

# A Monitoring and Identification Scheme for Power Quality Assessment

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**Abstract**—The paper presents an identification scheme for on-line monitoring and identification of power quality and system disturbances caused by nonlinear loads. The wide proliferation of distributed renewable energy and green power sources, and rapid changes in utility load types with drive towards deregulation of the Power Market require affordable and robust on-line data acquisition and expert identification systems, especially for the utilization grid power systems. The proposed technique allows creating such expert systems with the extensible knowledge base, which can be used for identification of power distortion events created by consumer nonlinear loads.

**Key words**—Power Quality, Nonlinear Load, Harmonic Disturbance, Expert System.

## I. INTRODUCTION

The increasing use of nonlinear electric load has created alarming power quality (PQ) problems, which are complex difficult to detect. The most important contributor to power quality problems is the customer using sensitive types of nonlinear loads in all sectors (Industrial, Commercial and Residential) [1].

Nonlinear type loads contribute to the degradation in the electric supply's power quality (PQ) through the generation of harmonics. The increased use of nonlinear loads makes the harmonic issue (waveform distortion) a top priority for all equipment manufacturers, users and electric utilities. So, it is very important to monitor and measure the harmonic distortion on-line, especially in the utilization power systems.

The use of intelligent knowledge-based power quality (PQ) monitoring, measurement and identification systems is definitely helpful at the present time for the low-cost and precise identification of disturbances caused by single - as well as three - phase nonlinear loads, which are widely presented in the utilization power systems.

There are many existing intelligent approaches, techniques and expert systems. The main intelligent tools of interest include expert systems (ES), artificial neural networks (ANN), and fuzzy logic (FL). Several approaches for automatic identification of power quality events have been proposed in a number of papers [2-10]. There are three dimensions for classification of these approaches:

- 1) Type of the signal: stationary (harmonic distortion) and non-stationary (voltage sag, swell, and interruption);
- 2) Type of the expert system: rule-based, ANN-based, decision table-based, etc.
- 3) Type of the power system: generation, transmission, distribution, or utilization.

Papers [2-6] cover identification of harmonic disturbances, while [7-9] describe approaches dealing with non-stationary signals, and the work [10] covers both stationary and non-stationary signals. A number of approaches discuss the idea of using artificial neural networks (ANN) to identify power quality events [3] [10], while the majority of approaches are rule-based ones [2] [4-9] focused on the identification of harmonics caused by nonlinear loads. Most of work concentrates on transmission and distribution power systems [3-5] [7-10] but a few work on utilization ones [2] [6]. So, it is important to bridge a gap in monitoring and identification of power quality (PQ) events in utilization power systems.

The present paper proposes an approach for monitoring PQ events based on the Total Harmonic Distortion (THD) and identification of various types of three-phase non-linear loads (which cause harmonic distortions) based on the measurement of THD and individual harmonic components of currents in three phases.

The top-level architecture of the low-cost system, which uses the proposed approach of knowledge-based monitoring, measurement and identification of PQ events, is presented in Fig. 1. Since the system is intended to identify disturbances caused by nonlinear loads, we call it the Non-Linear Load Identification System (NLLIS). The NLLIS consists of the data acquisition system including the measurement module (M), Fast Fourier Transform module (FFT) and knowledge-based software, or expert system (ES) for identification of the non-linear load. The system is connected to the monitored power system (PS).

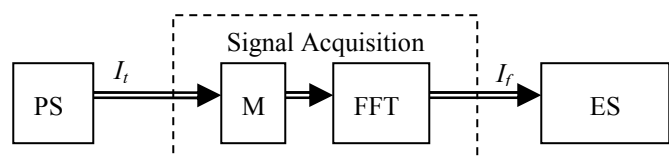


Fig. 1. The Non-Linear Load Identification System (NLLIS) architecture

The central unit of the NLLIS is knowledge base (KB), which can be built using any knowledge representation model, such as decision trees and tables, neural networks, probabilistic models, first-order logic and production rules. In the present work, we use a kind of decision table, which identify conditions (non-linear) load. The recommended actions can be then added by experts in the area of operating power systems. The knowledge base can be in future replaced by a more effective knowledge representation. Section 2 of this paper presents the knowledge base (KB) structure and the expert system functioning; section 3 proposes a simulated approach of population of the knowledge base and evaluation; and section 4 describes an FPGA-based implementation of the data acquisition subsystem.

