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MODIFICATION OF DYNAMIC PROGRAMMING METHOD IN DETERMINING ACTIVE COMPOSITION OF WIND POWER STATIONS

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Abstract: The article presents the results of modification of the dynamic programming method to solve of the knapsack problem in determining the active composition of a wind power station with regard to the effectiveness of each wind turbine and the use of an accumulating element in the structure of the system under investigation.

The comparative analysis of the modification of dynamic programming method for the determination of the active composition of a wind power station using the classical method of dynamic programming and that at an increased load by the experimentally founded percentage has defined advantages and disadvantages of using each of the methods under investigation.

It has been found that the modification of the dynamic programming method for solving the knapsack problem shows the possibility of improving the conditions of equality of generation and consumption of electricity compared to the classical method of dynamic programming to the standard deviation of 0.046 %, and makes it possible for this method to be applied to determine the active composition of a wind power station.

Key words: wind power station, method of dynamic programming, active composition of a wind power station

1. Introduction

As a wind speed is a probability characteristic, it is important to ensure the operational stability of wind turbines in particular, and a wind power station as a whole. Given the uncertainty of wind speed, there is a need for a dynamic analysis and rational choice of the wind turbines (hereinafter referred to as “active composition of WPS”) required to be switched on at a given moment which would make it possible to meet customers’ needs taking into account energy parameters of wind, installed and instantaneous capacity of each wind turbine, as well as boundary conditions of their applications (insufficient or excessive wind speed, critical technical conditions, etc.).

To improve the justification for the control algorithms of dynamic-energy modes of a wind power station, the methods of data mining are used to determine a set of wind turbines switched on at a given moment (an active set of wind turbines). The works [1, 2, 5] substantiate the application of dynamic programming method for solving the knapsack problem to determine the active composition of WPS.

The specificity of applying the knapsack problem in this case is that its solution should include such a set of items whose total weight is equal to the knapsack capacity. Such a solution is difficult to obtain for some methodological and technical reasons. Using the method of dynamic programming to solve the problem of knapsack packing in determining the active composition of a wind power station causes the problems of providing consumers with load 100 % as the total capacity of WPS in most cases will be less than the consumers load. The difference between the required load (hereinafter referred to as “load”) and the capacity of the active composition of WPS expressed in percentage terms determines the percentage of shortfall.

For the classical problem of knapsack packing to be formalized, it is necessary to assign two parameters, price and weight. If it is used to determine the active composition of WPS, the weight assumes consumer load to be provided; the price assumes effectiveness of each individual wind turbine at a given moment. The wind turbine effectiveness is a criterion defined by such parameters as indicators of technical condition, the number of on/off states, the amount of energy generated and the number of hours worked, the coefficient, which determines the readiness and usefulness of WT application. A multicriterion assessment method for the wind turbine effectiveness is given in [3, 4].

The purpose of the work is to improve the method of dynamic programming for the purpose of solving the problem of knapsack packing in substantiating the active composition of a wind power station taking into account capacity and effectiveness of each individual WT of the wind farm at a given moment.

2. Research methods

The problem of knapsack packing belongs to a class of combinatorial optimization problems. Conventionally, it consists in filling a knapsack able to withstand a specific weight with objects each of which has its own weight and price so as to maximize the total value, but not to exceed the maximum weight. Using the dynamic programming method in solving the knapsack problem for the needs of WPS allows some number of wind turbines with the "power" and "efficiency" properties to be selected so as to obtain the maximum total efficiency while meeting the requirements of total WT capacity which should not exceed the load (being equal).

In general, the algorithm for solving the knapsack problem consists of a direct and reverse way. The process of finding a maximum value of the objective function is called a direct way, but the process of items set recovery based on the objective function found – a reverse way.

