Engineering

DEVISING A NOVEL METHOD TARGETED AT IMPROVING THE PREDICTION ACCURACY OF THE PRODUCED AND CONSUMED ENERGY IN PHOTOVOLTAIC POWER PLANTS COMPRISING SOLAR PANELS FIELDS LOCATED AT A CERTAIN DISTANCE

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ABSTRACT:
IN THIS PAPER, WE HAVE DEVELOPED, USING AN ARTIFICIAL NEURAL NETWORK (ANN) APPROACH, A NOVEL METHOD AIMING TO IMPROVE THE FORECASTING ACCURACY OF TWO CRITICAL INDICATORS FOR PHOTOVOLTAIC POWER PLANTS: THE AMOUNT OF PRODUCED AND CONSUMED ENERGY. THE METHOD IS ESPECIALLY USEFUL IN THE CASE OF PHOTOVOLTAIC POWER PLANTS COMPRISING SOLAR PANELS FIELDS LOCATED AT A CERTAIN DISTANCE. OF PARTICULAR INTEREST WAS TO DEVELOP AND IMPLEMENT CUSTOM ARTIFICIAL FITTING NEURAL NETWORK ARCHITECTURES, IN ORDER TO ACHIEVE A SPATIAL INTERPOLATION WITH A HIGH DEGREE OF PRECISION, REGARDING THE INPUT METEOROLOGICAL PARAMETERS CORRESPONDING TO THE RESPECTIVE FIELDS OF SOLAR PANELS. OUR METHOD IS USEFUL FOR THE PHOTOVOLTAIC POWER PLANTS OPERATORS THAT MUST PROVIDE DETAILED REPORTS REGARDING THE FORECASTED QUANTITY OF ENERGY PRODUCTION AND CONSUMPTION, TO THE NATIONAL AUTHORITIES. THE DEVISED METHOD POSES ADVANTAGES IN ASSESSING WHETHER A CERTAIN AREA IS APPROPRIATE FOR SUSTAINING A PHOTOVOLTAIC POWER PLANT DEVELOPMENT, THUS IF FINANCIAL RESOURCES ARE WORTH INVESTING. ONCE IMPLEMENTED AND COMPILED, THE METHOD BECOMES A SPECIALIZED FRAMEWORK, THAT IS USEFUL FOR THE DEVELOPMENT OF A WIDE RANGE OF CUSTOMIZED APPLICATIONS FOR PREDICTING PERFORMANCE INDICATORS IN THE FIELD OF RENEWABLE ENERGY.

KEY WORDS: ANNs, PHOTOVOLTAIC ENERGY, SOLAR PANELS, FORECASTING METHOD

INTRODUCTION

A series of papers from the scientific literature[3] and patents from the international databases in the energy field tackle issues regarding the solar or wind energy and the

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[3] Abuella, Mohamed, Chowdhury, Badrul; *Solar power forecasting using artificial neural networks, Proceedings of the 47th Annual North American Power Symposium,* Charlotte: University of North Carolina at Charlotte, 2015; Beale, Mark Hudson, Hagan, Martin, Demuth Howard; *Matlab Neural Network Toolbox User's Guide, R2016b,* http://www.mathworks.com/, 2016; Lungu, Ion, Bâra, Adela, Caruțașu, George, Pîrjan,

prediction of the amount of the produced energy, based on the meteorological data. However, to our best knowledge, none of the works so far have approached the development of methods for forecasting the quantity of energy production and consumption using a prediction method based on a meteorological spatial interpolation of the input parameters for photovoltaic power plants comprising solar panels fields located at a certain distance, like the method that we have developed and presented within this paper. The meteorological spatial interpolation is based on a set of input meteorological parameters, provided by a specialized institute, that correspond to a certain location. Starting with the set of values that is known, the values of the same parameters, corresponding to other locations situated at a certain distance from the first one, are estimated using an artificial neural network (ANN) approach.