## II. KNOWLEDGE BASE

The format of the proposed knowledge base is the following data structure:

$$KBE = \{NLI, NLC, NLT\} \quad (1)$$

where  $KBE$  – knowledge base element;  
 $NLI$  – nonlinear load identifier;  
 $NLC$  – characteristics of nonlinear load;  
 $NLT$  – type and class of nonlinear load.

The characteristics of a nonlinear load are set of parameters, which allow distinguishing one type of nonlinear load from other ones. For nonlinear loads, which create harmonic disturbances, the most useful parameters are: individual harmonic components of current in three phases, direct current component, total harmonic distortion (THD), crest factor, and form factor. In the present work, for identification of the type of nonlinear load we use harmonic components ( $DC, f_f \dots f_6$ ) and  $THD$ . The current in a three-phase power system is the vector:

$$I = \{I_a, I_b, I_c\}, \quad (2)$$

where  $I_a, I_b, I_c$  – currents in three phases.  
Each phase current can be characterized by the vector (for instance, phase A current):

$$I_a = \{I_{adc}, I_{aff}, \dots, I_{af9}, I_{athd}\}, \quad (3)$$

where  $I_{adc}$  – direct current component;  
 $I_{aff}, \dots, I_{af9}$  – harmonic components;  
 $I_{athd}$  – THD.

So, the three-phase current can be characterized by the array:

$$I = \{I_{adc}, I_{aff}, \dots, I_{af9}, I_{athd}; \\ I_{bdc}, I_{bff}, \dots, I_{bf9}, I_{bthd}; \\ I_{cdc}, I_{cff}, \dots, I_{cf9}, I_{cthd}\} \quad (4)$$

This array serves as a characteristic of a disturbance for distinguishing of a nonlinear load, which cause this disturbance; hence  $NLC = I$ . Thus the knowledge base element has the following structure:

$$KBE = \{NLI; \{I_{adc}, I_{aff}, \dots, I_{af9}, I_{athd}; \\ I_{bdc}, I_{bff}, \dots, I_{bf9}, I_{bthd}; \\ I_{cdc}, I_{cff}, \dots, I_{cf9}, I_{cthd}\}; NLT\} \quad (5)$$

The knowledge base of the expert system must be trained by various examples of existing power system models and various

disturbances, which may occur in the systems. The details of the training are presented in Section 3. After the training is conducted and the knowledge base is formed, they can assist in identification of disturbances in power systems and in future recommendation of the action.

Non-Linear Load Identification System (NLLIS) works as follows:

- 1) Harmonic components and THD of the three currents of a three-phase power system are measured in the on-line mode by the data acquisition subsystem and delivered to the expert system through a communication channel;
- 2) If  $(I_{athd} \leq 0.05) \& (I_{athd} \leq 0.05) \& (I_{athd} \leq 0.05)$  then the system does not identify any PQ event and continues monitoring;
- 3) Else (PQ event occurs), the measured harmonic components and THD of currents in three phases are compared with values in the knowledge base associated with the particular system. The most similar NLC is selected in the knowledge base, and the current PQ even is assigned with NLI and NLT. This knowledge then can be used by the power system operator to take an appropriate action.
- 4) After the PQ event is verified, its NLC is added to the knowledge base.