3. Direct way of algorithm

Given: N objects, W stands for the knapsack capacity, $w = \{w_{1,}, w_2, .., w_N\}$ represents the corresponding set of positive integer weights, $p = \{p_{1,}, p_2, .., p_N\}$ expresses the corresponding set of positive integer values. We need to find a set of binary values $B = \{b_{1,}, b_2, .., b_N\}$, where $b_i = 1$ if the item n_i is included in the set, $b_i = 0$ if the object is not included in the set, thus we must follow the following requirement:

$$b_1 w_{1+...+} b_N w_N \leq W$$

$$b_1 p_{1+...+} b_N p_N \to \max$$

The algorithm of solving the knapsack problem using the classical method of dynamic programming can be defined as follows:

Let $A(k,s)$ be the maximum value of the items that can be put into a knapsack of s capacity, if only first k items can be used – i.e. $\{n_{1,}, n_2, .., n_k\}$ is a set of acceptable items for $A(k,s)$, with $k \in [0; N]$, and $s \in [0; W]$

$$A(k,0) = 0$$

$$A(0,s) = 0$$

4. The algorithm of finding intermediate optima $A(k,s)$

If an item k does not get into the knapsack, $A(k,s)$ equals the maximum cost of the knapsack of the same capacity and a set of acceptable items $\{n_{1,}, n_2, .., n_{k-1}\}$, i.e. $A(k,s) = A(k-1,s)$.

If an item k gets into the knapsack, $A(k,s)$ equals the maximum cost of the knapsack, where the weight s decreased by the weight of the *k*-th item, and a set of acceptable items $\{n_{1,}, n_2, .., n_{k-1}\}$ plus the cost of k-th object, i.e.:

$$A(k-1, s-w_k) + p_k .$$

That is:

$$A(k,s) = \max\left(A(k-1,s), A(k-1, s-w_k) + p_k\right).$$

A block diagram of the direct way of algorithm is presented in Fig. 1.

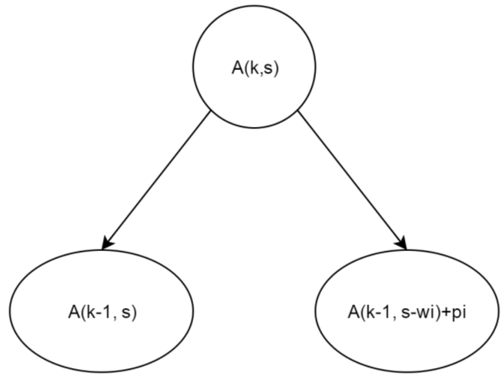

Fig. 1. Block diagram of the direct way of algorithm.

The cost of the desired set is equal to $A(N,W)$

5. Reverse way of algorithm

This stage ensures the recovery of a set of items included in the knapsack providing the cost $A(N,W)$ and capacity of the knapsack, W.

The algorithm work starts with $A(i,w)$ that is an element of a $[N \times W]$-matrix, where $i = N$, $w = W$. At this stage we determine whether the object n_i is a part of the desired set. For this we compare $A(i,w)$ with the following values:

the maximum cost of a knapsack with the same capacity and a set of acceptable items $\{n_{1,}, n_2, .., n_{i-1}\}$, i.e. $A(i-1,w)$;

the maximum cost of a knapsack with the capacity that is less by w_i and a set of acceptable items $\{n_{1,}, n_2, .., n_{i-1}\}$ plus the cost p_i, i.e. $A(i-1, w-w_i) + p_i$.

While developing a matrix A of $[N \times W]$ dimension employing the direct-way algorithm, at each iteration of the algorithm we set $\max\left(A(k-1,s); A(k-1, s-w_k) + p_k\right)$, therefore with the reverse-way algorithm, if $A(i,w)$ is equal to $A(i-1,w)$, the item n_i is not a part of the desired set, otherwise it is.

Using the classical method of dynamic programming to solve the knapsack problem in determining the active composition of a wind power station does not provide the opportunity to obtain the best solution because the solution to this problem in most cases is a set of wind turbines, the total capacity of which is less than the load required. This leads to the determination of a set which is not capable to fully cover the load. Another disadvantage of this method is its low speed, because the knapsack problem belongs to a class of combinatorial optimization problems, the complexity of the algorithm of its solution is $O = N \times W$ that with large values of N and W leads to significant time delays.

To deal with the above disadvantages we have investigated and proposed the following two approaches:

1. The first approach is to increase the consumers' load by the experimentally established percentage. This is provided by a computer simulation of WPS performance.

The load value is introduced at the entrance to each iteration, and the method of dynamic programming contributes to the definition of a set of WT, WPS capacity, and average value of the coefficient of shortfall.

