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Voltage Measurement and Control System for a Distributed Traction Power Supply System

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Abstract—One of the problems to introduce the high-speed traffic is the need to improve the efficiency of the DC traction power supply system. The most promising method of improving this system is the transition to a distributed power supply system for traction load. During its implementation, there is a problem in measuring the voltage levels in the traction network to ensure the effective operation of the system. The article discusses the use of the sensory method for determining the voltage sensors location and checks the range of the antennas to provide redundancy of information transmission in a distributed traction power supply system.

Keywords — traction power system, voltage level, voltage sensor, sensory method.

I. INTRODUCTION

When introducing a system of distributed and controlled power supply, the problem arises in measuring the voltage levels in the traction network to ensure the effective operation of the system. It should be noted that the voltage control must be carried out at several points distributed along the electrified section in order to identify its change during movement by the intersubstation zone of any number of trains.

In order to solve the problem of voltage regulation in the traction network in the mid-1970s, a method was developed to measure voltage levels on 3.3 kV tires of two adjacent traction substations, to further calculations the average voltage drop at the power supply zone and the voltage regulation in the system STARNK [1].

To improve the automatic voltage regulation in the contact network, a method [2] was also developed, which additionally measures the voltage at the section posts adjacent to the traction substation, comparing the measured values with the set voltage settings and generating a control action on the voltage control unit on the tires traction substation depending on the ratio between the voltage of the section posts and the need to minimize additional losses powerfully the occurrence of circulating currents between the other traction substations.

To control the voltage levels in the contact network directly to the current collectors of the electric rolling stock, regardless of the trains number in the intersubstation area, a method was developed at the Department of Intelligent Power Supply Systems of the DNURT, the essence of which is to determine the voltage in the contact network of the electrified DC section adjacent traction substations and on post tires to sectioning within the intersubstation area. In addition, the voltage distribution along the intersubstation areas is measured additionally [3].

II. MATERIAL AND METHOD

In order to obtain reliable information on the voltage levels in the traction network when constructing a control system for the operation of the traction power system, one of the main issues is to determine the location of the voltage sensors. The placing strategy of voltage sensors should be based on the provision of accurate information control system of the traction power supply. It is also necessary to take into account the qualitative and cost indicators of the system. A small number of sensors (1-2 units) on the intersubstation area can provide correct measurement results, but will not allow the amplifier to work properly. So there can be the "blind-spots" on the site, where on the voltage reduction the boosting system will not respond. The given task is a multi-purpose optimization problem with a large number of variables (in the general case it is the number of sensors, their transmitting capacity and type), in addition, some of the variables are analog (currents, capacities, length of sections, track profile), and part of discrete data (sensor locations and their number).

Another direction of the structural analysis of complex electric power systems is the use sensory method, which uses the evaluation of the nodes voltage reaction in changing the loads in them [4, 5]. The definition of sensor nodes for the task of locating voltage measurement devices in a distributed traction power supply system is the most informative, and their response to a change in load is indicative. To solve the problem, depending on the parameters of the system, it is necessary to determine from the calculated voltage modes

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the weak points of the traction network. Considering a way of this method implementation on the example of an electrified portion of a distributed power supply (Fig. 1).

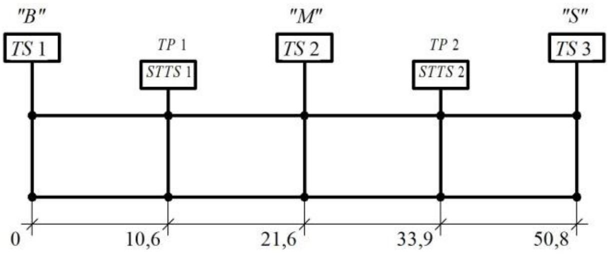


Fig. 1. Scheme of the calculated area of distributed power: TP - traction substation, STTS - single-transformer traction substation, TP - tie post.

The calculated section is double-track, 50.8 km long, has 4 intersubstation zones and receives power from 3 traction substations according to the nodal scheme; additionally, one-unit traction substations are located at the partitioning posts. Traction substations have the same voltage on 3300 V tires, the traction network along the entire length is the same - M120 + 2MФ100 + A185 + P65. The sensory nodes were studied with a resolution of 1 km.