Our method addresses the needs of the photovoltaic power plants operators, of the potential investors that want to develop solar power plants, as well as other categories of users whose activity requires accurate forecasting methods for the produced and consumed energy within the production process. These methods must be effective, resourceful, fast, reliable and economically advantageous. In this context, our developed method provides a solution for achieving this goal, based on a set of input parameters consisting in the meteorological data (the solar irradiation level, the environmental temperature, the humidity, the atmospheric pressure) and finally provides a method of predicting the produced and consumed energy within the production process with a high level of accuracy.

The devised photovoltaic energy prediction method is based on developing and implementing artificial neural networks, which are carried out in two stages. During the first stage of the method, a meteorological prediction artificial neural network is developed and applied afterwards to predict the necessary parameters. During the second stage of the photovoltaic energy prediction method, an energy prediction artificial neural network is developed and used in order to forecast the produced and consumed energy. In the following, we present our novel method, aiming to improve the forecasting accuracy of two critical indicators for photovoltaic power plants: the amount of produced and consumed energy.

THE DETAILED DESCRIPTION OF THE DEVISED PHOTOVOLTAIC ENERGY PREDICTION METHOD

The method targeted at improving the prediction accuracy of the produced and consumed energy in photovoltaic power plants comprising solar panels fields located at a certain distance, aims to improve the forecasting accuracy of the existing methods, by developing an estimation technique in two stages. The meteorological data supplied by the specialized institute is related to a particular solar panels field, but if the photovoltaic power plant is large in size, comprising several solar panels fields that are situated at a distance from the initial one, the weather data is no longer appropriate.

Our proposed photovoltaic energy prediction method solves this deficiency and proves to be best suited for photovoltaic power plants comprising solar panels fields located at a certain distance that is large enough so that the meteorological data of the first solar panels

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Alexandru, Oprea, Simona Vasilica; *Prediction Intelligent System in the Field of Renewable Energies Through Neural Networks, Economic Computation and Economic Cybernetics Studies and Research*, Bucuresti: Editura Academia de Studii Economice, 2016; Lungu, Ion, Carutasu, George, Pîrjan, Alexandru, Oprea, Simona-Vasilica, Bâra, Adela; *A two-step forecasting solution and upscaling technique for small size wind farms located in hilly areas of Romania, Studies in Informatics and Control*, București: ICI Publishing House, 2016; Nassehzadeh, Shahram Tabriz, Behboodi, Elham, Aliyev, Fagan; *Towards Renewability by Applying Solar Energy Technologies for Improved Life Cycle, International Journal on Technical and Physical Problems of Engineering*, International Organization of IOTPE, 2012; Oprea, Simona Vasilica, Pîrjan, Alexandru, Lungu, Ion, Fodor, Anca Georgiana; *Forecasting solutions for photovoltaic power plants in Romania, Proceedings of the 15th International Conference on Informatics in Economy*, Bucuresti: University of Economic Studies Press, 2016 field is not representative to the other solar panels fields as to obtain an accurate forecasting of the produced energy, but small enough to fit into the weather resolution area (WRA).

The new photovoltaic energy prediction method comprises two stages, the first one containing 4 steps and the second one 3 steps (figure 1).

During **Stage 1**, according to the photovoltaic energy prediction method, a meteorological prediction artificial neural network is developed and once trained, the network is used to predict the meteorological parameters corresponding to the solar panels fields that are situated at a distance from the initial one. The neural meteorological prediction network of the method is developed based on the Bayesian Regularization algorithm[4], using the following architecture: one neuron for each of the input data (the solar irradiation level, the environmental temperature, the humidity, the atmospheric pressure), 16 neurons for the hidden layer, 4 neurons for the exit layer and 4 for the output data (the solar irradiation level, the environmental temperature, the humidity, the atmospheric pressure, predicted within the WRA). The initial conditions for starting the first stage consist in knowing beforehand the statistical meteorological data recorded by the solar panels fields' sensors, consisting in representative samples for a suitable period of time, so that it covers at least one year. During the first stage, the following conditions must be met: in order to obtain the rebuilt data set for training the photovoltaic energy prediction neural network it is necessary to know the statistical meteorological data recorded by the first solar panels field's sensors and the forecasted meteorological data for the other solar panels fields, using the developed meteorological artificial neural network; in order to rebuild the dataset that will be used in the prediction of the produced and consumed energy using photovoltaic energy prediction neural network, there are necessary the meteorological data recorded by the first solar panels field's sensors and the forecasted meteorological data for the other solar panels fields, obtained using the developed meteorological artificial neural network (figure 1).

