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PREDICTION OF THE WIND SPEED CHANGE FUNCTION BY LINEAR REGRESSION METHOD

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Abstract: In the article the approximation of the function of wind speed changes by linear functions based on Walsh functions and the prediction of function values by linear regression method is made. It is shown that under the condition of a linear change of the internal resistance of the wind generator over time, it is advisable to introduce the wind speed change function with linear approximation. The system of orthonormal linear functions based on Walsh functions is given. As an example, the approximation of the linear-increasing function with a system of 4, 8 and 16 linear functions based on the Walsh functions is given. The result of the approximation of the wind speed change function with a system of 8 linear functions based on Walsh functions is shown. Decomposition coefficients, mean-square and average relative approximation errors for such approximation are calculated. In order to find the parameters of multiple linear regression the method of least squares is applied. The regression equation in matrix form is given. The example of application of the prediction method of linear regression to simple functions is shown. The restoration result for wind speed change function is shown. Decomposition coefficients, mean-square and average relative approximation errors for restoration of wind speed change function with linear regression method are calculated.

Key words: wind speed change function, prediction, method of linear regression, approximation error.

1. Introduction

The Energy Strategy approved by the Government of Ukraine foresees that by 2035 the share of renewable energy sources (RES) in the energy sector will be 11 % [1]. At the end of 2016, 1.1 MW of the capacity of renewable energy sources was installed which produces about 1 % of the total amount of released electricity. The largest part of renewable energy sources in Ukraine is represented by wind power stations, which in 2016 produced 925 GW*h of power [2].

The application of Heisenberg's uncertainty principle [3] leads to the fact that for ensuring maximum efficiency of wind power stations, it is necessary to implement two-channel control: first, by the basic interval to provide the necessary level of energy for the storage charge and, second, by the minimum duration of an observation interval to ensure the necessary level of maximum possible energy that can be obtained from wind power stations. The efficient work of the station is realized by predictive control in the basic interval according to the predictor–corrector method [4]. In the n^{th} interval there is a prediction of the wind speed change function, and in the $(n+1)^{th}$ interval a correction of values is made, for which the wind speed change function must be known, which in turn should be approximated by orthogonal functions with the slightest approximation error [5].

Therefore, the problem of predicting the function of the wind speed change on the basis of approximation by orthogonal functions arises.

2. Approximation of wind speed change function

The dynamic change in the magnitude and direction of the wind speed and in the result of the internal resistance of the equivalent wind generator source leads to the change in the conditions for selecting the maximum energy. The selection is obtained by assuming that the parameters of the source change linearly over time [6]. Thereby, the problem of representing the wind speed change function by linear approximations arises. Linear orthogonal approximating functions, in particular, include the orthonormal Franklin functions [7]. But taking into account their non-periodicity and asymmetry, it is expedient to use a system of orthonormal linear functions based on Walsh functions [8]:

$$\begin{cases} W_{linear\,0}(t)=1 \\ W_{linear\ i}(t)=\left(n\sqrt{3}-k\sqrt{3}\right)wal_{nk}(t) \end{cases}, \qquad (1)$$

where i is the number of piecewise-linear function, $i = 0...n$; n are system dimensions; k is the number of partitioning interval; $wal_{nk}(t)$ is a value of i^{th} Walsh function at the k^{th} partitioning interval; $\{n,k\}=0\ldots2^m-1$. Given system of functions satisfies the conditions of Gram-Schmidt orthogonalization.

The equation of a function approximated by linear functions based on Walsh functions has the following form [9]:

$$y(t)=\sum_{i=0}^{N-1}c_i W_{linear\ i}\left(\frac{t}{T}\right), \qquad (2)$$

where $c_i = \frac{1}{T}\int_0^1 y(t) W_{linear\ i}\left(\frac{t}{T}\right) dt$ are decomposition coefficients for a series of linear functions based on Walsh functions.

As an example, let us provide the approximation of the linearly increasing function $y(t) = t + 1$ by a system of 4, 8 and 16 linear functions based on the Walsh functions. The results of the approximation are shown in Fig. 1 a, b, c.

