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Features Generation by Means of Currents' Physical Components for Load Identification

Abstract. *In this paper the process of extracting a set number of features that uniquely describe a nonlinear load is described. The method is used for classifying and identifying as well as determining the operation state of harmonic nonlinear loads. The method is based on harmonic spectral decomposition of periodic waveforms and on sorting and calculating the features by means of Currents' Physical Components Theory. Using this theory enables to create features with physical meaning and to enable to calculate the actual various currents and powers of these loads.*

Streszczenie. *W artykule przedstawiono proces wyodrębniania zbioru cech, które w sposób jednoznaczny opisują odbiornik nieliniowy. Metoda ta została użyta w celu identyfikacji, klasyfikacji oraz określenia stanu pracy odbiorników nieliniowych. Metoda oparta jest na rozkładzie przebiegów okresowych na harmoniczne oraz na sortowaniu i obliczaniu cech przebiegów za pomocą Teorii Składowych Fizycznych Prądów. Teoria ta umożliwia identyfikację cech mających sens fizyczny oraz umożliwa obliczanie różnych, mających sens fizyczny, prądów i mocy.* ***Generacja cech w celu identyfikacji odbiornika za pomocą Składowych Fizycznych Prądów***

Keywords: Energy transport theory, Harmonics, Nonlinear load, Nonintrusive monitoring.
Słowa kluczowe: Teoria przesyłu energii, harmoniczne, odbiorniki nieliniowe, obserwacje niezakłucające.

Introduction

In recent years Smart Grids research and implementation are growing rapidly. The need for energy conservation, responsible management of the demand response of the grid, and the ability to implement advanced technologies in this new Smart Grid, yields the emerging research and investments in Smart Grids all over the world [1]-[3]. Smart grid is a general name for combining various communication technologies, smart meters and control abilities for creating a well-managed Smart Grid. Smart Meters, as well as Smart Monitors (which also measure and calculate power quality parameters), are an essential part of this new system.

The penetration of smart meter technology (or monitor) which include high performance computing abilities enable new features which have not been thought of before. Load identification is a good example for new developed ability which is enabled by new technologies which are penetrating these smart grids. There is a lot of interest in load diagnostics, analysis and recognition in recent years. There are numerous works done on these subjects. For example, [4] deals with finding the correlation between faulty equipment on the power networks, and the signal-to-noise ratio of the power-line signal induced, thus showing the possibility of developing a new method of faulty loads recognition in power networks. In [5], current decomposition provides a suitable approach to determine how disturbances propagate among circuits. The application of Fryze-Buchholz-Depenbrock - FBD power theory revealed useful results by using statistical analysis of the indices. These above-mentioned works describe anomalies and harmonic faults. In this paper non-linear loads are considered as a power quality problem and therefore these methods might apply.

This paper describes a method for load identification by means of Currents' Physical Components (CPC) Theory [6]-[9]. This theory is applied on sampled time domain current and voltage waveforms of a measured (or simulated) nonlinear load. These samples are transformed to the frequency domain with FFT procedure. The resulting harmonics are then sorted to their physical components, using the Current Physical Component power transport Theory (CPCT) [6] which will be reviewed in section III. The method is based on producing admittance spectrums according to CPC theory, and calculates the active, reactive, scattered and apparent powers.

The use of CPC enables a set of constant finite number of feature which uniquely defines any nonlinear load. It should be emphasized here that these features are not dependent on the extent of non-linearity of the load. Namely, the method produces a set of 10 features regardless of the number of harmonics generated by the load. This characteristic makes this method applicable when combined with Artificial Neural Network (ANN) which can be used for identification of the load in a later stage. Moreover, the use of CPCT enables a set of features with physical meaning and the ability of directly calculate the various powers and currents of the identified load. The method described in this paper yields a tool for identifying electric loads as well as analyzing non-linear loads which are connected to the grid. The paper describes the theory for analyzing harmonic loads. Then the theory is demonstrated on simulated waveforms from Simulink, as well as recorded current and voltage wave in power quality monitors.

II. Currents' Physical Components Theory Overview

The procedure described in the last section is based on, first converting the time domain measured waveform of the currents and voltages to the frequency harmonic spectrum of the signals by performing FFT on the signals.

The spectrums of each waveform are used to define the waveform origin by means of CPCT. CPCT was developed by L. S. Czarnecki [6]. It is considered as one the most advanced energy transport theories. Since it was first publicized, there were developments and adaptations of this power theory [7]-[9]. Next, the theory is briefly presented. However, the presentation of the theory here is taking into consideration that the inputs of the simulator are voltages and currents only and the CPCT is presented accordingly.