During **Step 1** of the **Stage 1**, according to the method, a meteorological prediction artificial neural network is developed based on the Bayesian Regularization algorithm, using the above-mentioned architecture. In order to start the first step, one must know the statistical meteorological data recorded by the solar panels fields' sensors.

During **Step 2** of the **Stage 1**, according to the photovoltaic energy prediction method, one obtains the forecasted meteorological data for the other solar panels fields. These data will be used later for the reconstruction of the data set that will be used to train the energy prediction artificial neural network. The initial conditions for starting the second step consist in knowing the statistical meteorological data recorded by the first solar panels field's sensors and the meteorological prediction artificial neural network, previously developed during the first step.

During **Step 3** of the **Stage 1**, according to our developed method, one obtains the reconstructed meteorological data set that will be needed in order to train the energy prediction artificial neural network. In order to start the third step, one must know the meteorological data recorded by the first solar panels field's sensors and the forecasted data that have been obtained at Step 2.

During **Step 4** of the **Stage 1,** according to our photovoltaic energy prediction method, one obtains the forecasted meteorological data set for the other solar panels fields that will be used for reconstructing the data set, the data set been mandatory in order to be able to forecast using the energy prediction artificial neural network. The initial constraints that must be met in order to start the fourth step consist in having the meteorological data set delivered by the

[4] Beale, Mark Hudson, Hagan, Martin, Demuth Howard; *Matlab Neural Network Toolbox User's Guide, R2016b*, http://www.mathworks.com/, 2016

specialized institute for the first solar panels field and the meteorological prediction artificial neural network that has been previously trained in the first step.

During **Stage 2** of the photovoltaic energy prediction method, an energy prediction artificial neural network is developed and used in order to forecast the produced and consumed energy. The energy prediction artificial neural network of the method is developed based on the Bayesian Regularization algorithm, according to the following architecture: one neuron for each of the input data (the solar irradiation level, the environmental temperature, the humidity, the atmospheric pressure) for each of the solar panels fields, 14 neurons for the hidden layer, 2 neurons for the exit layer and 2 for the output data (the produced and consumed energy). The initial conditions that must be met in order to start the second stage consist in knowing the meteorological reconstructed data set obtained after executing the third step of the first stage, as well as the data regarding the production and consumption of energy. During the second stage, the following constraints must be satisfied: in order to reconstruct the meteorological dataset that will be used for forecasting the production and consumption of energy, one needs the meteorological data from the specialized institute for the first solar panels field and also the data set that has been obtained after executing the fourth step of the first stage; in order to forecast the produced and consumed energy for the photovoltaic power plant, one needs the reconstructed meteorological dataset that has been obtained after having executed the sixth step of the second stage, as well as the energy prediction artificial neural network that has been previously trained, at the fifth step of the second stage (figure 1).

During **Step 5** of the **Stage 2**, according to our photovoltaic prediction method, an energy prediction artificial neural network is developed and once it has been trained, the network is used to forecast the amount of produced and consumed energy. The energy prediction artificial neural network of the method is developed based on the Bayesian Regularization algorithm, according to the above-mentioned architecture. In order to start the fifth step, one must know the meteorological reconstructed dataset that has been obtained after executing the third step of the first stage, as well as the data regarding the production and consumption of energy.

During **Step 6** of the **Stage 2**, according to the devised method, one obtains the reconstructed meteorological dataset that is useful for predicting the amount of produced and consumed energy. The initial conditions for the sixth step consist in knowing the meteorological data, provided by the specialized institute, from the first solar panels field as well as the data set obtained in the fourth step.

