Problems of the use of renewable energy sources in the structure of railway power supply

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Abstract. The paper presents the main indicators of the renewable energy sources in the railway transport structure of European countries. A new structure of railway power supply systems, energy storage systems and control algorithms under the conditions of stochastic mode of renewable energy sources operation are defined as the main problematic issues. Further directions for sustainable development of such systems and factors that influence the modes of operation of traction substations and electric networks were identified. Average power and a random component are two criteria that were used to build local systems. The paper presents the real schedules of daily load on the traction substation terminals and solar insolation with determined power distribution changes. The power deviations indicators depending on the time interval and the type of generation were determined. A normal law of distribution of a random component was determined as a result of all calculations. It is possible to determine the shortage or excess of electric power in the local system in a certain area and to plan the direction of its development in the near future by analyzing the nature of the determined average power change.

1. Introduction

According to the latest statistical data on the level of power generation in Europe – the best dynamic is in renewable energy sources (RES) [1]. Their market share was 34.6% in the total energy production by 2019. Providing further stable increase of their share can be achieved by expansion of the field of use. One of the promising directions of use of distributed generation sources (DGS) is in the railway transport [2]. The main problem of further development of such systems is to evaluate the possibility of using 100% renewable energy for different transport systems [3]. The development of a new hierarchy structure of traction power supply based on “smart grid” technologies [4], Electric Storage System [5] and control algorithms in terms of the stochastic nature of RES pertain to problem issues [6]. A number
of issues characterizing the impact of DGS by connecting electricity to the overall structure of railways been considered, namely, the degree of influence of solar generation in operation traction substations and stability of the traction power systems, system’s stability reserve (level of robustness) [7] and the work of relay protection [8, 9]. However, the amount of research on development strategies for certain railway structures remains insufficient, leading to a complete lack of regulatory documents. In order to improve this situation, it is necessary to analyze the differences related to the characteristics of certain traction grids and renewable energy systems and to develop strategic directions for its further development. When analyzing the structure of railways traction grids, their geographical location must be considered, with further justification of possible integration with the systems of distributed generation, introduction of a comprehensive assessment of the impact of DGSs on the modes of operation of traction substations and electric networks. Further development and improvement of load simulation methods and DRG characteristics, modes and decision-making are needed. They allow to take into account the multicriteria nature of these tasks and the inherent uncertainty of information.

2. The basic material

The key feature of Ukraine’s renewable energy system is using of solar and wind power (approximately 90% of total renewable power generation) [10]. The peculiarity of these systems is the stochastic nature, which depends on the time of day or the season and weather conditions. This circumstance can lead to a negative impact on the grid operation, including the stability of dynamic processes in power systems and supervisory control. Since the work of strong wind and solar power stations in the national grid has legal regulations, the simplest way would be to integrate these into the overall power network. Railways power supply thus would not depend directly on the renewables as their stochastic nature would be compensated by the total power capacity. However, the significant part of electricity consumption for the needs of transport, railways dispersion and large neighboring areas, it would be appropriate to consider independent renewables usage. In this case, wind or solar power stations, together with the consumer (railway transport structural element) can be considered as the local power grid. It can be defined as a combination of power-limited generators, power converters and load interconnected according to the network topology with the same electromagnetic processes. The following condition should be carried out:

$$\sum P_{\text{load}}(t) = \sum P_{\text{gen}}(t).$$  \hspace{1cm} (1)

In this case we should consider variable generation and consumption of energy as a single process. However, the proportion of energy consumed from the global network decreases, while the balancing demand for local network increases. Minimization of the uncontrolled spread of energy balance as the difference between generated and consumed energy is the natural demand in the construction of the electrical network based on RES. Since the stationer component of generation and consumption can be predicted and planned by the work schedule, there is a need to evaluate the random component of power fluctuations. Actual data about generation and consumption in form of time series can be the source for this evaluation.