The voltage and current waveforms u(t) and i(t) of a load are measured by a power monitor and their general representing as a series of harmonics by its Fourier series is:

$$\left.\begin{aligned} u(t) &= U_0 + \sqrt{2}\,\mathrm{Re}\left\{\sum_{n\in N} U_n e^{jn\omega_1 t}\right\} \\ i(t) &= I_o + \sqrt{2}\,\mathrm{Re}\left\{\sum_{n\in N} I_n e^{-jn\omega_0 t}\right\} \end{aligned}\right\} \quad (1)$$

where, U_0 and I_0 are the DC value of the voltage and current. U_n and In are the RMS voltage at the n^{th} harmonic.

For each harmonic the admittance Y_n can now be expressed as:

(2) $$Y_n = \frac{I_n}{U_n} = G_n + jB_n$$

where, G_n is the real part of the admittance and B_n is the imaginary part.

Then all harmonics are sorted into two groups. The first is the group of all harmonics which belong to the distribution system and the second is the group of harmonics which belong to the customer (load). This is done by the phase criteria as follows:

(3) $$\left.\begin{array}{ll} |\varphi_n| < \pi/2 & \rightarrow Distribution\ group \\ |\varphi_n| > \pi/2 & \rightarrow Customer\ group \end{array}\right\}$$

For each harmonics n the phase between the current element and the voltage element φ_n is calculated and the criteria in (3) enables the sorting of the harmonics. The justification of (3) is that this angle represents the averaged power flow towards or from the source as indicated in [6].

For each harmonics in the Distribution group (DG) the admittance is calculated by using (2) .Then the DG and customer group (CG) voltages , U_d and U_c are calculated as follows:

(4) $$\left.\begin{array}{l} U_d = \sum_{n \in N_D} U_n \\ U_c = \sum_{n \in N_C} U_n \end{array}\right\}$$

where, N_D and N_C are the number of harmonics which belong to the DG and the CG respectively. It should be mentioned that these voltages are the RMS values of the voltage. The same procedure is followed for calculating the DG and CG powers, the active power of each harmonics can be calculated as:

(5) $$P_n = U_n \cdot I_n \cos\varphi_n$$

This power exists only for the harmonics for which there is a component for the current as well as component for the voltage. Then, the DG powers and the CG powers P_d and P_c can be calculated as follows:

(6) $$\left.\begin{array}{l} P_d = \sum_{n \in N_D} P_n \\ P_c = \sum_{n \in N_C} P_n \end{array}\right\}$$

Now the various impedances of the physical components are calculated. First the equivalent conductance is:

(7) $$G_{eD} = \frac{P_d}{U_d}$$

For each harmonic in the DG, the G_nD and B_nD are known from (2). Then the scattered admittance is calculated using:

(8) $$G_{snD} = G_{nD} - G_{eD}$$

Now, the DG RMS values of the currents can be calculated from:

(9) $$\begin{array}{l} I_a = G_{eD} \cdot U_d \\ I_s = \sqrt{\sum_{n \in N_D} (G_{snD})^2 \cdot U_n^2} \\ I_r = \sqrt{\sum_{n \in N_D} (B_{nD})^2 \cdot U_n^2} \end{array}$$

where I_a, I_s, I_r, are the RMS values of the active, reactive and scattered components of the DG currents.

Regarding the harmonic current of the CG, this customer current I_C, is calculated as the net sum RMS value of all RMS values of all currents in this group:

(10) $$I_C = \sqrt{\sum_{n \in N_C} I_n^2}$$

After calculating all currents' physical components the corresponding powers can be calculated accordingly.

(11) $$\left.\begin{array}{l} P = I_a \cdot U \\ Q = I_r \cdot U \\ D_s = I_s \cdot U \\ D_c = I_c \cdot U \end{array}\right\}$$

where, P, Q, D_S and D_C are the active, reactive, scattered and customer powers respectively.

For checking the validity of the results of (9), (10) and (11), the total RMS current when summing the RMS of all components in (9) and (10) must be equal to the original RMS current of the measured current at the point of measurement, namely:

(12) $$I_{measured} = I_a^2 + I_r^2 + I_s^2 + I_C^2 = \sqrt{\sum_{n \in N} I_n^2}$$

When (12) is satisfied then the same can be verified for the total calculated or measured power $S_{measured}$:

(13) $$S_{measured} = U \cdot I = P^2 + Q^2 + D_s^2 + D_c^2$$

III. Feature Extraction

Defining unique signatures of loads can be implemented for load identification [10]. The theory presented in section II enables a unique decomposition of the current and voltage waveforms of a nonlinear load. There are two advantages to this method of presentation. The first is the ability to sort all harmonics into a finite and constant number of currents and powers. The second is that these components have a physical meaning and represent the real currents and powers of the load. Therefore, we found that this is ideal for creating meaningful features for defining the load as well as later on, use these features in ANN systems.

