th} harmonic.

$\omega = \frac{2\pi}{T}$ represents fundamental frequency.

The orthogonal coefficients A_k, B_k are calculated as:

$$A_0 = \frac{1}{T}\int_{-T/2}^{+T/2} i(t)dt, \quad A_k = \frac{2}{T}\int_{-T/2}^{+T/2} i(t)\cdot\cos\left(\frac{2k\pi t}{T}\right)dt \qquad (2)$$

and

$$B_k = \frac{2}{T}\int_{-T/2}^{+T/2} i(t)\cdot\sin\left(\frac{2k\pi t}{T}\right)dt. \qquad (3)$$

For the further analysis, it is convenient to represent current as complex vector, which k-th component $A_k + jB_k$ correspond to k-th harmonic:

$$\tilde{I} = \left[A_0 \quad A_1 + jB_1 \quad \ldots \quad A_m + jB_m\right]^T \qquad (4)$$

The total current, measured at the PCC, is equal to the vector sum of all loads' currents:

$$\tilde{I}_{PCC} = \tilde{I}_1 + \tilde{I}_2 + \ldots + \tilde{I}_n. \qquad (5)$$

Equation (5) provides means for efficient calculation of total currents corresponding to various combinations of different loads. One does not need to measure currents for all combination of loads, it is sufficient to measure currents for separate loads, and the total current for a combination is vector sum of separate currents.

B. Input parameters

In previous research [4],], only amplitudes I_k of current harmonics as inputs for classification of nonlinear loads were used. The parameter space of phase is S^1, which is not simply connected topological space with fundamental (first homotopy) group $\pi_1(S^1) = \mathbb{Z}$. The two infinitesimally close points can differ for 2π, which makes phase unsuitable as input parameter. However, the phase carries an information which should not be disregarded.

The solution is to represent components of current vector by real and imaginary parts $A_k + jB_k$ in Cartesian complex plane, which is simply connected topological space $\mathbb{R}^2$. This approach effectively doubles number of input parameters.

C. Training and identification

Artificial neural network is trained using input parameters: the set of measured harmonic amplitudes I_k, or calculated orthogonal components A_k, B_k for different combination of loads represents input parameters. Having in mind that harmonic amplitudes decrease with harmonic order, the highest harmonic order used is forty. Since even harmonics are not present in the spectrum of most electronic devices only odd harmonics are considered. Hence, one has only twenty input parameters in case of harmonic amplitudes used as input parameters, or forty in case of orthogonal components.

The process of identification is straightforward: once ANN is trained and look-up table is formed, the measured value of current in point of common coupling is transformed using (1) – (3), and corresponding amplitudes or orthogonal components used for identification.

III. SUPPLY VOLTAGE SECOND HARMONIC INJECTION – MEASURED VALUES

The number of input parameters is limited due to the absence of even harmonics in the current spectrum and the choice of the highest harmonic order used in training/identification. First limitation is intrinsic to the structure of nonlinear loads. The order of highest harmonic in the current spectrum taken into consideration is arbitrary but having in mind that harmonic amplitudes decrease (near) monotonically as harmonic order increases, the resolution of measuring equipment determines the highest order. Those limitations are illustrated in Fig. 2.

Fig. 2 presents current spectrum of nonlinear load (LED lamp, 6W) connected to 230VRMS, 50Hz sinusoidal voltage source:

$$v_1(t) = 230\sqrt{2} \cdot \sin(2\pi \cdot 50\text{Hz} \cdot t) \quad [\text{V}] \tag{6}$$

The highest measured harmonic is of order twenty. As voltage source, Omicron CMC365 instrument was used [5]. Measurements are performed using system for nonlinear load analysis [4].

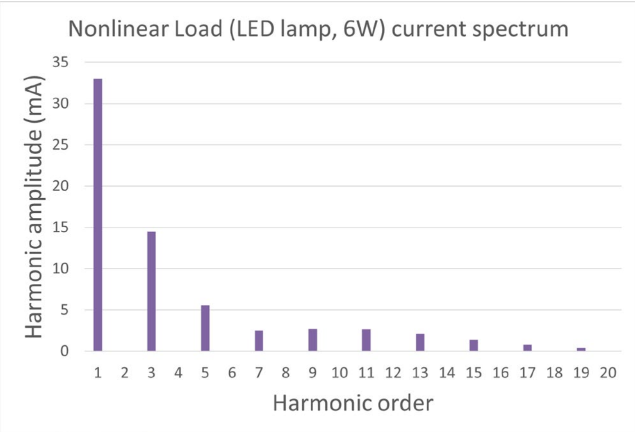

Fig. 2. The current spectrum of LED lamp, up to 20th harmonic. The limitations due absence of even harmonics and decrease of amplitudes are evident.

The current spectrum represented using orthogonal components A_k, B_k, for same load and conditions, are shown in Fig. 3. Each harmonic is represented with two real parameters.

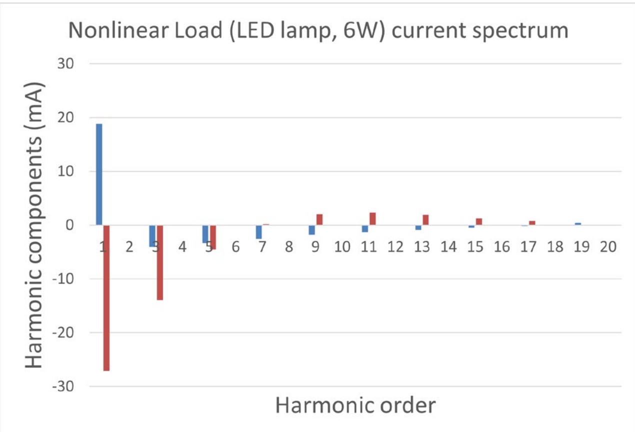

Fig. 3. The current spectrum of LED lamp, up to 20th harmonic, represented with orthogonal components, i.e., real (blue) and imaginary (red) part. The number of parameters is effectively doubled.

