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NONLINEAR LOADS CLASSIFICATION METHOD USING ALTERNATIVE REACTIVE POWER DEFINITIONS

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Abstract: In this manuscript, we will use values of alternative definitions of reactive power as ANN inputs for classification of nonlinear loads. The presented method is indirect, and also fits into NILM (Non-Intrusive Load Monitoring) category – we have used one measuring device for various combinations of nonlinear loads. The method consists of three phases: acquisition (measurement), calculations of reactive power using different devinitions and device identification and classification using ANNs.

Keywords: classification, non-intrusive load monitoring, nonlinear loads, reactive power definitions.

INTRODUCTION

The definitions of active, reactive and apparent power are well known, and their relation is given by quadratic equation $S^2 = P^2 + Q^2$. The quadratic nature of the given formula is due to current and voltage sinusoidal waveforms and definitions of their root mean square values. However, in non-linear circuits, we have voltages and currents whose waveforms deviate from the sinusoidal. Observed in the frequency domain, their spectra contain higher harmonics, which must be included in the calculations of power. Therefore, the decomposition of apparent power, and definition of reactive power as well, must be redefined [1].

There are a number of power decompositions and definitions for non-linear circuits presented in literature [1,2]. Those definitions can be used to characterize nonlinear loads and measure non-linearity. All power decompositions have some advantages and disadvantages over others. There is no generally accepted definition and the debate is ongoing.

The higher harmonic components in the current spectrum cause losses and disturbance in the power grid. Nevertheless, they can be regarded as specific signature of some nonlinear load, therefore providing the means for classifying nonlinear loads connected to the power grid [3]. The identification and classification methods of nonlinear loads can be direct – using harmonic components, or indirect – using some parameters that depends on harmonics. In our previous reports, we have presented an indirect method for classification of nonlinear loads using artificial neural networks (ANNs), based on active, reactive and distortion power [4,5]. The direct method, using current spectrum is elaborated in [3].

In this manuscript, we will use values of alternative definitions of reactive power as ANN inputs for classification of nonlinear loads. The presented method is indirect, and also fits into NILM (Non-Intrusive Load Monitoring) category – we have used one measuring device for various combinations of nonlinear loads. The method involves three phases: acquisition (measurement), calculations of reactive power using different devinitions and device identification and classification using ANNs.

The acquisition and calculations are achieved using system for nonlinear load analysis [6,7] (Figure 1).

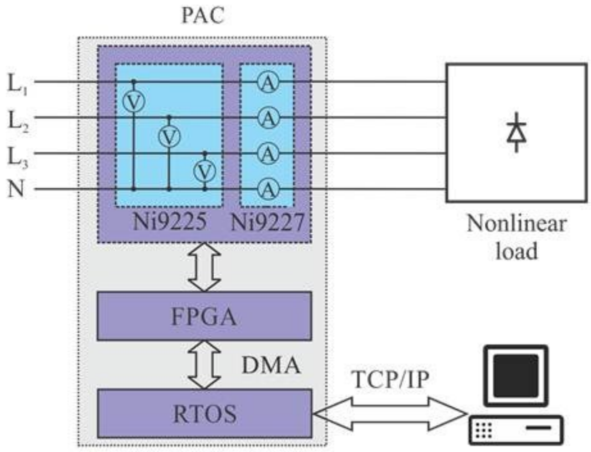

Fig.1 – *System for nonlinear load analysis, screenshot of the virtual instrument*

The active power (P) and seven different definitions of reactive power are calculated: Budeanu's (Q_B), Fryze's (Q_f), IEEE definition (Q_{IEEE}), Sharon's (S_q), Kimbark's (Q_k) and two Kusters-Moore definitions (Q_C and Q_L). The calculated values are used for ANN training.

Finally, the trained ANN is applied for identification of similar nonlinear loads and unknown groupings of loads connected to the power grid.

DEFINITION OF REACTIVE POWER

We will consider the most general case, when current and voltage are arbitrary functions of time: $i(t)$ and $v(t)$.