In each next iteration the load increases by the coefficient of shortfall obtained in the previous iteration. It can be displayed as follows: $P_{i+1} = P \times (1 + k_i)$, where $i \in [1;n]$, k is the coefficient of shortfall of the i-th iteration, P represents the load required.

The disadvantage of this approach includes the following, as the coefficient of shortfall is not a static quantity, but is correlated with many parameters such as wind speed, wind power station composition and the average number of active WT. Using this approach does not accurately adjust the necessary capacity.

2. The second approach is modification of algorithm for solving the knapsack problem consisting in changing the objective function so that the intermediate coefficient of and percentage of shortfall could be taken into account. For this we formalize this problem as follows: given: N of wind turbines, the i-th one has the capacity $p_i > 0$ and the effectiveness coefficient $k_i > 0$. It is necessary to select such a range/set of WP so that:

$$\Delta P = \left[\sum_{i=1}^{N} b_i p_i - P \right] \to \min$$

$$\bar{K} = \frac{\sum_{i=1}^{N} b_i k_i}{\sum_{i=1}^{N} b_i} \to \max,$$

where P is the required load.

The dynamic programming methods use the additive or multiplicative objective function to assess the benefits or the functions that can be reduced to them [7]. Using the logarithms characteristics, a multiplicative function can be transformed into an additive function by finding the logarithm of its right side:

$$\ln\left(\prod_{i=1}^{n} f_i(x_i) \right) = \sum_{i=1}^{n} \ln\left(f_i(x_i) \right)$$

To solve the problem of determining a set of wind turbines, we introduce the additive objective function W that depends on two parameters, $\Delta P, \bar{K}$:

$$W\left(\Delta P, \bar{K}\right) = a_1 \bar{K} + a_2 \left(1 - \Delta P\right) \to \max$$

where a_1 a_2 are the weight coefficients. The function of this kind has a range of values (-∞; 1] that causes its application.

In this case, the problem of determining a set of wind turbines is solved using the recursive algorithm described. The disadvantage of this approach is a large number of calculations, so to reduce their number we used memoization, which will reduce the time to work from $O(N) = 2^N$ till $O(N) = NP$.

Memoization is a special optimization technique that can speed up the implementation of the program by avoiding repeated calculations of the values already calculated [6, 8].

To use this optimization approach, it is necessary to discretize the weights of the elements with a certain frequency, for example 1. This implies that there is a finite number of different optimal sets that can be written as a matrix of N x P dimension and, if necessary, we can refer to them. Let these sets be denoted as $S(i, p)$.

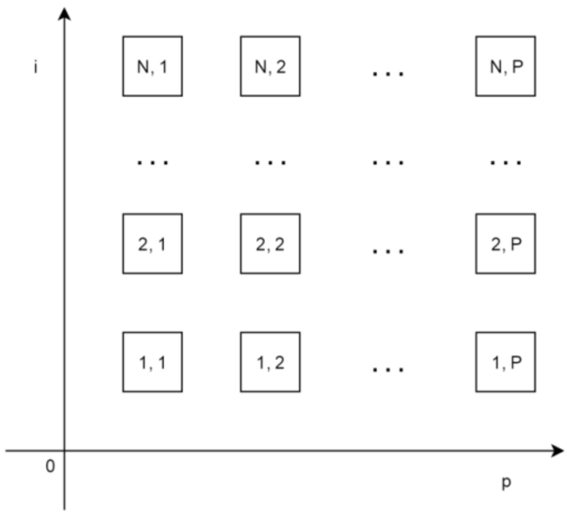

Fig. 2. Matrix of optimal sets.

The matrix elements $S(0, p)$ are filled in with zeros.

The elements $S(i, p)$ are calculated on the basis of the elements found at the previous steps of the algorithm and written in the cells $S(i-1, p)$, $S(i-1, \lfloor p-p_i \rfloor)$, $S(i-1, \lceil p-p_i \rceil)$. For this, we find the value of the objective function if the i-th WT $S(i, p)$ is not included.