The comparison of the current harmonic arrays (characteristics of nonlinear load) is conducted using the weighted Euclidean distance. The reason to use the weighted distance is that lower harmonics much higher contribute to the distance than higher one, so the weights equalize the contribution of harmonics. The tested harmonic array  $I_t$  is compared with the arrays from the knowledge base as follows:

$$d_k(I_t, I_k) = \sum_{i=1}^N w_i \times \sqrt{(I_{ti} - I_{ki})^2} \quad (6)$$

where  $I_{ti}$  and  $I_{ki}$  –  $i^{th}$  harmonic components of the tested array and the  $k^{th}$  array in the knowledge base;  
 $d_k(I_t, I_k)$  – distance between arrays;  
 $N$  – number of components in the array;  
 $w_i$  – weighting coefficient.

The weighting coefficient equalizes the contribution of harmonic components and calculated as:

$$w_i = \frac{I_{tf} + I_{kf}}{I_{ti} + I_{ki}} \quad (7)$$

where  $I_{ti}$  and  $I_{ki}$  –  $i^{th}$  harmonic components of the tested array and the  $k^{th}$  array in the knowledge base;  
 $I_{tf}$  and  $I_{kf}$  – fundamental harmonic components of the tested array and the  $k^{th}$  array in the knowledge base.

The shortest distance  $d_k$  between arrays identifies the PQ event.

As the knowledge base extends, the search becomes computationally complex; therefore, clustering of the knowledge base is necessary. The  $K$ -means clustering algorithm [11] can be used; and the distance (6) can be used as a criterion of classification. If the number of elements in knowledge base is  $M$ , and the number of clusters is  $\sqrt{M}$ , the computational complexity reduces from  $M$  to  $2\log(M)$ .

### III. EXPERT SYSTEM TRAINING

To populate the knowledge base we simulated a distribution/utilization power system, which is presented in Fig.2. The system consists of the AC source, feeder, and a nonlinear type load, which is presented in Fig.3. The load bus is connected to the nonlinear load.  $R_S$  and  $L_S$  represent the equivalent source transformer feeder resistance and inductance.  $V_S$  and  $V_L$  represent the supply and load voltage respectively.

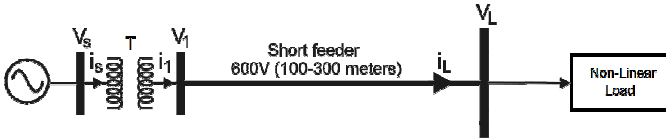


Fig. 2. Single line diagram of utilization system

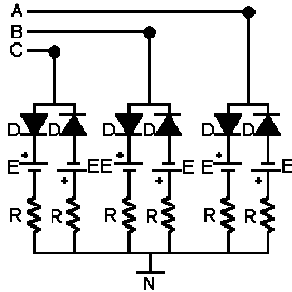


Fig. 3. Non-Linear Load in the utilization power system

The system simulation was conducted in the Matlab/Simulink environment. We obtained measures of the current harmonics  $NLL(i).ch$  of 30 different three-phase nonlinear loads through FFT analyses provided by Simulink, and stored these results in the knowledge base together with identifiers  $NLL(i).id$  and types  $NLL(i).tp$  of nonlinear loads. An example of the knowledge base element is presented below (numbers are given in percents):

```

NLL(i).id = i;
NLL(i).ch = [9.17,100,24.06,7.33,6.34,2.48,2.15,0.86,
0.69,0.55,26.18;
0.29,100,1.77,16.19,1.07,9.09,1.11,3.55,
1.13,1.97,19.18;
1.94,100,3.06,14.66,2.05,7.39,2.17,6.21,
1.78,0.67,18.16];
NLL(i).tp = '1.2e6,QL=1.0e6,Qc=0,(phase A)';
    
```

After creation of the knowledge base, it was verified to avoid duplications of knowledge base elements through comparison of each element with other elements in the knowledge base. Such verification showed 100% accuracy because there is no missing data in the communication channel. Some other test examples, which are not in the knowledge base, found the nearest match. The fragment of the knowledge base (two arrays of harmonic components), as well as the algorithms for comparison arrays of harmonic components, identification of

nonlinear load, and verification of the knowledge base coded in Matlab are presented in appendix.