The spectra of most nonlinear loads do not have even harmonics. In order to instigate even harmonics, the supply voltage should be non-sinusoidal, i.e., in addition to the fundamental harmonic, it should also contain a second harmonic:

$$\begin{aligned} v_2(t) &= 230\sqrt{2} \cdot \sin(2\pi \cdot 50\text{Hz} \cdot t) + \\ &+ 20\sqrt{2} \cdot \sin(2\pi \cdot 100\text{Hz} \cdot t) \quad [\text{V}]. \end{aligned} \tag{7}$$

The current spectrum of nonlinear load, measured with using voltage supply with second harmonic injection (7) is shown in Fig 4.

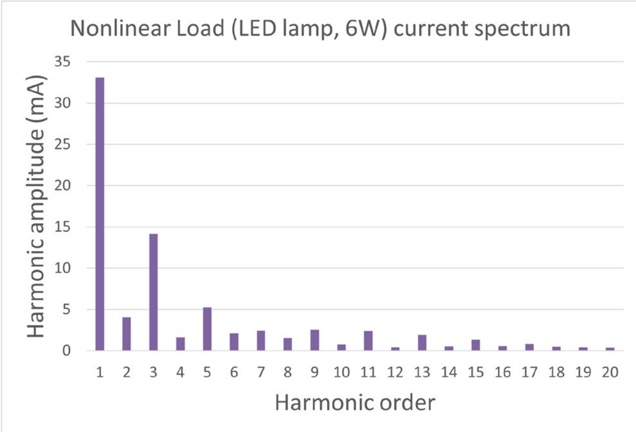

Fig. 4. The current spectrum of LED lamp, measured using supply voltage second harmonic injection.

By careful examination of measured spectrum (Fig 4.), one can conclude that even harmonics in current spectrum are not simple scaled and translated odd harmonics. This is due to nonlinear nature of load, and superposition theorem does not apply. The easiest way to see that is to notice new 4th, 8th and subsequent harmonics (of order divisible by four) emerging in the spectrum, and which would not exist if the voltage excitation consisted only of the second harmonic.

TABLE I
Current harmonic amplitudes

Harmonic order	Harmonic amplitude [mA]	
	Sinusoidal	2nd harmonic injection
1	32,98	33,11
2	0,02	4,07
3	14,5	14,16
4	0	1,65
5	5,57	5,25
6	0	2,1
7	2,52	2,45
8	0	1,54
9	2,72	2,56
10	0,01	0,74
11	2,66	2,41
12	0,01	0,4
13	2,1	1,91
14	0	0,54
15	1,39	1,32
16	0	0,57
17	0,79	0,82
18	0	0,5
19	0,41	0,43
20	0	0,39

The measured harmonic amplitudes for same load, obtained by sinusoidal and second harmonic injection voltage supply are compared in Table I.

Finally, modified spectrum obtained using (7) can be represented with orthogonal components instead amplitude, as shown in Fig 5.

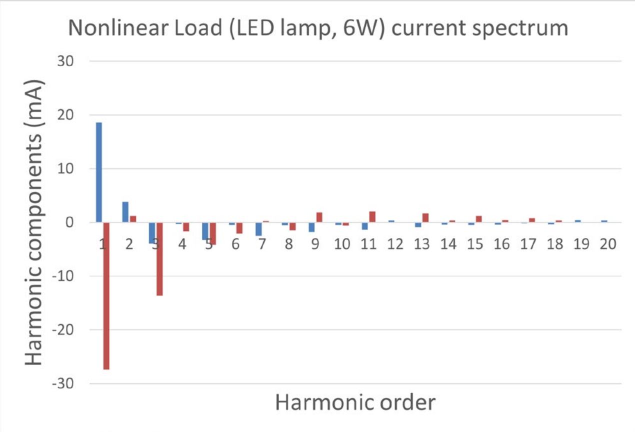

Fig. 5. The current spectrum of LED lamp, measured using supply voltage second harmonic injection, represented with orthogonal components, i.e., real (blue) and imaginary (red) part. The number of parameters is effectively multiplied by four.

IV. Conclusion

In this paper, three new improvements for improving nonlinear loads identification are proposed.

First, representing current harmonics as complex numbers in Cartesian coordinates rather than polar and using KCL enables establishing a west base of signatures related to various combinations of nonlinear loads, by measuring current spectrum of single loads individually. This approach significantly reduces number of measurements.

The Cartesian complex representation uses complete information that current harmonics have, by transforming harmonic phase which is unsuitable as input parameter and amplitude into orthogonal components. This method, in comparison with previously used harmonic-amplitude-only method for identification effectively doubles the number of input parameters for equal highest harmonic order.

The third improvement is addition of second harmonic into the voltage supply. In case of pure sinusoidal voltage supply, current spectrum contains only odd harmonics. By introducing second voltage harmonic, even harmonics emerge into current spectrum and can be used in same manner as input parameters. By combining second and third improvement, the number of parameters is effectively multiplied by four.

Acknowledgement

This work has been supported by the Ministry of Education, Science and Technological Development of the Republic of Serbia.

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