Ten features were selected for characterizing every load:

1. The RMS current of the measured current wave form- I
2. The RMS value of the active current- I_a
3. The RMS value of the reactive current- I_r
4. The RMS value of the scattered current- I_s
5. The RMS value of the customer current- I_c
6. The average active power- P
7. The average reactive power- Q
8. The average scattered power- D_s
9. The average customer power- D_c
10. The total measured apparent power- S

The first feature is calculated directly from the Fourier decomposition of the measured current waveform. Then features 2-9 are calculated according to the theory in section II, and finally feature 10 is calculated from multiplying the RMS value of the current (as in feature 1) and the RMS voltage as shown in (13).

IV. Experimental and Simulation Results

First a test current and voltage wave's equations were used to test the code. For enabling all types of physical components to be implemented, the voltage contains elements in the first and third harmonics. The current consists of three harmonics in the first, third and fifth harmonics, as demonstrated in (14):

$$(14)\quad \left. \begin{aligned} v(t) &= \sqrt{2}\cdot A\cdot\left(\cos(\omega_1 t)+0.5\cdot\cos(3\omega_1 t+30^0)\right) \\ i(t) &= \sqrt{2}\cdot A\cdot\begin{pmatrix} 0.5\cos(\omega_1 t+35^0)+ \\ +0.5\cos(3\omega_1 t-20^0) \\ +0.167\cos(5\omega_1 t+35^0) \end{pmatrix} \end{aligned} \right\}$$

where *A=220* and ω_1*=314rad/s*. phase angles are also introduced for generalizing the case.

First the voltage and current waveforms in the time domain and their Fast Fourier Transform (FFT) are shown in Fig. 1.

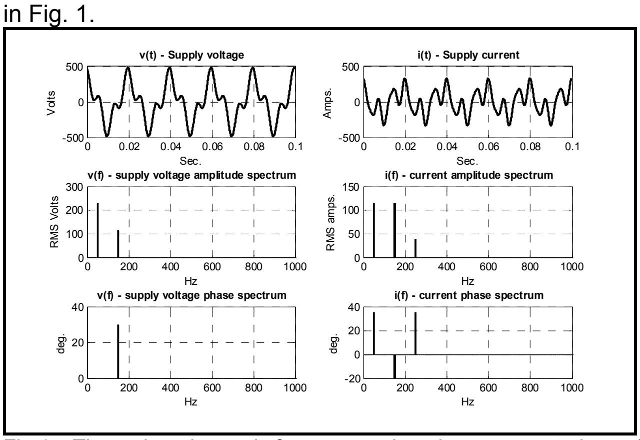

Fig.1. Time domain and frequency domain representation of harmonic voltage and current.

Next these waveforms were analyzed by the CPC code which has the following functions: 1) separates the currents to their physical components, as defined in CPC theory, and compares their sum to the calculated RMS total current. 2) Calculates the various powers and compares their sum as in (13) to the calculated apparent power. 3) generates the ten features as above mentioned

For the above waveforms, the calculated RMS voltage and current are: *V= 257.15V* and *I= 167.09A* , which yields an apparent power of *S=42967VA*. The calculated RMS values of the current's physical components in this case are: I_a *=117.32A*, I_s*= 21.455A*, I_r*= 110.05A*, I_c*= 38.333A*. It can be shown that the total current of all physical components is:

$$(15)\qquad \|i\| = \sqrt{\|i_a\|^2 + \|i_r\|^2 + \|i_s\|^2} = 166.75A$$

which is as was calculated from the waves themselves. The little deviation in this calculation (and all others) is due to the FFT precision and the sampling time rate.

The calculated powers in this example are: *P= 30167W*, *Q=28300VAR*, D_s*=5517.2VA*, *Dc=9857.3VA*. The total calculated apparent power is *S=42878VA*, which is in full agreement with the multiplication of the RMS values of *I* and *V*.

Next the feature extraction of real measured waveforms is presented. In Fig. 2 the waveforms measured in the laboratory when one of the air conditioners was turned on are presented. The waveforms are shown on the PAS program which is a program that is supplied with the *SATEC* power monitors. The three phase voltages are shown clearly at the top of the graph and the current of the air conditioner can be seen on phase 1. It is also evident that at the measuring time no loads are present in the other phases.