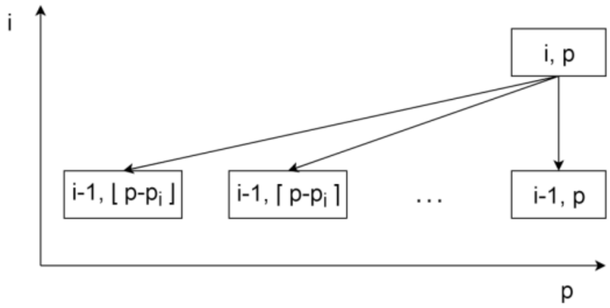

Fig. 3. Scheme of calculating the values of matrix elements.

If the i-th wind turbine is included in the set, it is necessary to find a set with the capacity of $p-p_i$, i.e. $S(i-1, p-p_i)$.

As the matrix elements are the values of the objective function only for integral capacity values, it is necessary to use the values which are as close to the required ones as possible, i.e. $S(i-1, \lfloor p-p_i \rfloor)$ i $S(i-1, \lceil p-p_i \rceil)$.

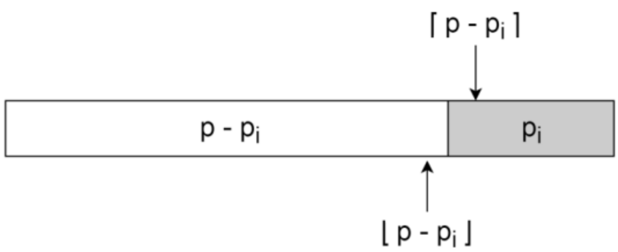

Fig. 4. Schematic representation of introducing the i-th element into a resulting set.

In the case when $\lfloor p-p_i \rfloor = \lceil p-p_i \rceil$, only one value of the objective function is calculated. The maximum value of the objective function is written as $S(i, p)$. In this way all the cells are filled.

The flowchart of the dynamic programming method modification to determine the active composition of a wind power station is shown in Fig. 5:

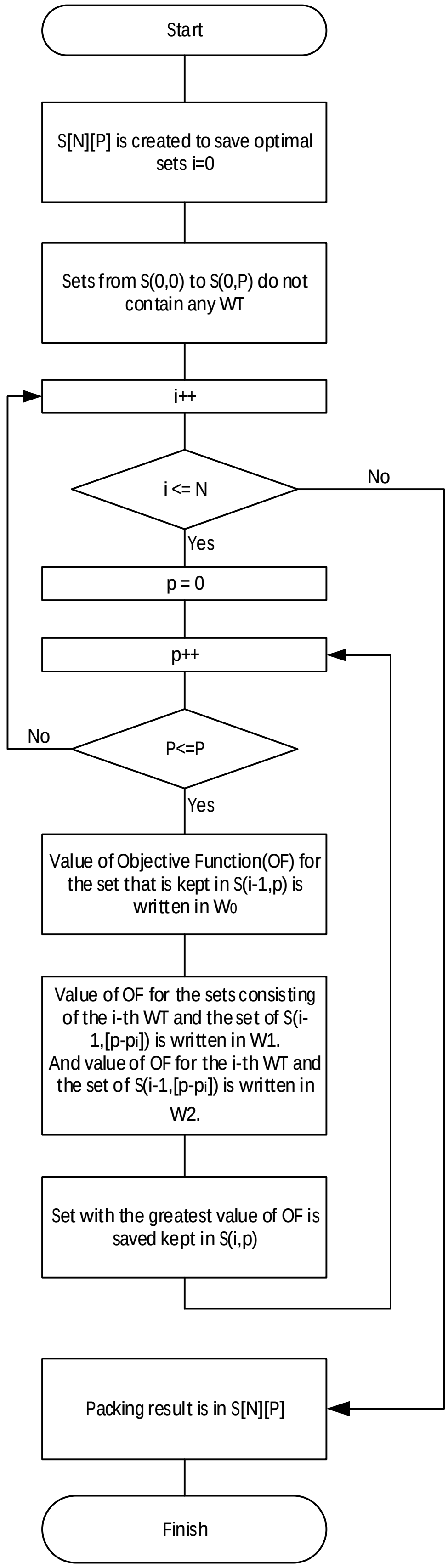

Fig. 5. Flowchart of modification of the dynamic programming algorithm for WPS.