An approximation error for each case is calculated by following equation [10]:

$$\delta = \sqrt{\frac{1}{T}\int_0^1 \left[y(t) - c_i W_{li}\right]^2 dt} \qquad (3).$$

$\delta_1 = 15.7\,\%$ for a system of 4 functions; $\delta_2 = 16.3\ \%$ for a system of 8 functions; $\delta_3 = 14.7\,\%$ for a system of 16 functions. Since the difference between the errors is no more than 1 %, for the coincidence of the break points of empirical data and approximating functions, it is expedient to use a system of 8 linear functions based on Walsh functions.

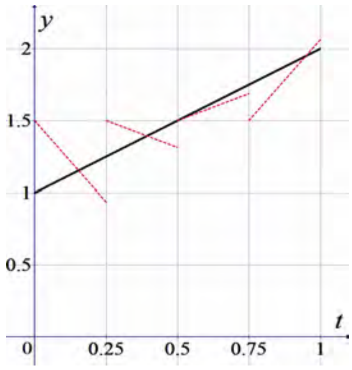

Fig. 1 (a). The results of approximation of the linearly increasing function $y(t) = t + 1$ by a system of 4 linear functions based on the Walsh functions.

Fig. 1 (b). The results of approximation of the linearly increasing function $y(t) = t + 1$ by a system of 8 linear functions based on the Walsh functions.

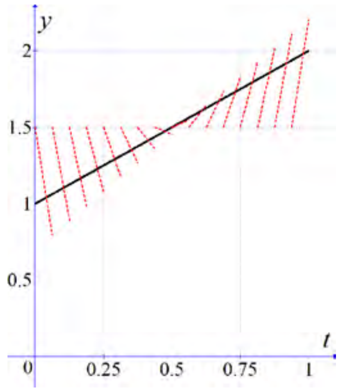

Fig. 1 (c). The results of approximation of the linearly increasing function $y(t) = t + 1$ by a system of 16 linear functions based on the Walsh functions.

In order to predict the wind speed change function, let us apply the approximation by linear functions based on Walsh functions to the data obtained from [11]. Table 1, for example, shows the wind speed values for the period from August 31, 2018 to September 7, 2018, which were taken every 3 hours.

Table 1

Wind speed data, m/s

Time / Date	0	3	6	9	12	15	18	21	0
08/31	1	1	2	3	2	2	1	1	1
09/01	1	1	2	3	2	3	2	3	3
…	…	…	…	…	…	…	…	…	…
09/06	1	2	2	3	4	2	2	2	2
09/07	2	2	2	3	1	2	3	1	0

Fig. 2 shows the result of the approximation of the wind speed change function on September 7, 2018 by a system of 8 linear functions based on Walsh functions according to equation (2).

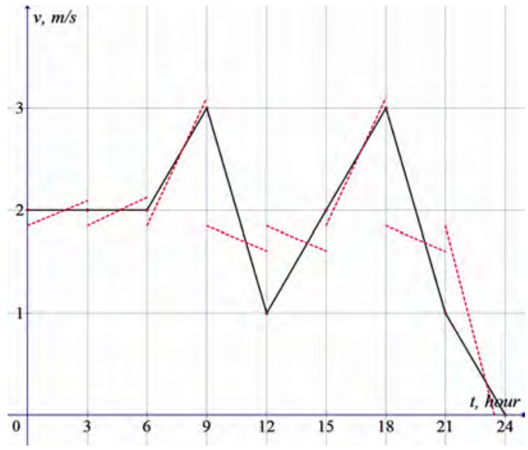

Fig. 2. The result of the approximation of the wind speed change function on September 7, 2018 by a system of 8 linear functions based on Walsh functions.

A mean-square approximation error for such decomposition is 79 % and an average relative approximation error $\Delta = \frac{1}{N}\sum_{i}^{N-1}\Delta_i$ in approximation nodes is 30 %.

Table 2 shows the values of decomposition coefficients for the values of the wind speed change function given in Table 1.

