Statistical Methods Application in Signals Spectral Classification for Power Quality Estimation in Power Transmission Lines with Fast Changing Loads

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Abstract – **The present paper proposes the statistical classification procedure for voltage signals in transmission lines with fast changing moving loads. Fast Fourier Transformation harmonics are accepted as classification criterions. The classification error dependence on criterions number has been analyzed. It has been shown that the relative classification error is no more than 15%.**

Index terms – **Classification, Fast Fourier Transformation, power quality, fast changing load, non-linear distortions.**

I. INTRODUCTION

IMPORTANT INDICATORS of power quality in power transmission systems are current and voltage unbalance and non-linear distortions degree [1]. Traction power supply systems with loads like moving electric trains are featured by abrupt time changes of current and voltage non-linear distortion factor values [2]. As traction motors control systems made of semiconductor switching elements are widely used, current or voltage spectrum often have a very complicated structure.

The spectrum structure depends on a traction motor power converter type including uncontrollable diode bridge, controllable thyristor or transistor bridge and etc. Traction currents and voltages are influenced by noises and distortions. Besides there can be different requirements on total harmonic distortion factor. For example, it should not exceed 0,03 or 3% in the short-term operating mode and it has to be no more than 0,02 or 2% [1].

Therefore, to make a decision on the total harmonic distortion agreement with international and national standards or on traction load type moving in a current time moment through a certain segment of a railway, it is necessary to classify current or voltage signals spectrums by statistical methods.

The classification of signal Fast Fourier Transform spectrums is applied in medical engineering for electrocardiograms analysis [3]. Such spectrum structure classification is also applied in troubleshooting complicated technical systems [4]. Fast Fourier Transformation spectrums classification is suitable for identifying a target type in passive seismic location systems [5].

II. STATEMENT OF PURPOSE

The present paper proposes to apply the statistical classification of phase voltages Fast Fourier Transformation spectrums of phase voltages to the estimate power quality in transmission lines with fast changing loads. The theory section states the explanation of the criterion space selection and general classification criterion. It contains also the classification procedure mathematical description. The experimental section describes computing experiments on investigation of the proposed classification procedure based on the maximum likelihood method.

III. THEORY

The 50 Hz frequency phase voltage with non-linear distortions is prepared for the computerized analysis by the Fast Fourier Transformation [7]

$$X_0(n) = 2\left|\sum_{i=0}^{J} x(i)\exp\left(\left(-2\pi j\right)/J\right)\right|, \qquad (1)$$

where $x(i)$ is the i-th sample of phase current or voltage, J is the sample numbers per cycle, j is the imaginary unit, n is the harmonic number.

To eliminate the influence of the distance between a load and a voltage measurement point the normalized spectrum is calculated from (1)

$$X(n) = X_0(n)/K_0 \qquad (2)$$

with the normalization factor

$$K_0 = \sqrt{\sum_{n=0}^{N} X(n)^2 / \left(J/2+1\right)}\,, \qquad (3)$$

where $N = J/2+1$.

The harmonics with the numbers $n = 2,3\ldots N$ are accepted to be the classification criterions for detection of voltage belonging to a certain class with respect to non-linear distortion level or type of a converter, which is forming such voltage.

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Each harmonic level statistics is described by the Rician distribution [8]

$$p(X \mid v,\sigma) = \left(X/\sigma^2\right)\exp\left(-\left(X^2+v^2\right)/\left(2\sigma^2\right)\right)\cdot I_0\left(Xv/\sigma^2\right) , \quad (4)$$

where v,σ are correspondingly the mean and standard deviation of the real and the imaginary parts of the complex Fast Fourier Transformation spectrum, described by the normal (Gaussian) distribution, I_0 is the Bessel function of the first type of zero order.

The classification is performed only on the voltage cycles where non-linear distortions with non-zero total harmonic distortion are detected.

The classification means the occurrence of C classes with the corresponding reference distributions with the parameters v_n^c,σ_n^c for each harmonic, where c is the class number. These reference values are found by the training procedure on voltage records caused by known loads.

The classification procedure or algorithm is performed on K voltage cycles. The likelihood function is calculated on each k-th period

$$p_k^c(X) = \prod_{k=1}^{K} p(X \mid v_n^c,\sigma_n^c) , \quad (5)$$

The maximal value of the function $p_k^c(X)$ gives the possibility to make a decision on voltage belonging to a certain non-linear distortion class.

To make the classification decision more exact the maximal likelihood function values are accumulated through several voltage cycles

$$p^c(X) = \prod_{k=1}^{K} p_k^c(X) , \quad (6)$$

To make the calculations less cumbersome the common likelihood function is replaced by the logarithmic likelihood function

$$L^c(X) = \sum_{k=1}^{K} L_k^c(X) , \quad (7)$$

where $L_k^c(X) = \ln\left(p_k^c(X)\right)$.

After the likelihood function accumulation the number of a voltage class is already found from the maximum of the accumulated likelihood functions calculated by (7)

$$\xi = c \,|_{\max L^c(X),\, c=1\ldots C} . \quad (8)$$

The expression (8) has to be interpreted as a function of the decision on voltage belonging to a certain class with respect to total harmonic distortion.