6. Research results

Five hundred experiments have been carried out for each of the above methods. These are:

• classical dynamic programming method for solving the knapsack problem in determining the active set of WPS;

• dynamic programming method with an increase in the load by the experimentally established percentage;

• modification of the dynamic programming method for the determination of the active composition of a wind power station.

A sample of loads was randomly generated in the range of [5.000; 15000] kW. We studied operating modes of a wind power station consisting of 45 WT (15 USW-56-100 wind turbines with a nominal power of 107.5 kW, 10 ENERCON-33 wind turbines with a nominal power of 330 kW, 20 ENERCON-53 turbines with a nominal power of 800 kW).

The power of each wind turbine depends on the wind speed at a given moment of time, nominal parameters and technical condition.

A sample of wind speeds was randomly generated in the range of [5, 15] m / s. The results obtained formed a database utilized to perform a statistical analysis. The results of the analysis are presented in Table 1.

Table 1

Research results

Name of algorithm	Dynamic programming (DP)	DP with a load increased by the experimentally established percentage	Modification of the DP method
Packings done	500	500	500
Time spent (sec)	1237	1297	1443
Deviation scattering (KW)	[-964; -9.17]	[-660.52; 292.28]	[-66.59; 111.53]
Average efficiency of a set %	0.5418	0.5417	0.6127
Maximum deviation %	-3.09801	-2.26	0.385
Arithmetic standard deviation (KW)	301.3613	-6.012	13.99
Dispersion	136402.30	45979.5738	1914.15
Quadratic mean deviation (KW)	369.33	214.43	43.75
Quadratic coefficient of variation (%)	1.231	0.715	0.146
Speed of algorithm (sec.)	2.475	2.594	2.886
Maximum deviation (%)	-3.386	-2.071	-0.23
Standard deviation relative to the capacity of the smallest WT (%)	-203.403	-5.937	9.192
Standard deviation relative to the capacity of the largest WT (%)	-21.006	-0.613	0.95
Standard deviation of WPS (%)	-1.005	-0.017	0.046

When applying the classical method of dynamic programming, the percentage of shortfall is 1.005 %. The given value was used to study the dynamic programming method with an increasing load by the experimentally determined percentage.

Using the method of dynamic programming with an increase in the load provides minimization of the percentage of shortfall, but extends the range of deviation scattering.

Table 1 shows that the modification of dynamic programming method in solving the knapsack problem to determine the active composition of a wind power station can reduce the standard deviation of the solution regarding the largest capacity of wind turbines from – 21.006 % of the maximum percentage of shortfall obtained by the classical method of dynamic programming to 0.95 % of repackaging (see Fig. 8).

The standard deviation of instantaneous capacity of WPS farm depends on the number of wind turbine types, technical conditions of individual wind turbines, nominal capacity of each type of wind turbines, wind speed, difference in capacities of different types of wind turbines and the total number of wind farm turbines.

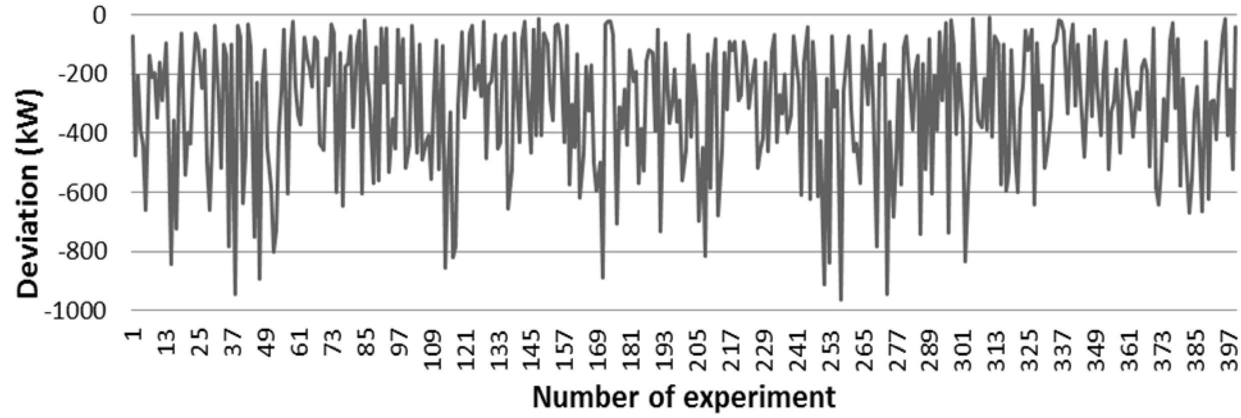

Fig. 6. Distribution of deviations for the classical method of dynamic programming.