Table 2

The values of decomposition coefficients for the wind speed change function

Coefficient \ Date	08/31	09/01	…	09/06	09/07
C_0	1.63	2.25	…	2.31	1.88
C_1	0.04	-0.04	…	-0.07	0.14
C_2	-0.11	-0.32	…	-0.22	0.22
C_3	-0.04	-0.04	…	0.14	-0.36
C_4	0.25	-0.32	…	0.14	0.22
C_5	-0.11	-0.04	…	-0.22	0.07
C_6	-0.40	-0.18	…	-0.36	-0.29
C_7	-0.18	-0.18	…	0	0.14

To predict the wind speed change function, let us predict the decomposition coefficients for a series of linear functions based on Walsh functions. For this a regression analysis is applied, and the comparison with results of approximation of corresponding empirical data is made.

3. Application of regression analysis

In order to find the parameters of multiple linear regression let us apply the method of least squares, according to which the decomposition coefficients of a series are calculated by the following equation [12]:

$$B = \left(C_{in}^{\ T} \cdot C_{in}\right)^{-1} C_{in}^{\ T} \cdot C_{out}, \qquad (4)$$

where C_{out} are coefficients of a series obtained on $(n+1)^{th}$ observation interval; C_{in} are coefficients of the series obtained on the n^{th} observation interval; B are coefficients of regression. All coefficients of the equation (4) are presented in the form of the following matrix:

$$C_{out} = \begin{pmatrix} C_1 \\ C_2 \\ \dots \\ C_n \end{pmatrix}, C_{in} = \begin{pmatrix} C_{11}C_{12}\dots C_{1n} \\ C_{21}C_{22}\dots C_{2n} \\ \dots\dots\dots\dots \\ C_{n1}C_{n2}\dots C_{nn} \end{pmatrix}, B = \begin{pmatrix} b_0 \\ b_1 \\ \dots \\ b_n \end{pmatrix}$$

By solving this system of equations, the matrix-column $\boldsymbol{B}$ of the coefficients of the linear multiple regression is obtained, while the mutual influence of the coefficients is not taken into account.

The system of equations for regression analysis is built as follows. Since the coefficients of the series depend on their values in the previous observation intervals, for each coefficient the input data C_{in} were the coefficients for a given number of previous observation intervals and the corresponding coefficient C_{out} in the current interval. These data form the first equation of the system. Next equations were formed in a similar way with the displacement of the observation interval to the right. The system of equations is built each time when it is necessary to make a prediction for new empirical data.

In Fig. 3, the results of application of such a prediction method to linearly increasing, piecewise-linearly increasing and piecewise-linearly decreasing functions are given. A solid line indicates input data, a dashed line indicates predicted data.

This prediction method being used, for example, for the 7th day, matrixes C_{in} and C_{out} will look as follows:

$$C_{in} = \begin{pmatrix} C_1C_2C_3 \\ C_2C_3C_4 \\ C_3C_4C_5 \end{pmatrix}, C_{out} = \begin{pmatrix} C_4 \\ C_5 \\ C_6 \end{pmatrix}.$$

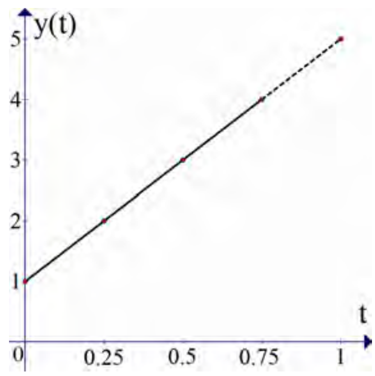

Fig. 3 (a). The results of application of prediction method to linearly increasing (a) functions.

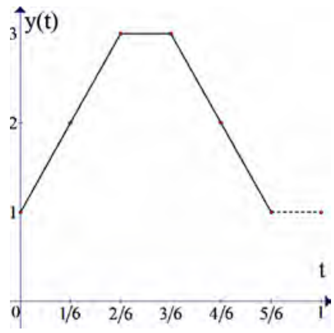

Fig. 3 (b). The results of application of prediction method to piecewise- linearly increasing (b) functions.

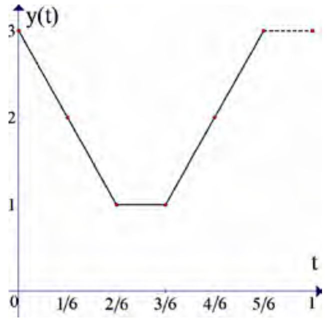

Fig. 3 (c). The results of application of prediction method to piecewise- linearly decreasing (c) functions.