During the last step, **Step 7** of the **Stage 2**, according to the photovoltaic energy prediction method, one obtains the forecasted data regarding the energy production and consumption. In order to start the seventh step, one must know the reconstructed meteorological dataset resulting after having executed the sixth step of the second stage, as well as the energy prediction artificial neural network previously developed, in the fifth step of the second stage.

The block diagram of our photovoltaic energy prediction method has been synthetized in (figure 1).

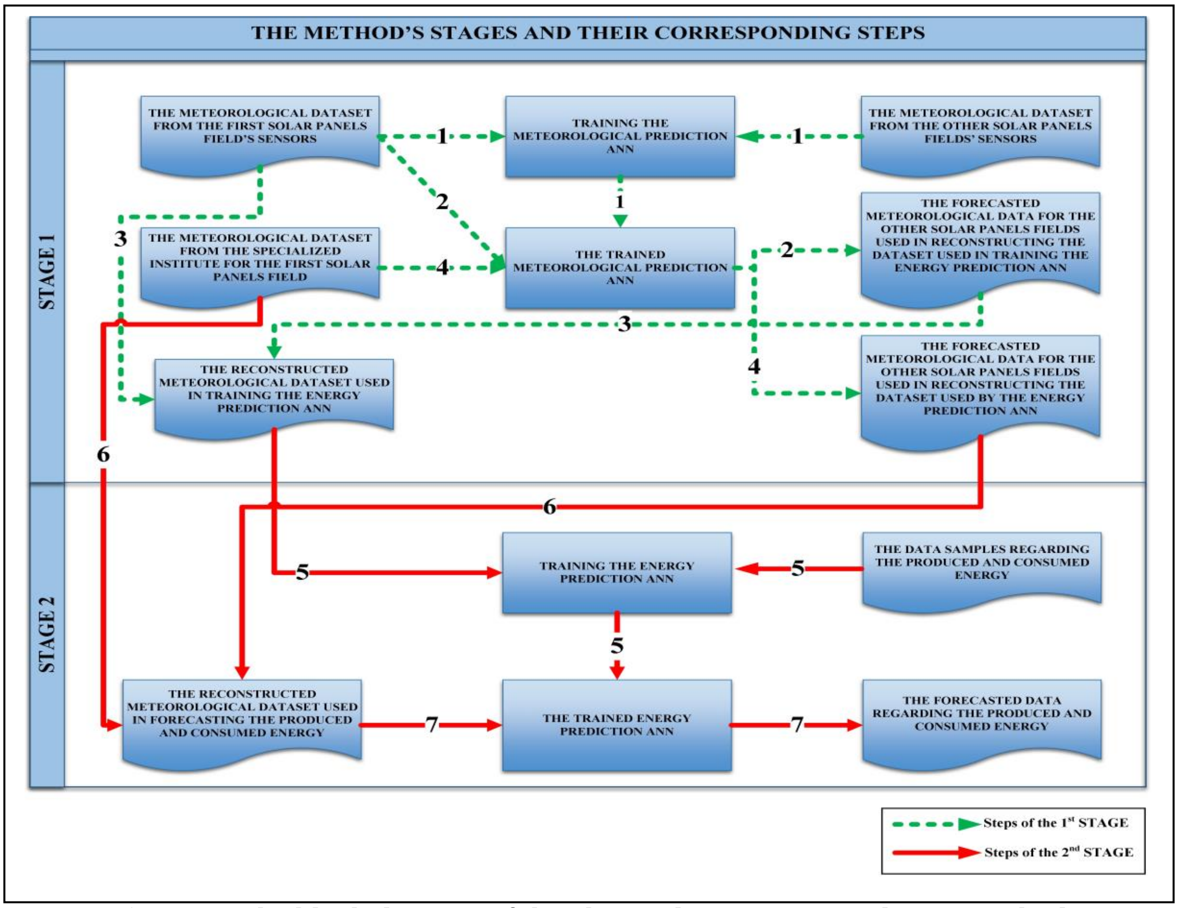

Figure 1. The block diagram of the photovoltaic energy prediction method

In the following we present an eloquent but nonlimitative example of how our devised method can be successfully applied to a solar power plant located in the Giurgiu County, Romania.

