A neuro-modeling approach to implementing Intelligent harmonic monitoring system for electrical girds

Neuro-modelne podejście do realizacji inteligentnego systemu monitorowania harmonicznych dla sieci elektrycznych

Yuriy Varetsky

Wrocławska Wyższa Szkoła Informatyki Stosowanej
ul. Wejherowska 28, 54-239 Wrocław

Treść. Przedstawiono nową koncepcję inteligentnego systemu monitorowania harmonicznych. Do oceny wskaźników harmonicznych napięcia na szynach rozdzielni sieci dystrybucyjnej, zasilającej obciążenia nieliniowe, wykorzystano sztuczną sieć neuronową. Zaproponowano uczenie sieci neuronowej na podstawie zbioru danych, które otrzymano w wyniku symulacji w przestrzeni czasowej warunków pracy elektrycznej sieci dystrybucyjnej. Omówiono przykład opracowanego inteligentnego systemu monitorowania.

Słowa kluczowe: sieć neuronowa, modelowanie w przestrzeni czasowej, symulacja, elektryczna sieć dystrybucyjna, monitorowanie harmonicznych.

Abstract. A new concept of intelligent harmonic monitoring system for electrical distribution grid is presented. For estimation of voltage harmonic indices at the distribution grid substation buses supplying nonlinear loads an artificial neural network has been used. It was proposed to train the neural network on the data set obtained from simulation of the electrical distribution grid operating conditions in the time domain. An example of the carried out intelligent monitoring system is discussed.

Keywords: neural network, time domain modeling, simulation, electrical distribution grid, harmonic monitoring.

1. Introduction

The expression “intelligent system” is often used to denote any combination of the usage of artificial neural networks (ANN), expert systems, fuzzy logic systems and other technologies, such as genetic algorithms in particular. Unlike conventional approach, intelligent system does not require mathematical models of a real objects. As compared with human being, the computer with artificial intelligence can rapidly solve problems. Computer operates continuously “tirelessly”. It is not influenced by emotions or other human drawbacks. These systems are constructed on mathematical relations, which inherit “intelligence” or “knowledge” from expert estimations or field observation data, presented, as a rule, in the form of input/output pairs.

In general, relations between input and output variables are known only approximately, and a lot of efforts must be applied to find acceptable approximate correspondences. Systems of neural networks are able to “learn” automatically approximated relations between inputs and outputs, bypassing the overcoming the problem of the size complexity of the task. These approximated relations are often more efficient than the obtained on the basis of physical description of the phenomenon. It happens since these relations usually connect real values of input and output variables (for instance, measurements data) and are free from assumptions of certain theories, based on some human prejudices. Besides, neural network does not require any information regarding dependences themselves or their efficiency, which is defined by the chosen law of phenomenon description. Due to large volume of input information, the approximation error can be gradually reduced. Theoretically neural network can be trained to provide exact correspondence between input and output data. In general, systems of neural networks are able to “study” dependences in preset volume of data and establish input-output relations, based exclusively on certain subset of data. Thus, it is expedient that subset data used for “training” represent complete set of data. Dependences which are not “seen” in the selected subset will not be “studied” by the neural network. It should be noted, that the same restriction concern conventional algorithms of regression and classification.

Harmonic monitoring has become an important tool for harmonic management in electrical distribution systems. An increasing number of electric distribution system service providers are interested in installing harmonic monitoring equipment to measure the harmonic voltage and current waveforms in their power system to detect and mitigate the harmonic distortion problems. This can be explained by the fact, that more and more loads with non-linear characteristics are used in distribution systems. On the other hand, practically all power systems are characterized by constant varying loads. Such variation can be of daily or long term character as well as of random character – i.e. depending on the operation requirements, and occur even several times a minute. So operating and maintenance staff of utility companies and commercial consumers can not identify the level of investments for preventive measures and means to avoid possible harmful consequences of the problem. The key task in solving the problem is the implementation of an effective power quality monitoring system in the distribution systems.

2. Concept of the monitoring system

Monitoring power quality in distribution systems is performed to study varying quality indices during certain time interval. Depending on the specific features of a distribution system monitoring can be carried out continuously (based on stationary instruments), periodically (within certain intervals, for instance, once year) or as requires (in the process of connection of new powerful loads, compensating devices, etc.)