The instantenious power is defined as

$$p(t) = i(t) \cdot v(t). \tag{1}$$

The active power is usually defined as energy flow delivered from generator to load per unit of time:

$$P = \frac{1}{T}\int_0^T p(t)\,dt = \frac{1}{T}\int_0^T i(t) \cdot v(t)\,dt. \tag{2}$$

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If voltage and current are periodic functions, T represents the fundamental period.

Usually, current (or voltage) is represented by root mean square value (*rms*), defined as:

$$I_{\text{RMS}} = \sqrt{\frac{1}{T}\int_0^T i^2(t)\,dt}. \tag{3}$$

Physically, current (voltage) root mean square value is equal to constant current (voltage) that dissipate same power on pure resistive load.

Apparent power, S is defined as product of current and voltage *rms* values:

$$S = V_{\text{RMS}} \cdot I_{\text{RMS}}. \tag{4}$$

In case of constant voltage/current, or sinusoidal voltage/current waveforms in the circuits with pure resistive linear loads (phase diference between waveforms are 0), apparent power and active power are equal. If reactive linear loads are present in the circuit with sinusoidal generators, there is phase difference between voltage and current waveforms. Apparent and active power differs and one can introduce reactive power, Q. The relation between apparent, active and reactive power are well known formula:

$$S^2 = P^2 + Q^2. \tag{5}$$

The physical meaning of reactive power is not trivial, it can be understood as energy flow that "oscillates" in the circuit, but is never dissipated.

A cicuit with nonlinear loads is more complicated case. Current (and voltage) waveforms are not sinusoidal and one can introduce more power components in the equation (5). This process is refered as *power decomposition*.

We will briefly review most common power decompositions and reactive power definitions which arise from them.

Budeanu's definition

The Budeanu's definition is the most used definition of reactive power Q_{b}, given by the following equation:

$$Q_{\text{b}} = \sum_{k=1}^{+\infty} I_{k,\text{RMS}} \cdot V_{k,\text{RMS}} \cdot \sin(\varphi_k), \tag{6}$$

where k is harmonic order, $I_{k,\text{RMS}}$ and $V_{k,\text{RMS}}$ *rms* values of k^{th} harmonic and φ_k phase difference.

The apparent power is decomposed into two orthogonal components, active power (2) and non-active power N_{b},

$$N_{\text{b}} = \sqrt{S^2 - P^2} \tag{7}$$

which is further separated into reactive power and distortion power:

$$D_{\text{b}} = \sqrt{N_{\text{b}}^2 - Q_{\text{b}}^2}. \tag{8}$$

IEEE Standard 1459-2010

The IEEE Standard 1459-2010 introduces reactive power calculated as:

$$Q_{\text{IEEE}} = \sqrt{\sum_{k=1}^{+\infty} I_{k,\text{RMS}}^2 \cdot V_{k,\text{RMS}}^2 \cdot \sin^2(\varphi_k)}. \tag{9}$$

Definition (9) ensures that the total reactive power Q_{IEEE} is always greater than reactive power of the fundamental component.

Kimbark's definition

Alike Budeanu's definition, this definition assumes that apparent power consists of two orthogonal components, active power defined as average power (2) and non-active power N_{k}. The non-active power is decomposed into two components, reactive Q_{k} and distortion power D_{k}. Reactive power is calculated with respect to first (fundamental) harmonic:

$$Q_{\text{k}} = I_{1,\text{RMS}} \cdot V_{1,\text{RMS}} \cdot \sin(\varphi_1). \tag{10}$$

Furher, distortion power is calculated as

$$D_{\text{k}} = \sqrt{S^2 - P^2 - Q_{\text{k}}^2}. \tag{11}$$

Fryze's definition

The Fryze's decomposition introduces instantaneous current division into two components refered as active and reactive current, calculated as

$$i_{\text{a}}(t) = \frac{P}{V_{\text{RMS}}^2} v(t) \tag{12}$$

$$i_{\text{r}}(t) = i(t) - i_{\text{a}}(t). \tag{13}$$

The corresponding power definitions are

$$P = V_{\text{RMS}} \cdot I_{\text{a}} \tag{14}$$

$$Q_{\text{f}} = V_{\text{RMS}} \cdot I_r \tag{15}$$

where I_{a} and I_{r} are rms values of (12) and (13), calculated using equation (3).