EXPERIMENTAL RESULTS AND THEIR ANALYSIS

The experimental data has been obtained from a solar power plant located in the Giurgiu County, Romania and they consist in a number of 9214 samples (after the exclusion of the irrelevant ones), that have been obtained through hourly measurements, during a one year period (from the 1st of January to the 31st of December 2014). The solar power plant comprises two solar panels fields, located at a distance of 1500 meters from each other.

The values corresponding to the input parameters are provided by the specialized meteorological institute (the solar irradiation level, the environmental temperature, the humidity, the atmospheric pressure), the forecast being provided at a horizontal weather resolution of 10 km[5]. The energy producer can also acquire a forecast with a more refined resolution, of 5 km, however the high cost involved for acquiring this forecasting service makes it unaffordable for most of the renewable energy producers[6].

Even in the case of refined weather resolutions (such as the one of 1500 m, presented in the case study) there are recorded changes regarding the direct beam solar irradiation, the atmospheric reflection, the atmospheric absorption, the reflected low wave solar irradiation

[5]*http://www.meteoromania.ro/anm2/despre-noi/meteorologie-operationala/prognoza-numerica/modelul-aladin/*, accessed on 2 July 2017

[6] *http://www.meteoromania.ro/anm2/despre-noi/meteorologie-operationala/prognoza-numerica/modelul-alaro/*, accessed on 2 July 2017

determined by different surfaces (Albedo), the diffuse-scattered solar irradiation, all of these influencing the amount of solar irradiation captured by the collector surfaces of the solar panels, even in the case of panels that are equipped with auto-directing mechanisms towards the sun.

The neural meteorological prediction network of the method forecasts with high accuracy within the same WRA, thus obtaining adjusted meteorological parameters for the other solar panel field(s) located at a certain distance within the WRA, consequently refining the forecasting accuracy within the weather resolution area of the forecasting provided by the specialized meteorological institute.

For both the meteorological prediction artificial neural network and the energy prediction one we have benchmarked different alternatives related to the allocation of the dataset in subsets required by the developing phases of the ANNs (in the case of the networks developed using the BR algorithm, these stages are the training and the testing phases).

For both networks, the setting that has offered the best results was the one in which we have allocated 75% of the data samples in the training process and the remaining percentage in the testing phase. Both of the artificial neural networks have been developed, trained and tested using the Neural Network Toolbox from the development environment MatlabR2016b[7].

Using the meteorological data recorded by the sensors of the two solar panels fields (from the 1st of January to the 31st of December 2014), we have developed the meteorological prediction artificial neural network, according to the first stage of our method. Afterwards, we have used this ANN in order to forecast the meteorological dataset corresponding to the second solar panels field, when the meteorological dataset corresponding to the first solar panels field are delivered by the national specialized institute. The obtained results are used in order to obtain an accurate meteorological dataset, as close as possible as if the data had been provided by the sensors themselves.

This reconstructed dataset that contains the meteorological data corresponding to the first solar panels field and the forecasted meteorological dataset corresponding to the second solar panels field, will be used along with the dataset containing the production and consumption of energy, in the second stage of our devised method, for training the energy prediction artificial neural network. This network has been developed using the Bayesian Regularization algorithm.

Once trained, the energy prediction artificial neural network is used in order to forecast the amount of energy production and consumption within the solar power plant, using a reconstructed dataset that contains the meteorological dataset corresponding to the first solar panels field delivered by the national specialized institute and the forecasted meteorological data set for the other solar panels field, obtained by using the meteorological prediction artificial neural network.