### IV. FPGA-BASED IMPLEMENTATION

This section presents an FPGA (Field Programming Gate Array) based implementation of the subsystem for signal acquisition of the Non-Linear Load Identification System (NLLIS). The advantages of use of FPGA are relatively low cost, reconfigurability, and availability of peripherals, i.e. Analog-Digital Converter (ADC), Ethernet network module, etc. The desired configuration of the proposed FPGA-based signal acquisition must include 3-channel ADC to measure current in three phases, FPGA-based Fast Fourier Transform (FFT), some complimentary logic to extract harmonic components, and Ethernet peripheral module to transmit the values of harmonics and THD to a computer with expert system. Thus, relatively low-cost FPGA-based detectors can be spatially placed among nodes of distribution/utilization systems to monitor and measure power quality, and provide data for the identification of disturbances caused by nonlinear loads.

For experimentations and prove of the concept, the Xilinx Spartan-3 board with pluggable 8-bit ADC's AD7823 was chosen. The limited capabilities of Spartan-3 XC3S200FT256-4 configuration, the size of the FFT IP core realizing the Cooley-Tukey FFT algorithm [12], and a lack of software to work with Ethernet caused some temporary changes in the experimental design of the signal acquisition subsystem. The design is presented in Fig. 4. A part of future work is to improve the FPGA-based implementation using more powerful FPGA board and peripherals with available software for Ethernet.

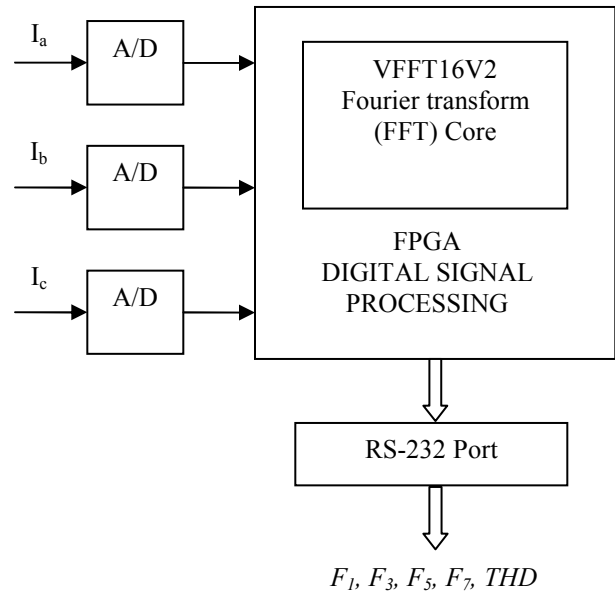


Fig. 4. Design of the data acquisition subsystem

In the current software / FPGA-based hardware design the knowledge base element  $NLL(i)$  is simplified to  $\{F_1, F_3, F_5, F_7, THD\}$ . The motivation of such a simplification is the limitation

of capabilities of the selected FPGA platform. Moreover,  $F_3$ ,  $F_5$ ,  $F_7$  are the most significant contributors to disturbances cause by nonlinear loads, so it is assumed that thee proposed concept can be proven, but its precision will require further improvement. Harmonic components  $F_1$ ,  $F_3$ ,  $F_5$ ,  $F_7$  of the signal are extracted from the FFT output as 60<sup>th</sup>, 180<sup>th</sup>, 300<sup>th</sup> and 420<sup>th</sup> samples respectively (fig. 5), and then sent via RS-232 to computer for processing. So, the knowledge base element is modified as follows:

```
NLL(i).id=i;
NLL(i).ch=[100, 7.33, 2.48, 0.86, 26.18;
           100, 16.19, 9.09, 3.55, 19.18;
           100, 14.66, 2.17, 1.78, 18.16];
NLL(i).tp='1.2e6,QL=1.0e6,Qc=0,(phase A)';
```

Although the proposed approach generally works, the precision of its implementation requires improvements mainly through the use of more powerful FPGA platform, 12- or 16-bit ADC, and more sophisticated algorithm for extraction of harmonic components.