In the calculated section, the schedules of three pairs of trains are implemented in such a way that the reactions of the sensor nodes were first determined separately from each load, then with a gradual consolidation of the range to 10 minutes (Fig. 2). The currents of electric rolling stock are presented in fig. 3

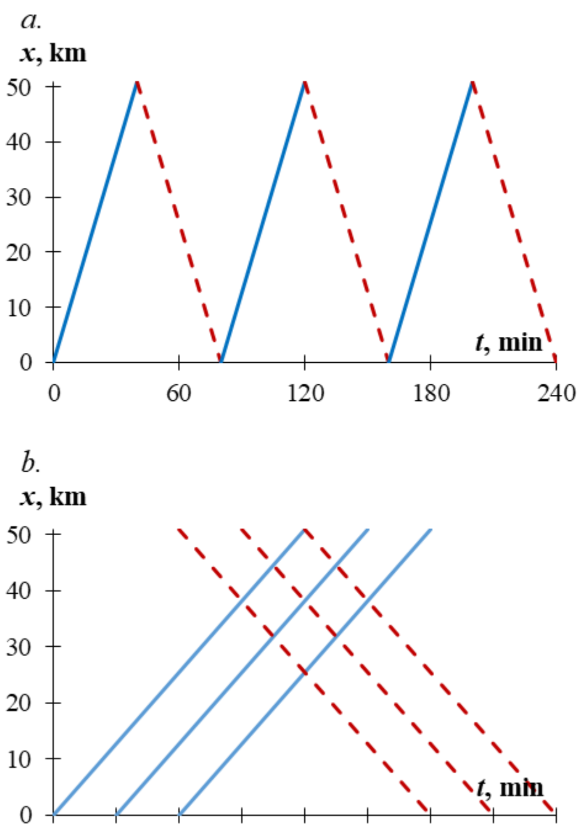


Fig. 2. Schedule of trains by section: a - train interval 80 minutes; b - train interval 10 min.

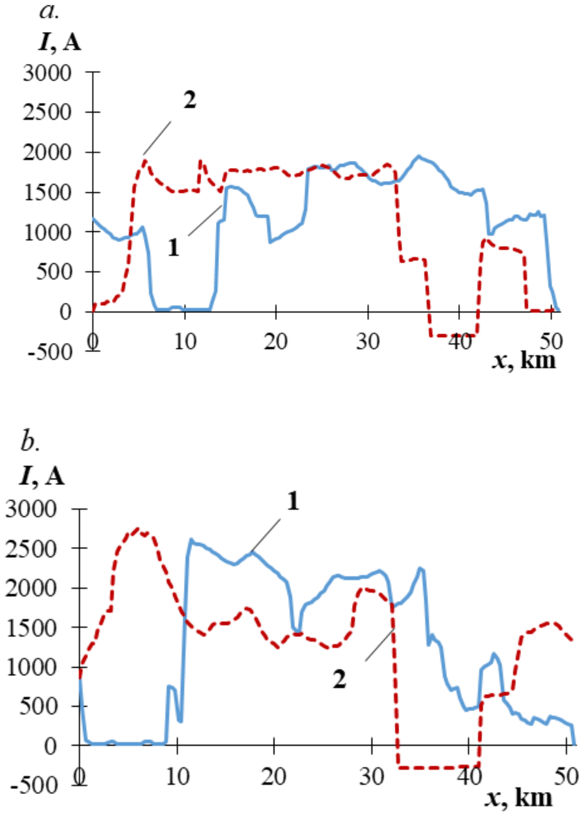


Fig. 3. Currents of an electric rolling stock: a - train interval of 80 min; b - train interval 10 min; 1 - pair direction; 2 - unpaired direction

The definition of sensory nodes in the system was carried out as follows:

1 step. For each schedule, for each discrete node, the voltage change (interval 1 min) was calculated during the implementation of the train schedule. The voltage at any point in the traction network was determined using the developed model [6]. This takes into account the mutual influence of loads on the passing and, depending on the power scheme, on adjacent tracks:

$$U_j(t,x) = U_B(t) - I_j(t,x)\cdot f_R(x) - \sum_{\substack{k=1\\ k\neq j}}^{n_1} \Delta U'_k(t,x,x_k) - \sum_{k=n_1}^{n_1+n_2} \Delta U''_k(t,x,x_k). \quad (1)$$

Where:

$U_B(t)$ is the voltage on the buses of the traction substations at the moment *t*, V;

$I_j(t,x)$ is the current of electric rolling stock at the moment *t* in coordinate *x*, A;

$f_R(x)$ is the resistance function, Ohm;

k is the load number on the corresponding track;

n_1, n_2 is the number of loads on the 1st and 2nd tracks;

$\Delta U'_k(t,x,x_k)$ is the function of the voltage drop from the loads on the passing track, V;

$\Delta U_k''(t, x, x_k)$ is the same on the adjacent track, V.