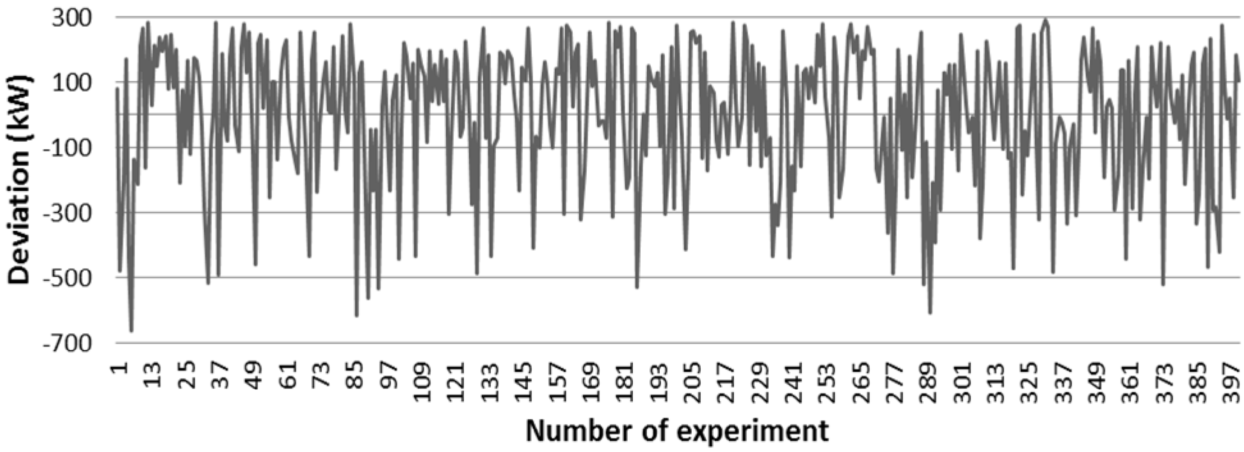

Fig. 7. Distribution of deviations for the method of dynamic programming with the load increased by the experimentally determined percentage.

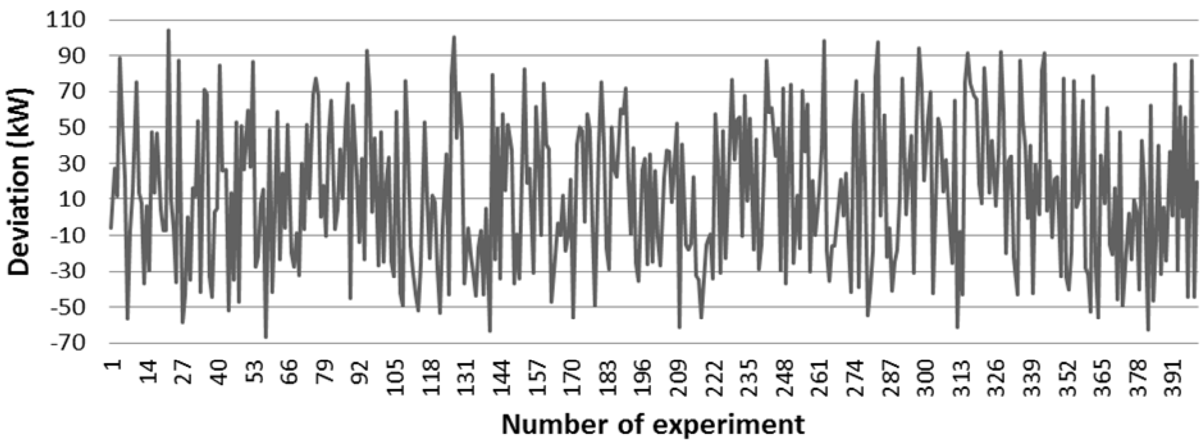

Fig. 8. Distribution of deviations for the modification of the dynamic programming method to determine the active composition of a wind power station.