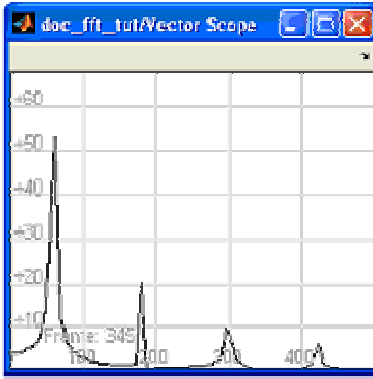


Fig. 5. Extraction of harmonic components from FFT output

## V. CONCLUSIONS

This paper presented a novel low cost approach for monitoring and identification of power quality and system disturbances caused by nonlinear electric loads. The FPGA-based device implementation is used for full signal acquisition of feature vector, which is an integral part of the on-line approach. Although this technique works well during simulations, some further improvements of the implementation may be required. The main task of any future extensions is to manage the tradeoff between system overall capabilities with hardware and full cost of on-line implementation of power quality monitoring and identification system.

## VI. APPENDIX

### %Finding a weighted distance

```
function dist = wdist(TS,TD)
dist=0;
for (i=1:3)
for (j=1:10)
w=(TS(i,2)+TD(i,2))/(TS(i,j)+TD(i,j));
dist=dist+w*abs(TS(i,j)-TD(i,j));
end
```

```
j=11;
dist=dist+abs(TS(i,j)-TD(i,j));
end

%Finding the shortest distance between
%An arbitrary table and existing KB elements
function [shdist, id, tp]=NLLIS_t(NLLA, NLL, N)
shdist = wdist(NLLA, NLL(1).ch);
id = NLL(1).id;
tp = NLL(1).tp;
for i=2:N
dist = wdist(NLLA, NLL(i).ch);
if (dist<shdist)
shdist=dist;
id = i;
tp = NLL(i).tp;
end
end
```

### %Knowledge base element examples

#### %Nonlinear load1:P=1.2e6,QL1=0; Qc1=0;(phase A)

```
NLL(1).id=1;
NLL(1).ch=
[0.04,100,0.23,14.89,0.08,9.20,0.03,4.29,0,0.79,18.04;
0.44,100,0.68,15.74,0.88,8.54,0.83,4.38,0.9,1.72,18.59;
1.21,100,2.08,14.35,1.99,8.57,1.83,6.23,1.86,1.01,18.2]
NLL(1).tp='P=1.2e6,QL1=0; Qc1=0;(phase A)';
```

#### %Nonlinear Load30: P=1.2e6, QL=P=1.2e6, QC=1.0e6; (Phase c)

```
NLL(30).id=30;
NLL(30).ch=
[0.09,100,0.64,15.42,0.45,10.54,0.39,3.62,0.31,0.59,
19.06;0.90,100,1.51,16.86,2.35,5.96,1.84,5.43,1.31,2.63,
19.21;9.91,100,15.97,16.43,12.89,10.49,8.19,8.61,1.57,
2.13,30.81];
NLL(30).tp='p=1.2e6, QL=p=1.2e6, Qc=1.0e6;(phase c)';
```

### %Verification of the knowledge base

```
for i=1:30
[shdist, id, tp] = NLLIS_t(NLL(i).ch, NLL, 30);
if (i~=id)
fprintf('duplication: shtdist=%f, id=%d, id=%d\n', shdist, id, i);
end
end
```

### %An arbitrary nonlinear load example

```
NLL A=[0.03,100,0.28,31.95,0.03,9.54,0.07,2.04,0.03,4.1
7,33.67;0.41,100,0.61,17.64,0.83,7.75,0.78,3.67,0.87,1.
68,19.74;1.26,100,2.19,16.60,2.08,7.71,1.91,6.87,1.94,2
.11,20.08];
```

### %Identification of nonlinear load

```
[shdist, id, tp] = NLLIS_t(NLL A, NLL, 30);
fprintf('L5: shtdist=%f, id=%d, tp=%s\n', shdist, id,
tp);
```

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