The determination of the voltage drop distribution function in the contact network takes into account the voltage drop from all trains moving by the electrified section and the voltage drop from the flow of circulating current:

$$\Delta U_{K1}(t,x) = \sum_{i=1}^{n_1} \Delta U_{K1}(2i-1,t,x) + \sum_{i=1}^{n_2} \Delta U_{K1}(2i,t,x) + I_{cc}(t) \cdot r_0 \cdot x. \qquad (2)$$

Where:

$2i-1$, $2i$ is the numbers of an odd and double train;

$I_{cc}(t)$ is the magnitude of the circulating current, A;

r_0 is the traction network resistance, Ohm;

2 step. At each point, the maximum and minimum voltage values were determined, on the basis of which the dependences of Fig. 4,

3 step. The point with the maximum amplitude of the voltage corridor, i.e. the point corresponding to condition (3) was determined as a sensitive sensor node for a given part of the circuit (for each intersubstation area).

$$s = \max_{[a;b]} \left(U_{\max j} - U_{\min j} \right). \qquad (3)$$

Where:

a is the coordinate of the section beginning;

b is the coordinate of the section end;

j is the number of the investigated node;

$U_{\max j}$ is the maximum value of the voltage at the *j* node;

$U_{\min j}$ is the minimum value of the voltage in the *j* node;

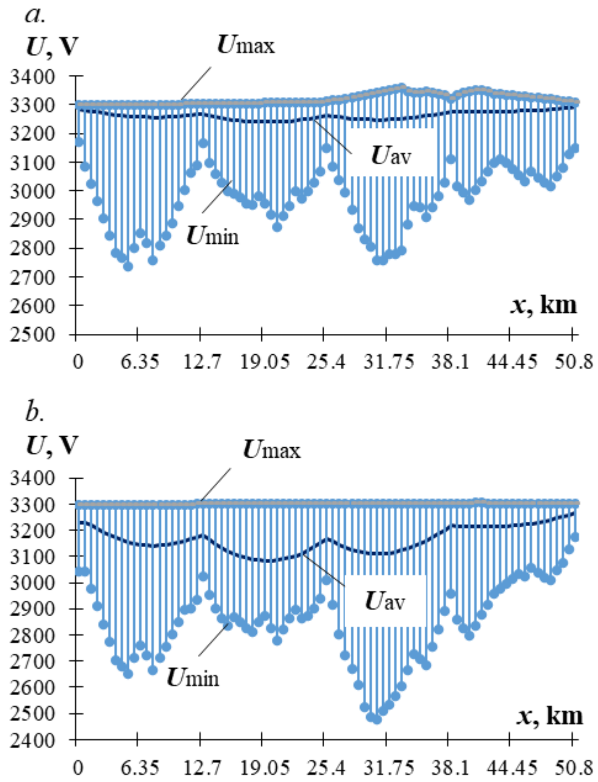
Fig. 4. Voltage change corridor for train schedules: a - the interval of 80 minutes; b - interval of movement 10 min; Umax - the maximum voltage level; Umin - the minimum voltage level; Uav - the average voltage value.

The results of calculating the most sensitive nodes for the experimental area in accordance with the results are shown in Table 1

TABLE I. SENSOR NODES FOR THE CALCULATED AREA

Interval of train movement, min	**Coordinate of the most sensitive sensor node for each intersubstation area, km**			
	1	2	3	4
80	5	20,3	30,5	40
10	5	20,3	30,5	40

For further calculations, the weakest points of the contact network, determined by coordinates: 5 km, 20.3 km, 30.5 km, 40 km. As can be seen from the obtained results, the distance between the weakest points of the traction network is 10.2 - 15.3 km.



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Currently, the Ukrainian railway network uses mostly analogue radio communication systems with very limited data transmission capabilities.