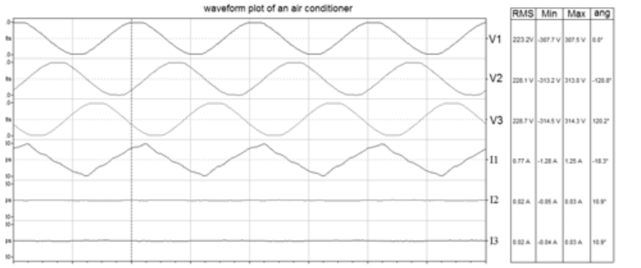

Fig.2. The waveforms measured in SATEC EM720 for an air-conditioner.

The data of these waveforms as was extracted from the monitor, was transferred to the waveform analysis program and in Fig. 3 the resulting waveform and a filtered one is shown clearly.

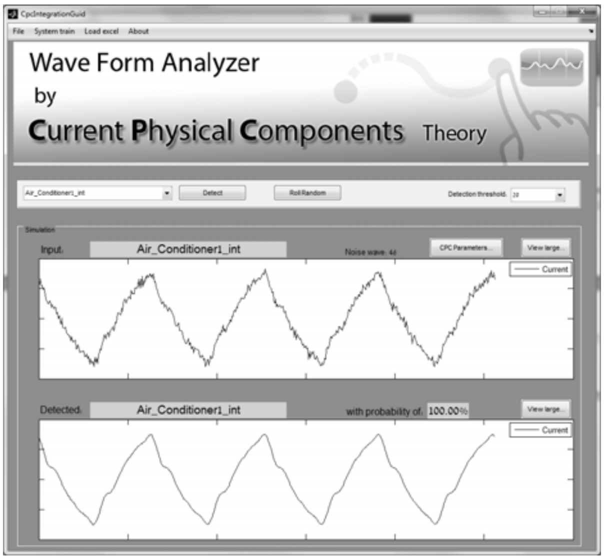

Fig.3. The results of the analysis by CPC theory.

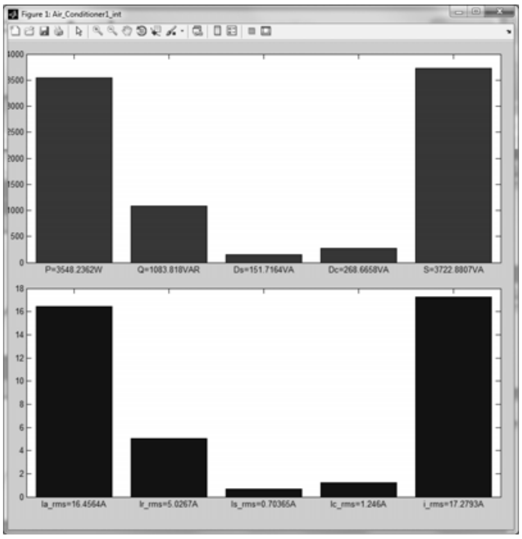

Fig.4. The features extracted by the analysis with CPC theory

In Fig. 3 it can be seen that the top graph is the waveform as was measured. This is equivalent to the current waveform in Fig. 2. The program implements the presented theory and the final result after using the various features generated the air-conditioned waveform as appears in the database as shown in the lower graph of Fig. 3 (it should be mentioned here that the database include around 40 different waveforms and by using the CPC features it recognizes the appropriate one). In Fig. 4 the CPCT based features for the above air-conditioner example are presented, these features are unique to the measured waveforms and are used as inputs to ANN based system.

The next example introduces a case in which feature extraction is performed on a load with various operation modes. As an example a simple dimmer with various excitation angles was chosen.