Table 3

Predicted decomposition coefficients for the 7th, 8th and 9th day

Coefficient / Date	09/06	09/08	**09/07**
C_0	-0.49	2.90	**1.21**
C_1	0.13	-0.58	**-0.22**
C_2	-0.22	27.70	**13.74**
C_3	-3.60	-1.37	**-2.49**
C_4	0.39	0.04	**0.21**
C_5	2.23	-3.11	**-0.44**
C_6	-0.84	3.98	**1.57**
C_7	0.01	-151.1	**-75.53**

Table 4

Statistical parameters of decomposition coefficients

Parameter / Coefficient	M	σ	$M-3\sigma$	$M+3\sigma$
C_0	2.08	0.65	0.13	4.03
C_1	-0.01	0.11	-0.34	0.32
C_2	-0.15	0.24	-0.87	0.57
C_3	0.06	0.05	-0.09	0.21
C_4	-0.03	0.25	-0.78	0.72
C_5	-0.12	0.17	-0.63	0.39
C_6	-0.29	0.32	-1.25	0.67
C_7	-0.05	0.18	-0.59	0.49

The matrix of regression coefficients B having been obtained and values $(C_4 C_5 C_6)$ having been substituting into the regression equation, we can obtain values for the 7th day. For the 9th day the calculation will be similar. The only difference is that the matrix will have a dimension of 4x4. According to the predicted decomposition coefficients for the 7th and 9th days, the decomposition coefficients for the 8th day are determined as the arithmetic mean of the obtained values (Table 3).

In order to avoid false values in prediction and increase its efficiency, all values out of boundaries 3σ are considered as false. Instead, values 3σ can be used with a sign corresponding to the sign of the predicted value. Statistical parameters, such as the expected value and mean square deviation for 7 days are given in Table 4.

Taking this into account, the predicted decomposition coefficients for the 7th, 8th and 9th day are as follows:

Table 5

Corrected predicted decomposition coefficients for the 7th, 8th and 9th day

Coefficient / Date	09/06	09/08	**09/07**
C_0	0.13	2.90	**1.52**
C_1	0.13	-0.34	**-0.11**
C_2	-0.22	0.57	**0.17**
C_3	-0.09	-0.09	**-0.09**
C_4	0.39	0.04	**0.21**
C_5	0.39	-0.63	**-0.12**
C_6	-0.84	0.67	**-0.09**
C_7	0.01	-0.59	**-0.29**

The regression equations for the corresponding decomposition coefficients are summarized in Table 6. C_i is the predictive value of the coefficient, and $C_{i-1} \div C_{i-4}$ are the values in the previous observation intervals.

Table 6

Regression equations for the corresponding decomposition coefficients

Coefficient	Equation
C_0	$C_{0i} = 1.15C_{0(i-4)} - 0.09C_{0(i-3)} + 0.02C_{0(i-2)} - 0.05C_{0(i-1)}$
C_1	$C_{1i} = 2.11C_{1(i-4)} - 0.42C_{1(i-3)} - 1.14C_{1(i-2)} - 1.2C_{1(i-1)}$
C_2	$C_{2i} = -33.4C_{2(i-4)} - 0.9C_{2(i-3)} + 12.23C_{2(i-2)} + 31.68C_{2(i-1)}$
C_3	$C_{3i} = -7.42C_{3(i-4)} + 0.37C_{3(i-3)} - 0.75C_{3(i-2)} + 0.61C_{3(i-1)}$
C_4	$C_{4i} = -0.23C_{4(i-4)} - 0.23C_{4(i-3)} - 0.49C_{4(i-2)} + 0.25C_{4(i-1)}$
C_5	$C_{5i} = 4.79C_{5(i-4)} - 4.83C_{5(i-3)} + 2.17C_{5(i-2)} - 0.28C_{5(i-1)}$
C_6	$C_{6i} = -1.54C_{6(i-4)} + 1.21C_{6(i-3)} + 2.02C_{6(i-2)} + 1.77C_{6(i-1)}$
C_7	$C_{7i} = 298.85C_{7(i-4)} - 97.25C_{7(i-3)} - 261.04C_{7(i-2)} - 153.6C_{7(i-1)}$

According to predicted values of decomposition coefficients, let us restore the wind speed change function for the 8th day (September 7, 2018). The restoration result is shown in Fig.4, where the dashed line denotes a function restored by the predicted coefficients and the solid line denotes empirical data.