Sharon's definition

This definition introduces two quantities: reactive apparent power

$$S_{\text{q}} = V_{\text{RMS}} \cdot \sqrt{\sum_{k=1}^{+\infty} I_{k,\text{RMS}}^2 \sin^2(\varphi_k)} \tag{16}$$

and complementary apparent power

$$S_{\text{c}} = \sqrt{S^2 - P^2 - S_{\text{q}}^2} \tag{17}$$

where S and P are apparent and active power, previously defined.

Kusters-Moore definitions

This decomposition introduces two different reactive power definitions, inductive reactive power and capacitive reactive power:

$$Q_{\mathrm{L}} = V_{\mathrm{RMS}} \cdot \frac{\sum_{k=1}^{+\infty} \frac{1}{k} \cdot V_{k,\mathrm{RMS}} \cdot I_{k,\mathrm{RMS}} \cdot \sin(\varphi_k)}{\sqrt{\sum_{k=1}^{+\infty} \frac{V_{k,\mathrm{RMS}}^2}{k^2}}} \tag{18}$$

$$Q_{\mathrm{C}} = V_{\mathrm{RMS}} \cdot \frac{\sum_{k=1}^{+\infty} k \cdot V_{k,\mathrm{RMS}} \cdot I_{k,\mathrm{RMS}} \cdot \sin(\varphi_k)}{\sqrt{\sum_{k=1}^{+\infty} k^2 \cdot V_{k,\mathrm{RMS}}^2}}. \tag{19}$$

PARAMETAR EXTRACTION

The parameter extraction is performed using system for nonlinear load analysis [6,7] (Figure 1).

First, the voltage and current waveform acquisition is achieved using acquisition modules with 16-bit A/D resolution, 100 kSa/s sampling rate and ±50 A dynamic range. The active power (P) and seven different definitions of reactive power (Q_{B}, Q_{IEEE}, Q_{k}, Q_{f}, S_{q}, Q_{C} and Q_{L}) are numerically calculated using equations (6) – (19), previously performing FFT algorithm on sampled sequences. In this experiment, we calculated voltage and current harmonics up to 40th harmonic.

The complete system is examined in detail in [6,7]. The system is capable for real-time operation, but due to the offline nature of ANN training, this capability is not used.

The parameter extraction is performed on 12 different combinations of various devices, shown in the Table I. We have considered devices that are typical for an office: one laptop, one server, one monitor, one kettle, one LED bulb, and an air-condition that can be in two operation modes: cooling and idle. Both the laptop coputer and the server operated with idle CPU utilization in all cases, so they can be treated as nonlinear stationary loads with constant power consumptions.

Table I

Characteristic combinations of the devices.

Code	Device
1	LED Bulb
2	Kettle
3	Server
4	Air-condition idle
5	Air-condition cooling
6	Server + monitor
7	Server + monitor + laptop
8	Server + monitor + laptop + kettle
9	Server + monitor + laptop + LED Bulb
10	Server + monitor + laptop + Air-condition idle
11	Server + monitor + laptop + Air-condition cooling
12	Server + monitor + laptop + Air-condition cooling + LED Bulb

The codes are given in the first column of the Table I, and also in the first row of the Table II. First column of the Table II represents the harmonic order, k. The values for various reactive power definitios are expressed in volt-amperes (VA) and value of active power in watts (W).

Table II

Values of powers for the combinations of devices

Code	Q_b	Q_f	Q_{IEEE}	S_q
1	-2.490	7.295	2.467	4.921
2	-5.009	4.979	4.994	5.215
3	-30.585	36.092	30.554	31.799
4	-23.424	76.159	22.743	67.388
5	-22.379	178.221	21.948	79.226
6	-20.766	54.554	20.317	32.250
7	-49.658	64.038	49.118	57.385
8	-8.601	36.561	8.203	26.352
9	-92.287	69.718	91.740	96.502
10	-92.826	98.032	92.099	99.796
11	-72.943	186.980	72.337	118.543
12	-79.992	183.875	79.493	115.861
Code	Q_k	Q_C	Q_L	**P**
1	-2.467	-1.709	-2.451	9.663
2	-4.994	-3.309	-4.959	1738.502
3	-30.554	-19.751	-30.334	60.166
4	-22.738	-16.727	-22.740	52.725
5	-21.942	-14.976	-21.931	546.094
6	-20.315	-14.744	-20.243	97.018
7	-49.117	-33.472	-48.840	126.300
8	-8.199	-6.755	-8.215	1849.744
9	-91.740	-61.242	-91.186	142.552
10	-92.098	-62.039	-91.556	150.536
11	-72.335	-47.734	-71.965	625.395
12	-79.491	-51.649	-79.057	636.184