IV. Simulation Results

The computer simulation of the proposed classification procedure was performed in Matlab Simulink. It is assumed that phase voltages are influenced by noises described by the normal distribution. Hence the Fast Fourier Transformation spectrums have statistical properties of the Rician distribution. Non-linear loads with controllable semiconductor rectifiers are accepted as phase loads. An evident example of such load is a traction motor with its semiconductor power converter like is some modifications of electrified locomotives.

The first step of the simulation was making the distribution map. Each cell of this map contains the distribution parameters v,σ for each criterion and each class. Usually the number of voltage harmonics taken as the classification criterions is limited. Here the class 1 corresponds to the total harmonic distortion factor no more than 0.02; the class 2 corresponds to the total harmonic distortion factor from 0.02 to 0.03; and the class 3 corresponds to the total harmonic distortion factor more than 0.03 (Table I).

TABLE I
PHASE VOLTAGES
DISTRIBUTION PARAMETERS

	$v_n^c;\sigma_n^c$		
n	$c=1$	$c=2$	$c=3$
2	$1\cdot10^{-4}$ 3; $3\cdot10^{-5}$	$1.5\cdot10^{-4}$ 3; $5\cdot10^{-5}$	$3\cdot10^{-4}$; $1\cdot10^{-4}$
3	$5\cdot10^{-5}$ 3; $1.6\cdot10^{-5}$	$7.5\cdot10^{-5}$ 3; $2.5\cdot10^{-5}$	$1.5\cdot10^{-4}$; $5\cdot10^{-5}$
4	$3\cdot10^{-5}$ 3; $1\cdot10^{-5}$	$4.5\cdot10^{-5}$; $1.5\cdot10^{-5}$	$9\cdot10^{-5}$; $3\cdot10^{-5}$
5	$2\cdot10^{-5}$ 3; $6.7\cdot10^{-6}$	$3\cdot10^{-5}$; $1\cdot10^{-5}$	$6\cdot10^{-5}$; $2\cdot10^{-5}$
6	$1\cdot10^{-5}$ 3; $3.3\cdot10^{-6}$	$1.5\cdot10^{-5}$; $5\cdot10^{-6}$	$3\cdot10^{-5}$; $1\cdot10^{-5}$

Then the classification procedure was executed for several voltage records. Each record belongs to one to the mentioned classes. The procedure processed from 15 to 20 voltage periods form each record. An example of the voltage classification is stated in Fig. 1.

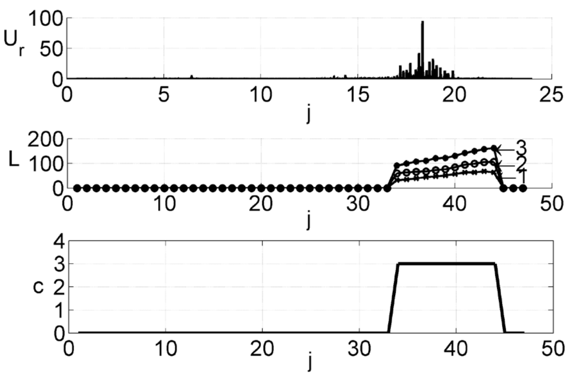

Fig. 1. Voltage classification on total harmonic distortion

In Fig. 1 j is the cycle number, U_r is the curve of cycle averaged voltage squares, containing all harmonics besides the fundamental one, L are logarithmic likelihood functions for the classes 1, 2, 3, *c* is the decision on voltage belonging to a certain class. In the considered example the decision function says that the voltage belongs to the class 3 when it is non-zero. Therefore this computing experiment is free from classification errors. It should be noticed that the more accumulated logarithmic likelihood functions are for each class the more difference between the truth class likelihood function and other likelihood functions takes place. Due to accumulation the right likelihood functions values found on later steps can compensate wrong likelihood functions values at earlier steps.

During the simulation ten voltage records for each of three mentioned classes were processed. For whole computerized experiment results the relative number of classification errors did not exceed 15% from the total number of classification decisions. The general harmonics number taking part in the classification procedure was varied from 5 to 15. The increase of the harmonics number up to 15 has led to the decrease relative errors number to 10%. The further increase of harmonics number almost did not effect on the classification errors number,

V. Discussion

The performed theoretical investigations and computing experiments show that the statistical approach is perspective for the voltages classification on their total harmonic distortions with respect to standard allowable values stated in actual normative documents.

Classification error depends on the number of classification criterions such as separate spectral components of the Fast Fourier Transformation per voltage cycle. This error is also influenced by spectral components distributions parameters difference degree.

Further it would be useful to perform similar computing experiments on non-linear loads with power converters where pulse-width modulation is used. In addition, to reduce classification procedure execution time it is desired to analyze how a decision is made by averages of several adjacent harmonics.

VI. Results And Conclusion

The proposed voltage classification procedure based on signal spectrum structure analysis for the power quality analysis in transmission lines with non-linear fast changing loads is proven to be workable. The classification was performed by the voltage spectral structure analysis with respect to maximal allowable non-linear distortions in short-term and long-term operation modes. The relative classification error for 5 harmonics as classification criterions was no more than 15%. When the number of harmonics achieved 15 the classification error became less than 10%. Taking too much classification criterions did not help to decrease classification errors quantity.

The obtained results are the base for further improvement of total harmonic distortion statistical classification method for the power quality analysis.

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