Building a network for data transmission, it is possible to use modern means of communication, for example, mobile communications, which can have a significant impact on the problem of redundant information transmission in a distributed traction power supply system. The system, built on the basis of mobile communication, will provide the maximum data transfer rate for the maximum distance, but at the same time it will be dependent on the mobile service provider. The paper proposes the construction of a data transmission network based on ZigBee technology. This concept will ensure the independence of the network from third-party service providers, as well as provide low power consumption. Since using the ZigBee technology, the maximum data transmission distance is 0.8 ... 1 km, antenna application is proposed to increase the data transmission distance. When placing voltage sensors with wireless data transmission at selected points (Table 1), such a distance can be maintained, provided that the neighboring devices have a direct view of the devices (Fig. 5). The line-of-sight length checking was performed using the Frenal method [5].

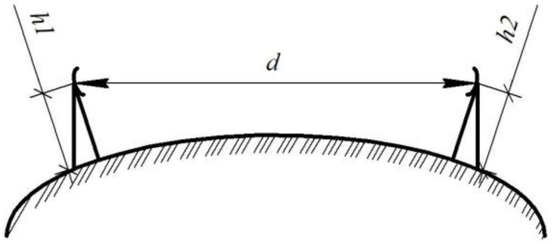

Fig. 5. Line-of-sight distance for sensor installation

Since the sensors will be placed on the pillars of the contact network, the installation height of the sensor can be in the range from 5 to 9.5 m (the absolute height was not taken into account).

To calculate the distance of the sensors location we use the Frenal formula.

$$d = 3{,}57 \cdot \left(\sqrt{h_1} + \sqrt{h_2}\right). \quad (4)$$

Where:

h_1 is the height at which will be installed sensor 1, m;

h_2 is the height at which will be installed sensor 2, m;

d is the distance of sensor installation, km.

As a result of the calculations, the maximum length of the line of sight of the sensors is in the range from 15.9 to 22 km, depending on the height of the installation, which significantly exceeds the distance between the weakest points of the traction network.

To provide connection between sensors at a considerable distance and to ensure reliable transmission of information, voltage measurement devices must be equipped with antennas. Since the voltage sensors will be located not only in sensor nodes of the area, but also in traction substations, it is necessary to provide redundancy of the antennas, that is, in order to prevent the failure of one of the sensors, the information could be transmitted to the next antenna. This way you can ensure the smooth operation of the measurement system.

The calculation of the maximum radius of the antenna area is performed by the formula:

$$R = 17.3 \cdot \sqrt{\frac{d}{4 \cdot f}} \quad (5)$$

Where:

d is the distance between antennas, km;

f - transmitter frequency, GHz.

Since the radius of the antenna's range reaches its maximum at the central point, and when the antenna approaches, the antenna's zone of activity decreases at a specific point, depending on the distance to it:

$$r = 17.3 \cdot \sqrt{\frac{1}{f} \cdot \frac{d_1 \cdot d_2}{d_1 + d_2}} \quad (6)$$

Where:

f is the frequency in GHz;

d_1 and d_2 is the distance to the point from antennas, km (Fig. 6).

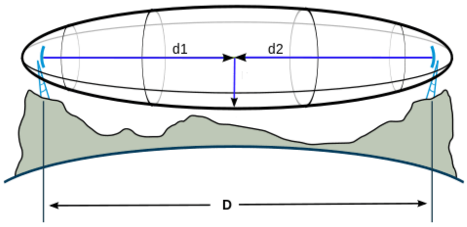

Fig. 6. Radius of the antenna covering

The results of radius antennas calculation are shown in Table 2.

TABLE III. MAXIMUM ANTENNA RANGE

Location of the sensor, km	Antenna radius (not more than), km and sensor installation location
0	20,9/TS1
5	25,2/ plain track
10,6	21,4/STTS
20,3	20,6/ plain track
21,6	22,6/TS2
30,5	19,8/ plain track
33,9	26,5/STTS2
40	19,8/ plain track
50,8	26,5/TS3

As can be seen from the results of the calculation, the antenna range exceeds the distance between neighboring sensors and provides a backup of information transmission when the output of one sensor fails.

III. CONCLUSION

When implementing a distributed power supply system, it is necessary to develop a voltage control system in the traction network. Conducted research found that the maximum length of the line of sight of the sensors is in the range from 15.9 to 22 km, depending on the height of the installation, which is significantly longer than the distance between the weak points of the traction network. In this case, the radius of action of the antennas exceeds the distance between adjacent sensors and provides redundant transmission of information when a single sensor fails.

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