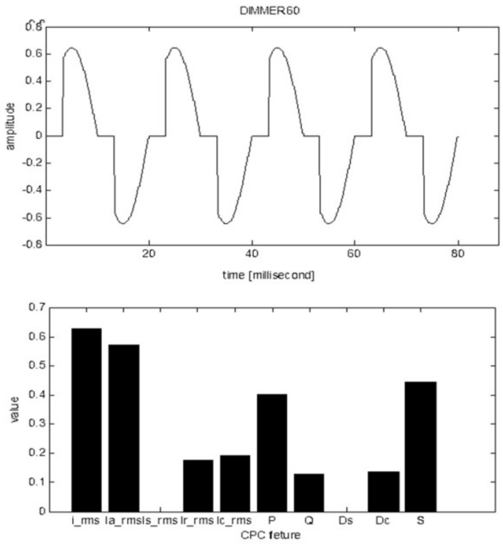

Fig. 5. Dimmer with excitation angle 600 current & CPC features

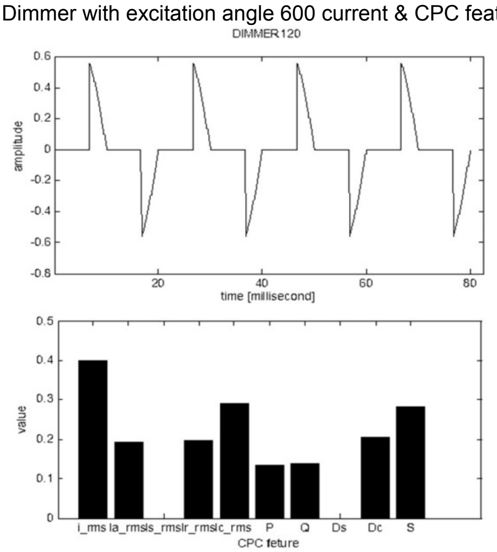

Fig. 6. Dimmer with excitation angle 1200 current & CPC features

In Fig. 5 and Fig. 6 the results of an experiment with a light dimmer with two excitation angels are shown. The example shows excitation angles: 60^0 and 120^0. The resulting features for each excitation angle have different values. For example the RMS current for 60^0 excitation angle is over 0.6 (the graph is normalized) while for the 120^0 excitation angle as shown in Fig. 6 the RMS current is around 0.4 and so on for all the other features.

It should be noticed here that for very different type of loads such as the air-conditioner and a dimmer, the features are differ in both existence of and value. Nevertheless, for similar loads such as a dimmer in various operation modes as in Fig. 5 and Fig. 6, the same types of features appear, but with different values. Therefore, the results support the theory that this type of feature extraction is unique to not only each load, but also to various operation modes of the same load.

VI. Conclusions

In this paper we have shown the extraction of uniquely defining features for load identification by means of CPCT. The theory was outlined from the point of view of implementation of the theory with measured current and voltage waveforms. It was stated that the use of CPCT as the base for feature extraction for load characterization and identification has the benefits of a constant finite number of features (10 in this case) and moreover, these features are presenting physical components from which the actual various currents and voltages can be calculated.

The results show this unique representation of the features. Features are shown to define nonlinear loads in a unique way as well as various operation modes of a load such as a dimmer with various excitation angles.

These features can be used to later on help with identifying the load with ANN systems as briefly demonstrated and discussed.

REFERENCES

[1] Hashmi M., Hänninen S., and Mäki K., Survey of Smart GridConcepts, Architectures and Technological Demonstrations Worldwide, 2011 IEEE PES Conference on Innovative Smart Grid Technologies (ISGT Latin America), 1-7, Nov, 2011,1-7

[2] Hammerstrom D. J., AC Versus DC Distribution Systems - Did We Get Right?, IEEE Power Engineering Society General Meeting, 2007,1-5

[3] Mohamed A., and Mohammed O., Smart Power Flow Control in DC Distribution Systems Involving Sustainable Energy Sources, 2010 IEEE/PES Transmission and Distribution Conference and Exposition: Latin America, 8-10 Nov. 2010, 372-379.

[4] Kapareliotis E. S., Drakakis K. E., Dimitriadis H. P. K., and Capsalis C. N., Fault Recognition on Power Networks via SNR Analysis, *IEEE Transactions on Power Delivery*, 24(2009), No. 4, 2428-2433

[5] Pavas A., S´anchez H. T, and Staudt V., Statistical Analysis of Power Quality Disturbances Propagation by Means of the Method of Disturbances Interaction, 2012 3rd IEEE PES Innovative Smart Grid Technologies Europe (ISGT Europe), 1-9, Berlin, 2012, 1-9

[6] Czarnecki L. S., Currents' physical components (CPC) concept: A fundamental of power theory, in Nonsinusoidal Currents and Compensation, 2008. ISNCC 2008. International School on, 2008, 1-11.

[7] Czarnecki L.S., Swietlicki T., Powers in nonsinusoidal networks, their analysis, interpretation and measurement, *IEEE Trans. Instr. Measur.*, IM-39 (1990), No. 2, 340-344

[8] Czarnecki L.S., Scattered and reactive current, voltage, and power in circuits with nonsinusoidal waveforms and their compensation, *IEEE Instr. Measur.*, 40 (1991), No. 3, 563-567

[9] Czarnecki L.S., Meta-theory of electric powers and present state of power theory of circuits with periodic voltages and currents, *Przegląd Elektrotechniczny*, 89(2013), No. 6, 26-31

[10] Calamero N., Beck Y., shmilovitz D. , Defining the Unique Signatures of Loads Using the Currents' Physical Components Theory and Z-Transform, *IEEE Transactions on Industrial Informatics*, 11 (2015), No.1, 155,165

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