ANN TRAINING AND IDENTIFICATION

Artificial neural network needs to be trained for modeling the look-up table. It is a feed-forward neural network with one hidden layer. The measured values from the Table II are inputs to the network, and the Code is network output to be learned. It means that the neural network has eight input neurons and one output neuron. After training was completed, the number of hidden neurons in the resulting ANN was three, what was found by trial and error after several iterations starting with an estimation based on [8], and [9].

The structure and the parameters of both obtained ANNs are verified by exciting the ANN with the given inputs. Responses of the ANN show that there were no errors in identifying the codes what is presented in the Table III. Negligible discrepancies may be observed.

Table III
Characteristic combinations of the devices.

Expected Code	ANN Output (20 hidden neurons)
1	0.999713
2	1.99972
3	2.99644
4	3.99765
5	4.99778
6	5.99762
7	6.994
8	7.99931
9	8.98835
10	9.98908
11	10.9922
12	11.9916

CONCLUSION

Presence of nonlinear loads in AC circuits causes nonsninusoidal conditions, which causes many negative impacts on distribution system. In this case, simple decomposition of apparent power is no longer valid. There is a number of approaches to overcame this problem and characterize nonlinear lodas – power decompositions.

Most of the known NILM methods for identification devices use artificial neural networks. In this manuscript, ve have demonstrated a nonintrusive load monithoring method for nonlinear load identification and classification whis uses different definitions of reactive power. Those quantities are measured and calculated in order to be used as training set for AAN.

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REFERENCES

[1] Emanuel, A. E., *Power Definitions and the Physical Mechanism of Power Flow*. J. Wiley and Sons, 2010. ISBN 978-0-470-66074-4.

[2] Balci, M. E., Hocaoglu, M. H.: *Quantitative comparison of power decompositions*. Electric Power Systems Research, 2008, No. 78, pp. 318-329.

[3] Dimitrijević, M., Andrejević Stošović, M., Stevanović, D.: *Classification of Nonlinear Loads using Current Spectrum*. IcETRAN, 2019, accepted for publication.

[4] Andrejević Stošović, M., Stevanović, D., Dimitrijević, M., *Monitoring and Classification of Nonlinear Loads Based on Artificial Neural Networks*, 13th Int. Conference on Advanced Technologies, Systems and Services in Telecommunications (TELSIKS), Niš, October 2017, pp. 443-446, 978-1-5386-1799-1, doi: 10.1109/TELSKS.2017.8246320.

[5] Andrejević Stošović, M., Stevanović, D., Dimitrijević, M., *Classification of Nonlinear Loads Based on Artificial Neural Networks*, IEEE 30th International Conference on Microelectronics (MIEL), Niš, October 2017, pp. 221-224, 978-1-5386-2561-3, doi:10.1109/MIEL.2017.8190107.

[6] M. Dimitrijević, *Elektronski sistem za analizu polifaznih opterećenja baziran na FPGA*, PhD Thesis, Faculty of Electronic Engineering, University of Niš, Niš, Serbia, 2012.

[7] M. Dimitrijević, Stevanović, D., Andrejević Stošović, M., *Real-time System for Nonlinear Load Analysis in 50A Current Range*, Proc. Of the 8th Small Systems Simulation Simposium, pp. 83-88, February 12-14, 2018, Niš, Serbia

[8] T. Masters, “Practical Neural Network Recipes in C++”, Academic Press, San Diego, 1993.

[9] E. B. Baum, and D. Haussler, “What size net gives valid generalization”, Neural Computing, Vol. 1, 1989, pp. 151-60.