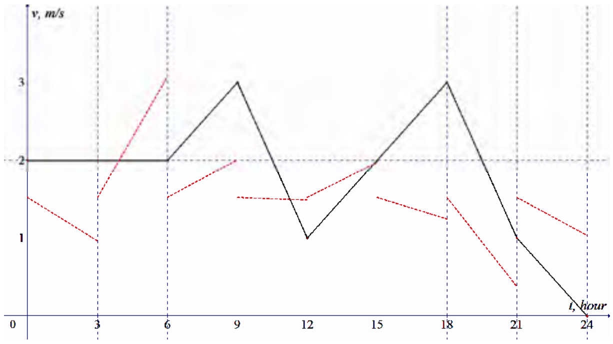

Fig. 4. The restoration result for wind speed change function for the 8th day (September 7, 2018)

In general, the approximate function can be used to observe the main trend (character of change) of the function in each approximation interval.

The mean-square approximation error for such restoration is 88 % and the average relative approximation error in approximation nodes is 40 %.

The graph shows that at the ends of the interval, the deviations of approximating values are maximum. This is similar to the Gibbs phenomenon [13]. Taking it into account, the mean square approximation error decreases to 33 %, and the average relative approximation error in approximation nodes decreases to 23 %. Approximation error can be reduced by the correction of the predicted decomposition coefficients according to a form of the wind speed change function.

4. Conclusion

Thus, the application of regression analysis methods to the decomposition coefficients of a series of linear functions based on Walsh functions allows the prediction of the wind speed change function with the error of not more than 33 % which can be reduced by correction of the predicted coefficients according to a form of the wind speed change function.

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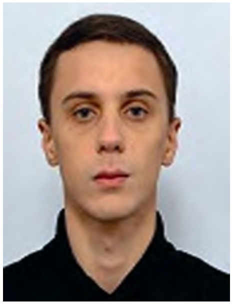
ПРОГНОЗУВАННЯ ФУНКЦІЇ ЗМІНИ ШВИДКОСТІ ВІТРУ МЕТОДОМ ЛІНІЙНОЇ РЕГРЕСІЇ

Катерина Клен, Вадим Мартинюк, Михайло Яременко

У статті зроблено апроксимацію функції зміни швидкості вітру лінійними функціями на основі функцій Уолша та прогнозування значень функцій методом лінійної регресії. Показано, що за умови лінійної зміни внутрішнього опору вітрогенератора в часі доцільно ввести функцію зміни швидкості вітру з лінійною апроксимацією. Наведено систему ортонормальних лінійних функцій на основі функцій Уолша. Як приклад, наведено наближення лінійно-зростаючої функції із системою з 4, 8 та 16 лінійних функцій на основі функцій Уолша. Показано результат наближення функції зміни швидкості вітру із системою з 8 лінійних функцій на основі функцій Уолша. Розраховано коефіцієнти розкладення, середньоквадратичні та середні відносні похибки такої апроксимації. Для знаходження коефіцієнтів множинної лінійної регресії використано метод найменших квадратів. Наведено рівняння множинної лінійної регресії в матричній формі. Показано приклад застосування методу лінійної регресії в простих функціях. Показано результат відновлення функції зміни швидкості вітру. Розраховано коефіцієнти розкладення, середньоквадратичні та середні відносні похибки апроксимації для відновлення функції зміни швидкості вітру методом лінійної регресії.



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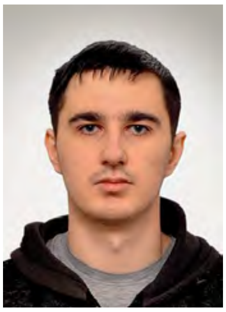

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