Fig. 6–8 show the results of solving the knapsack problem by the classical dynamic programming method (hereinafter referred to as "Method 1"), dynamic programming method with an increase in the load by the experimentally determined percentage (hereinafter referred to as "Method 2"), and modification of the dynamic programming method for the determination of active composition of a wind power station (hereinafter referred to as "Method 3"). A computer simulation was based on test data samples and conducted for the three described methods under the above conditions.

As seen in Fig. 6, the maximum percentage of shortfall when solving the problem by Method 1 after 500 experiments is 3.098 % of repackaging that is equal to -964 kW. While under identical conditions, the result obtained by using Method 2 is 0.463 % of repackaging, or 144.04 kW, and the result obtained by using Method 3 equals 0.202 % of repackaging, or 62.89 kW, the given patterns are shown in Fig. 7 and 8 respectively.

As seen in Fig. 7, the maximum percentage of shortfall for Method 2 is -2.07 % that is equivalent to -660.52 kW. Under identical conditions, the result obtained by using Method 1 equals -2.07 % of repackaging that is equivalent to -660.52 kW, and the result obtained by Method 3 is 0.069 % that is equivalent to 22.08 kW of repackaging.

As seen in Fig. 8, the maximum percentage of shortfall for Method 3 is -0.232 % that is equivalent to -66.59 kW. Under identical conditions, the result obtained by using Method 2 is -0.476 % of shortfall that is equivalent to -136,65 kW, and the result obtained by Method 1 is -0.470 % of shortfall that is equivalent to -134.65 kW.

The analysis of the results obtained leads to the conclusion that the proposed modification of dynamic programming method for the determination of active composition of wind farms can significantly reduce the shortage of capacity, provide better customer load at maximum possible efficiency of the wind power station.

Another advantage of the modification of dynamic programming method for the determination of active composition of wind farms is reducing the linear coefficient of variation. These three methods having been studied, we can see that the standard deviation of wind farm capacity from the load for Method 3 is 0.046 % vs -1.005 % defined for Method 1 and -0.017 % for Method 2.

Method 2 and Method 3 can be used to determine the active composition of a wind power station using an accumulator, because under certain conditions they define the sets capable of efficiently generating the surplus of electricity. The excess energy obtained in this way can be accumulated by AB, and used during periods of adverse weather conditions or maximum consumers load.

7. Conclusions

The modification of dynamic programming method makes it possible to efficiently use the solution to the knapsack problem for the substantiation of the active composition of a wind power station with the utilization of an energy accumulating element.

The analysis of the results obtained shows the possibility of improving the conditions of equality of generation and consumption of electricity compared to the classical method of dynamic programming to the standard deviation of 0.046 %.

These results can be used in the design of control systems of dynamic-energy modes of a wind power station, as well as to improve the effectiveness of the existing WPS.

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МОДИФІКАЦІЯ МЕТОДУ ДИНАМІЧНОГО ПРОГРАМУВАННЯ ПІД ЧАС ВИЗНАЧЕННЯ АКТИВНОГО СКЛАДУ ВІТРОВОЇ ЕЛЕКТРИЧНОЇ СТАНЦІЇ

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Викладено результати модифікації методу динамічного програмування для розв’язання задачі пакування рюкзака під час визначення активного складу вітрової електричної станції з урахуванням ефективності кожної ВЕУ вітропарку та використанням акумулювального елемента в структурі досліджуваної системи.

Здійснено порівняльний аналіз модифікації методу динамічного програмування для визначення активного складу вітрової електричної станції з класичним методом динамічного програмування та методом динамічного програмування із підвищенням навантаження на експериментально встановлений відсоток, визначено переваги та недоліки використання кожного з досліджуваних методів.

Встановлено що, модифікація методу динамічного програмування для розв’язання задачі пакування рюкзака показує можливість покращення умови рівності генерації та споживання електричної енергії порівняно з класичним методом динамічного програмування до середнього відхилення 0,046 % та дає змогу застосувати цей метод для визначення активного складу вітрової електричної станції.

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