Actual data about wind speed, solar insolation and energy consumption is the information for the study and for real mathematical modeling. Work schedule for alternating current traction substation (Poltava South) in winter period and weather data related to the central region of Ukraine for the same season were used in this example. The assumption that the short-term (less than one hour) fluctuations in generation and consumption are independent random variables is proven by authors. Analysis of statistical data shows that operation of WES and SES have some average power and a random component, which are a function of time. The average power can be considered as well-predictable for the short terms and controlled setting. The expression for determination of power balance will be [11]:

$$p_{ij} = (a_{ij} - a_{i}) - [(w_{ij} - w_{i}) + (s_{ij} - s_{i})],$$  \hspace{1cm} (2)

where $a_{i}$ – energy consumption; $w_{i}$ and $s_{i}$ – WES and SES power respectively; $i$ – time index (time interval number); $j$ – day number, $p_{ij}$ – deviations from the load schedule.
One-index RES indicators are averaged for a certain hour of the day (called daily variation). $a_i$ corresponds to the planned schedule of consumption, while $p_i = a_i - w_i - s_i$ corresponds to the planned so-called "pure" load. The length of time interval selection ($\Delta t$) is determined by the characteristics of energy sources – for wind farms 10 minutes interval is usually taken. For SES – 1 minute. Short-term load changes can have a seconds-scale dimension. Available weather data make it possible to assess the capacity of a typical wind and solar power plants in conventional units, or the fate of the nominal units (maximum achievable) capacity. The same way the load can be described. Examples of typical modes of power change is shown on Figure 1, 2.

![Figure 1](image1.png)

**Figure 1.** The diurnal variation of solar radiation (the maximum attainable and actual).

![Figure 2](image2.png)

**Figure 2.** The load power (time interval – 1 min).
Selection of an elementary time interval determined by the properties of an object, such as rate changes of specific parameter. When comparing process of different variability, they must be given for the same time period. The change of interval length causes a change of variance values of the time series. When averaging consolidation scope is used rule that the population variance is the sum of interval mean and variance interval variance: 
\[ \sigma^2 = \sigma_0^2 + M \{ \sigma_k^2 \} , \]
where \( \sigma_0^2 \) – variance of average values at each interval, \( \sigma_k^2 \) - variance on the k-th interval M - symbol of mathematical expectation. It should be borne in mind that the number of intervals must provide a valid statistical error [12] and as a general population can be considered a long process in which its basic properties are sufficiently manifested.

Since RES’s critical factor is the balancing process variability, differentiated (in finite differences) series, elements of which are the difference of successive values of power: 
\[ dp_j = p_{i+1j} - p_{ij} \]
is considered. Such a series can be built for a total power balance as well as for the generation and consumption: 
\[ da_j, dw_j, ds_j. \]
Distribution of random variables in rows corresponds to the received hypothesis of normality. Since the received series of successive changes (fluctuations) power may vary considerably, it is necessary to remove cases of extreme emissions, for example to evaluate the range of possible values with confidence probability of 0.99 and 0.95, respectively rejecting one and five percent of the sample. Analysis of the actual power fluctuations in conventional units while changing the scatter range for different network parts, increasing time interval \( \Delta t \) and giving in the form of nominal power (extreme, confidence intervals, standard deviations \( \sigma_d \)) is shown in Figure 3. From the comparison of variability is clear that with the time’s interval the fluctuation increases as well. Nonlinear dispersion growth is limited from the above and changes significantly depending on the size of the confidence interval and significantly reduces after some extreme values rejected. Proper load changes for the same time intervals have greater relative values than RES power change (Figure 3, the horizontal scale is nonlinear).

![Figure 3](image-url)

**Figure 3.** The standard deviation of changes in power depending on the time interval.

Current variances of local power grid components have different relative values; the total variance of power balance must be defined as the sum of covariation components including their weights. Difference series variance that characterizes the rate of power balance change defines similarly:

\[
D(dp_j) = D(da_j) + wD(dw_j) + sD(ds_j),
\]

(3)
where \( w, s \) – weights that determine the share of wind and solar power plants respectively. The mutual independent power fluctuations are taken into account.