In order to validate our developed method, after the networks have been trained, the method has been applied using the dataset for the year 2015, provided by the photovoltaic power plants' operator, comparing the forecasted results with the actual ones, recorded by the solar panels' sensors.

The obtained results have confirmed the accuracy of the developed method, thus resulting in a solution that forecasts the produced and consumed energy within the production process of photovoltaic energy when knowing a set of input parameters consisting in the meteorological data (the solar irradiation level, the environmental temperature, the humidity, the atmospheric pressure).

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[7] Beale, Mark Hudson, Hagan, Martin, Demuth Howard; *Matlab Neural Network Toolbox User's Guide, R2016b*, http://www.mathworks.com/, 2016

In the following, we present and analyze the prediction accuracy recorded by the energy prediction artificial neural network, developed using the Bayesian Regularization algorithm. In this purpose, we have represented the plots highlighting:

- the performance analysis through the minimum value of the Mean Squared Error MSE (figure 2);
- the error histogram highlighting the range of the registered errors (figure 3);
- the regressions between the network targets and network outputs, highlighting the minimum values of the correlation coefficient corresponding to the training phase, the testing phase and the global one (figure 4).

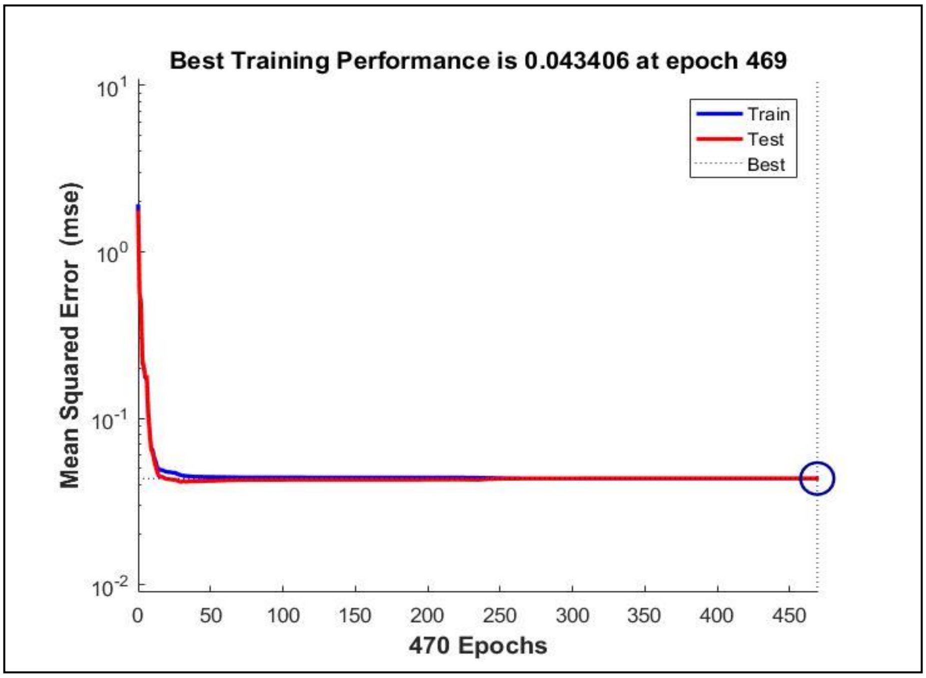

Figure 2. The best training performance of the energy prediction artificial neural network