It should be noted, that according to the requirements of majority of actual standards harmonic monitoring should be performed at least during one week. It is expedient to choose the points of harmonics monitoring as close as possible to the equipment (consumers) sensitive to voltage distortion. It is important to have information regarding all changes of the distribution system configuration (connection/disconnection of capacitor bank, harmonics filters, buses sections, transformers etc.).

To provide electromagnetic compatibility in a distribution system the voltage distortion indices in "common point" should meet the requirements of the actual standard. Testing procedure is carried out on the basis of corresponding measurements. Measurements are performed by certified laboratories in accordance with standard technique and with a certified and specialized measuring instruments such as harmonic analyzers. It is obvious, that such measurements are performed occasionally, this is why information regarding real state of the system may not be available for a long period of time, hence, the network and consumers will experience negative (in case of non conformity with the requirements) influence of harmonics. Changes of operating conditions in distribution system require the application of special measuring instruments, which are seldom installed at the stations due to their high cost. Besides at tie-substations there is permanent operating staff for servicing these devices and for the analysis the measurements. The analysis of the problem shows that it is desirable to perform continuous monitoring of the system operating conditions. Monitoring performed with minimum instruments and telemetry allows the dispatcher to evaluate voltage distortion in control points and perform necessary steps to eliminate the problem.

In the literature one can find references to already known methods of adequate harmonic sources identification in conditions of incomplete provision of distribution system with measuring facilities. Solutions based on conventional approaches are suggested in [1,2]. Some approaches using methodology of artificial neural networks for determination of characteristics of harmonics sources in electric network are suggested in [3,4]. Research published in [3] presents structural neural network for identification of harmonic sources in distribution system equipped with a few stationary installed instruments for harmonic measurement.

The suggested concept of the monitoring system does not require harmonic analyzers in controlled points of the distribution system and the development of a special network for transfer measurements to observation point [5, 6]. Existing telemetry channels and measuring devices available at the distribution system substations can be used for this purpose. It have been suggested to use neural network for "recognition" (identification) of voltage distortion indices at the buses of distribution system substations on the basis of the operating condition parameters available in the point of observation through telemetry (corresponding active and reactive powers, currents, power factors etc.). Outline concept of the monitoring system is shown in Fig. 1. An important feature of the developed monitoring system is the possibility to perform observation in real a time over the change of operating conditions of a distribution system segment and not only over one substation. Besides, such monitoring does not impose rigid requirements regarding the accuracy of a measuring devices and allows for the definition of the voltage distortion indices on the basis of measurements available at tie-substations. After collection and analysis of a data obtained as a result of monitoring, the decision concerning the necessity of measurements by specialized harmonics analyzers on the problem buses can be made.

On its merits we deal with indirect measurements of voltage distortion indices, since their values are obtained not on the basis of analysis of voltage waveforms, but by means of "recognition" its relations between values of powers, currents, etc. measured in different points of distribution system derived by a neural network.

It is known that the spectrum of harmonics and their magnitudes in electric network depend on active and reactive powers of non-linear loads, operating conditions of reactive power compensation equipment. It is obvious that under continuous variations of these factors it is difficult to define functional dependence between the parameters and harmonic magnitudes in several points of the distribution system. So, the possibility to apply the intelligent system for the solution of the problem is very attractive idea, because it can identify the required relations.