For example, if the nominal capacity of WES and SES are equal and are equal to the maximum load power, the normalized standard deviation of fluctuations in the power range for averaging interval of 10 minutes will increase from 0.23 (without RES) to 0.25. Similarly, in the averaging interval of 30 minutes deviations increase from 0.25 to 0.30. This is a potential increase in the standard deviation of the current power balance changes. If the standard deviation is known, confidence intervals for current power fluctuations with required accuracy can be defined. The distribution of these fluctuations as random variables described by normal (Gaussian) law (Figure 4).

![Figure 4. Current power balance changes histogram.](image)

It should be noted that in this example the weights coefficients reflect the nominal RES capacity while effective (or averaged) power indicators are significantly lower. Thus, for the wind power stations utilization coefficient of rated power is 0.3-0.4 depending on location and season and for solar power stations 0.14-0.18. This fact should be taken into account when calculating the energy contribution of RES. The economic components thus are determined by standard means [13]. For stability and reliability ensuring current power fluctuations are important.

Another indicator is representing energy and power curves and further operations on them. All generation and consumption graphics must be set as functions for later use. Curve extremes are determined graphically (Figure 5).

After that the curve is divided into a number of extreme negative areas. The equation of the curve for each section is determined by formula:

\[
\begin{bmatrix}
x^2 & xy & y^2 & x & y & 1 \\
x_1^2 & x_1y_1 & y_1^2 & x_1 & y_1 & 1 \\
x_2^2 & x_2y_2 & y_2^2 & x_2 & y_2 & 1 \\
x_3^2 & x_3y_3 & y_3^2 & x_3 & y_3 & 1 \\
x_4^2 & x_4y_4 & y_4^2 & x_4 & y_4 & 1 \\
x_5^2 & x_5y_5 & y_5^2 & x_5 & y_5 & 1
\end{bmatrix}
= 0. \tag{4}
\]
where \((x_1; y_1), (x_2; y_2), (x_3; y_3), (x_4; y_4), (x_5; y_5)\) – points that are in this part of the curve. In this case, two of them are extreme points of the investigated area.

![Figure 5. Schedule and its extremes example.](image)

Equation (3) is valid only when the three given points are collinear, and if none of the four of them are collinear. Each function that has been defined by the formula (4), will correspond to a certain section of the main graph (Figure 6).

![Figure 6. Example of schedule, which consists of several functions.](image)

According to Figure 6, each function has its own definition range. The next step is to find the sum of all load schedules:

\[
(f + g + \ldots + i)(t) = f(t) + g(t) + \ldots + i(t).
\]

(5)

The total energy schedule for generators is defined similarly. After determining functions describing the two major graphics (power generation and power consumption) model calculates their difference and makes characteristic graph. An example of the difference between two energy curves is shown in Figure 7.
To simplify the example, each graph in Figure 8 is described by one function. In a real case, the number of features describing the energy curve can be much larger, depending on the number of objects (load and generators) and the curvature of the energy graphs of each object.

According to Figure 7, the difference of two functions mathematically could be written as:

\[(f - g)(t) = f(t) - g(t).\]  

The resulting graph \((f-g)(t)\) is shown in Figure 8.

This curve \((f-g)(t)\) is proposed as the end result of the model. Based on this schedule, the expert can make a conclusion about the shortage or excess of electricity at a certain time, and make a constructive decision to enable a new energy source or shut off the load at a certain time. Expert can also change load indicators of load (if projected). After correcting the outputs, the model calculates everything from the beginning and produces a corresponding result that is comparable to the previous one. The example shows the calculations of the electricity supply system during the year. The model can perform calculations for smaller periods of time, but due to the large amount of information uncertainty, the accuracy of such calculations will decrease proportionally to the time interval reducing.

3. Conclusions

Therefore, when choosing the type and capacity of RES (namely wind and solar) in the local grid, it is necessary to take into account their real energy characteristics in these climate conditions, which allow them to assess their impact on the stability of electricity supply. Another factor is the estimation of electricity needs and the consumption changes over time. Combined analysis of these data allows us to evaluate the real possibilities of using RES while ensuring the proper quality of electricity supply. These
findings relate to arbitrary local energy systems, but in the case of railway transport should be based on load features that are different from other load.

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