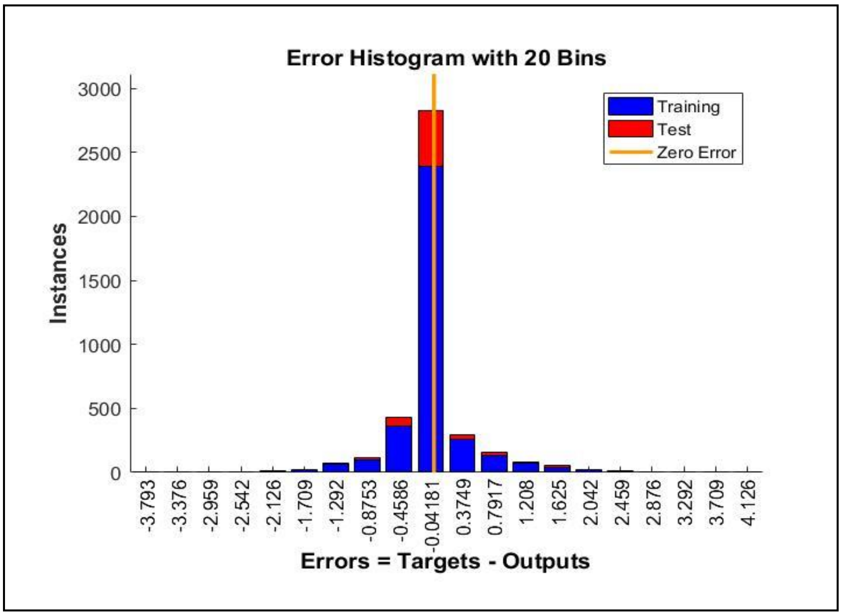

Figure 3. The error histogram of the energy prediction artificial neural network

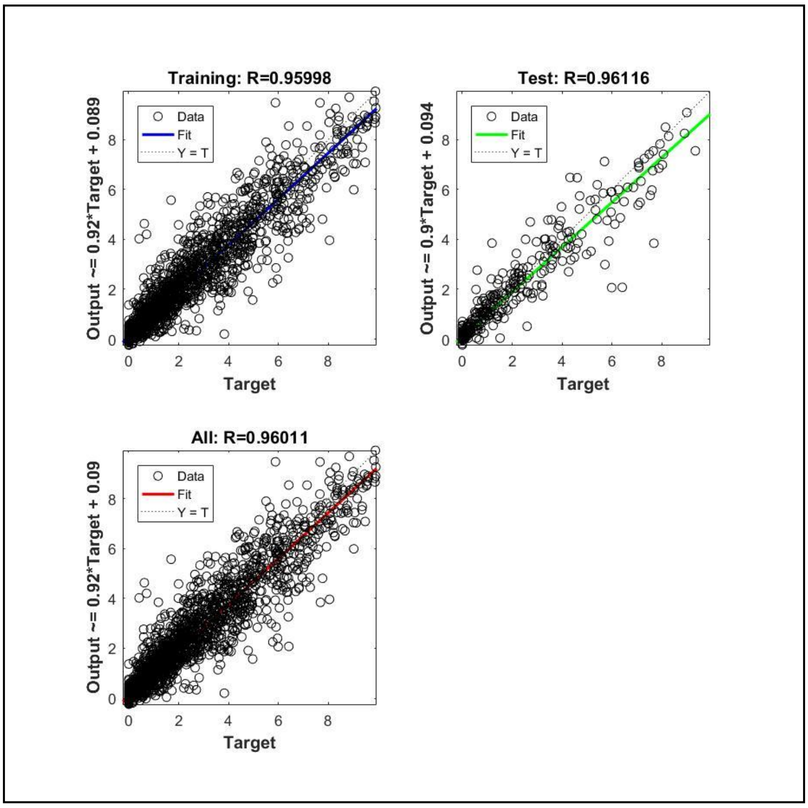

Figure 4. The regressions of the energy prediction artificial neural network

Analyzing the plots, one can notice that the value of the MSE coefficient is low (0.043406), the range of errors is narrow and all the values of the correlation coefficients are close to one.

CONCLUSIONS

The obtained results highlight the high level of forecasting accuracy and confirm the efficiency of our method that improves the prediction accuracy of the produced and consumed energy in photovoltaic power plants comprising solar panels fields located at a certain distance. Our method can be implemented and compiled, thus becoming a specialized framework, useful in developing a wide range of specialized applications that forecast accurately key indicators in the field of renewable energy.

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8. *http://www.meteoromania.ro/anm2/despre-noi/meteorologie-operationala/prognoza-numerica/modelul-alaro/* , accessed on 2 July 2017