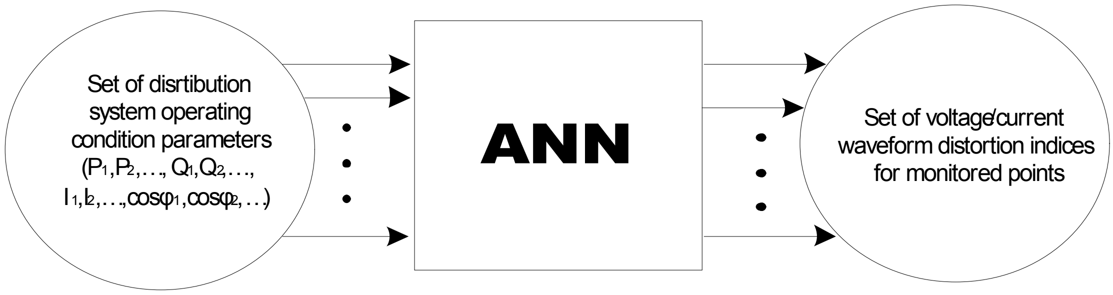

Fig. 1. Concept of the monitoring system

During the development procedure of such intelligent system, the most difficult problem is to obtain the data sets for ANN training. It is difficult to get needed data for the neural network training using field measurements. Problem is the collection of a data sets for all representative operating conditions during short time horizon. It was suggested to obtain these data from modeling the set of the representative operating conditions of the distribution system including non-linear loads in the time domain. The set of input and output pair obtained in such a way is the required training set for the neural network.

The next problem is the selection the neural network structure and acceptable method of its training. It is known that there are no exact criteria regarding the selection of neural network structure and the optimal method of its training. So, the commonly used approach has been chosen. In power engineering problems mainly the feed-forward neural networks are used. Their training is performed on the basis of training algorithm called "backpropagation". "Backpropagation" training algorithm is the method of iterative adjustment of weight coefficients until achieving the desired accuracy.

To obtain the best results, training set must correctly represent all expected changes in complete data set. That is why the correct choice of the load variations boundaries and electric network configuration changes are very important.

Majority of neural networks can be made very accurate (on the basis of training data) by means of increasing number of hidden layers and nodes in these layers. There are cases when the increase of independent variables makes the system more vulnerable to changes occurring in the output data. Thus, a large number of hidden layers and hidden nodes of the layer can make neural system more accurate for training data, but changes which will be presented in the following data (not included in training process) can be the reason of considerable shifts from expected result at the output. Thus it is necessary to find the compromise between the number of layers, nodes and the degree of accuracy, attainable with that training data.

3. Example of the intelligent monitoring system

A part of typical distribution grid including traction substations has been chosen. The grid substations are a source of harmonics and as a rule are supplied from a main line connected to 110 kV tie-substation bus. Supply of traction system is carried out through the 6 pulse diode bridge rectifier. Outline diagram of a monitoring system for the distribution grid is shown in Fig. 2.

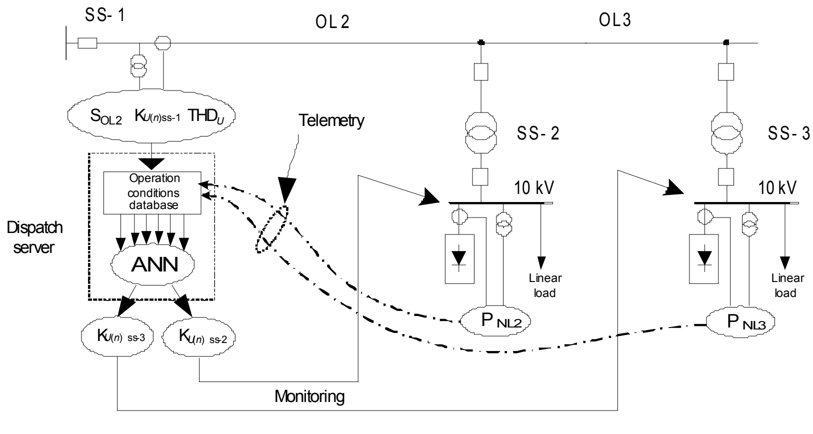

Fig. 2. Outline diagram of the monitoring system

Load of traction substation converters has a probabilistic character and can vary depending on the locomotive traffic schedule. Operating conditions both with practically zero loading of converters and with close to nominal are possible. The load can vary both continuously and by stepwise change (stop/start of the locomotive). The rectifier current harmonic magnitudes increase proportionally to the rectifier load. Substations in the investigated network are provided with standard measuring devices which are permanently installed on 10 kV buses of network substations.

Substations are not equipped with permanent devices for harmonic measurements. In the distribution system the permanent harmonic analyzer is provided only at PL-2 at substation 1 where permanent operating staff performs on-line control of the given section of the electric grid. The dispatcher can observe the dynamics of substation load changes in time horizon by telemetries. Fig. 3 shows the artificial neural network (ANN) for the system of harmonic monitoring taking into account the transfer of telemetries from the substations SS-2 and SS-3 to substation 1.

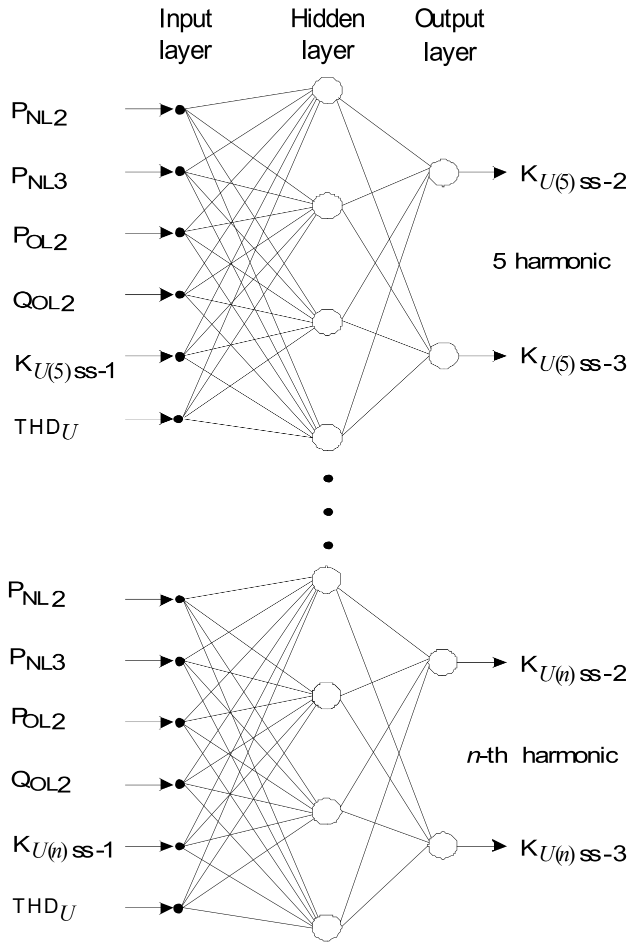

Fig. 3. The neural network architecture

Linear load of the substations changes in accordance with daily schedule of power consumption. Since the value of non-linear load is of stochastic character, there is no strict correspondence between the power of the system loads and variation of harmonics in the electrical grid.

Based on the experimental research for a given neural network the minimum number of necessary input signals (measurements) was defined to perform the monitoring task. The possibility of obtaining such measurements at substations of electric network and their transfer to control point at substation 1 is taken into account.

The neural network was created by means of subprogram NNTool from tools panel Neural Network of software MatLab. For neurons of the hidden layer, a transfer function in the form of hyperbolic tangent (TANSIG) is chosen. Function PURELINE is chosen as a transfer function for output layer neurons, since such a function can transfer any values in a wide range. Weight coefficients were adjusted to minimize complete root-square error between trained set of outputs and the set of real values. For training a neural network the function of scaled conjugate gradient (TRAINSCG) with back propagation of error is used.

Neural network was trained to evaluate coefficients of n-th voltage harmonic component at 10 kV buses of SS-2 та SS-3 (KU(n) ss-2, KU(n) ss-3) of the distribution grid. As it was pointed above, due to peculiarities of harmonic propagation calculations which allow for the analysis of the electrical grids separately for each harmonic. The neural network is divided into a number of parallel nets (individually for each harmonic) which have similar inputs and two outputs each, as it is shown in Fig. 3. Such approach allows for the improvement of the convergence and the increase of information memory. In the given case, only representative harmonics for the non-linear load of this distribution grid has been analyzed (5th, 7th, 11th etc).

In accordance with the proposed concept of intelligent monitoring system, simulations of the distribution system were performed to generate a training data set for the neural network. Modeling the distribution system for a variation of a load conditions in three-phase equivalent circuits in time domain has been carried out by means of MatLab tools (software Simulink). Voltage curves obtained as a result of computations for various load conditions have been decomposed in Fourier series. The voltage harmonic magnitudes characterize the corresponding values of powers chosen as inputs for the neural network. Set of operating conditions chosen for modeling comprised of a possible range of loads variations and combinations. Tab. 1 contains the fragment of the training data set for the neural network shown in Fig. 3. It illustrates the principle of generation of a training data set. Fig. 3. also contains testing data set which is not included to training data set. The testing data set is used for testing the neural network operation.

№	P_{NL2}, MW	P_{NL3}, MW	S_{OL2}, MVA	$K_{U(5)ss-1}$, %	$K_{U(5)ss-2}$, %	$K_{U(5)ss-3}$, %	K_U, %
1	1	0	5.4+j1.6	0,09	1,34	0,12	0,56
2	3	0	7.2+j2.2	0,25	3,8	0,34	0,99
3	5	0	8.9+j2.9	0,41	6,3	0,56	1,46
4	7	0	10.5+j3.7	0,56	8,47	0,75	1,78
5	0	1	5.5+j1.6	0,09	0,11	1,31	0,9
6	0	3	7.3+j2.1	0,26	0,34	3,85	1,61
7	0	5	9.0+j2.8	0,43	0,55	6,23	2,23
8	0	7	10.7+j3.6	0,58	0,74	8,61	2,66
.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.
21	1	7	11.6+j3.8	0,65	1,95	8,69	2,3
22	3	7	13.3+j4.5	0,82	4,52	8,94	2,11
23	5	7	15.0+j5.2	0,99	6,75	9,15	2,44
24	7	7	16.6+j6.0	1,13	8,8	9,28	3,53
Testing set							
25	2	5	10.8+j3.4	0,59	3,07	6,55	1,56
26	5	2	10.8+j3.4	0,58	6,14	3,21	1,71
27	4	6	13.3+j4.5	0,84	5,57	7,99	2,1
28	6	6	15.1+j5.3	0,97	7,15	7,68	2,22

Table 1. Example of training and testing data set for 5th harmonic

№	Real values		Training results		Absolute error	
	$K_{U(5)ss-2}$, %	$K_{U(5)ss-3}$, %	$K_{U(5)\ ss-2}$, %	$K_{U(5)\ ss-3}$, %	$\Delta K_{U(5)\ ss-2}$, %	$\Delta K_{U(5)ss-3}$, %
1	1,34	0,12	1,35	0,2	-0,01	-0,08
2	3,8	0,34	3,7	0,44	0,1	-0,1
3	6,3	0,56	6,17	0,65	0,13	-0,09
4	8,47	0,75	8,49	0,81	-0,02	-0,06
.	.	.	.	.	.	.
.	.	.	.	.	.	.
.	.	.	.	.	.	.
23	6,75	9,15	6,82	9,31	-0,07	-0,16
24	8,8	9,28	9,02	9,42	-0,22	-0,14
Results for testing set						
25	3,07	6,55	2,92	6,6	0,15	-0,05
26	6,14	3,21	6,27	3,11	-0,13	0,1
27	5,57	7,99	5,6	8,05	-0,03	-0,06
28	7,15	7,68	7,19	7,85	-0,04	-0,17

Table 2. Results of neural network training using the data of the set presented in Tab 1.2

Lines 25 – 28 in Tab. 2 show the results of evaluation of voltage waveform distortion indices at the buses of substations for data set that were not included in training set. Absolute error in Tab. 2 is calculated as the differences between real values obtained as a result of electrical grid operating condition simulations and data obtained as a result of neural network training.

Analysis of the results shows that the chosen structure of the neural network, both the set of input data and the step of change of training data pairs allow to provide desired accuracy of monitoring voltage distortion indices at the buses of the distribution grid substations.

4. Conclusions

1. A new concept of harmonic monitoring system for distribution grids was proposed. The concept allows for considerable reduction of the usage of expensive specialized instruments for monitoring harmonic sources in distribution systems.
2. The system enables monitoring voltage distortion indices in selected points of distribution system by the data of one or several stationary instruments for harmonics measurements and data available at lie-substations through existing telemetry channels (P, Q, U, I etc.).
3. The type of neural network for the developed of the monitoring system and the selection method of the training data sets is substantiated. The expediency of obtaining the training data sets for adjusting neural network through modeling of the number of operating conditions of the distribution grid is proved.

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