Coordinated control of active and reactive capacity generation in electrical power distribution networks of railways

E A Tretyakov*
Omsk State Transport University, Karl Marx Ave., 35, Omsk, Russian Federation

* E-mail: eugentr@mail.ru

Abstract. This article presents an agent-based model algorithm for voltage coordinated control using reactive capacity sources in electrical power distribution networks of railways. Voltage control in an electrical network is coordinately implemented by the managing system between all local regulators within the controlled zone. We present an approach to coordinate the work of local regulators basing on auction-type ranking of their possibilities for achievement the global control purpose. During operational voltage control in electrical network we proposed to use linearization of the control task, since the relationship between relative power gains and loads of individual nodes in the form of sensitivity matrix (Jacobi) is almost linear. We performed simulation and mathematical modeling of the proposed algorithm in the distribution electrical network of railways and present the obtained results.

1. Introduction
A power supply network company of the Russian Railways group while performing its innovative development of provision of electricity transmission services using electrical networks must agree it by technological parameters with the development strategy of the Russian Federation electrical grid complex (developed for the period up to the year 2030), with the program of innovative development of the public stock company “Rossetti” for the period 2016-2020 with the prospect up to the year 2025 [1, 2]. It should be aimed at creation of electrical power infrastructure based on distributed intellectual system of automation and control.

The most relevant and studied issues considering energy systems are questions on optimization of electrical network modes by voltage and reactive capacity, and in some cases by active capacity and frequency [3]. One of the disadvantages of centralized control (optimization) is the necessity of gathering, transfer and processing in one place of significant volume of information about the mode condition and power system elements. As a rule the given control methods are realized in electrical networks of high voltage.

The approaches and principles of group control of voltage in distribution electrical networks mostly of high voltage are presented in [4]. The most promising is electrical power system control based on the agent method, which is an integration of centralized and decentralized control [5–9].

In many cases the coordinated transformers control by solar inverters in electrical networks is implemented on base of multicriterial genetic algorithm [10], using the fuzzy set theory [11].

In [12] the authors offered a method for coordination of operation of virtual electrical power station and voltage regulation devices by solving the problem with limitations of bilinear matrix inequality.

The researches considering the influence of distribution-generation sources on the voltage in distribution network, the methods for increasing the static stability by voltage are shown in [13-16].
Nowadays there are no sufficiently developed agent-method algorithms of adaptive control of electrical transport in railways distribution electrical networks of average and low voltages, which are based on the principles of automatic coordinated control of the network regulators with the purpose of provision of the required quality of transmitted electrical power, the increase in efficiency of the electrical power transfer.

The relevance of this work is determined by the necessity of improvement the components of distributed system of voltage automation and control within the development of the active-adaptive electrical networks at railways.

A distinctive feature of the proposed approach to coordination of operation of local sources of active and reactive capacity (hereafter the local regulators) is ranking of their possibilities by auction type for achievement the global purpose of control basing on the agent approach.

2. The problem statement
The purpose of this research is detection the operation features of distributed intellectual automatization system and development of algorithm for coordinated control of voltage in distributed electrical networks of railways using the local regulators.

During operational voltage control in electrical network we proposed to use linearization of control task, since the relationship between relative power gains and loads of individual nodes in the form of sensitivity matrix (Jacobi) is almost linear.

The main components of coordinated voltage control system in electrical network is subsystem of assessment of electrical network condition (according to parameters of operation modes, regulators, position of the switching devices) and subsystem of decision-making and distribution of control actions based on database and the rules of agent control taking into account the information of the previous time points and prognostication [17].

Herewith in this work we will examine in more details the task of determination the control actions on the local regulators of electrical network to achieve the purposes of coordinated voltage control basing on the algorithm developed by the author without a detailed consideration of questions on database and complex logical rules in relation to specific energy district.

3. The theoretical part
The method for control the electrical power transport can be accepted as a basis for coordinated control of voltage in the distribution networks of railways. This method includes an architecture of the distribution control (controllers-moderators) based on measurements, ontology and high speed of data analysis, based on the agent systems; electrical sensors (current, voltage, capacity, parameters of quality of electrical energy) and sensors of non-electrical values (position of the switching devices, on-load tap-changer outlets, compensating devices etc.); local controllers of linear regulators [18].

The use of distributed agent control of voltage assumes that local regulators must coordinate their action with each other. For determination the control actions to the local regulators, some scientists propose to use regressive dependences of regulated parameters for control of operation modes, since they are described by nonlinear equations, as well as matrices of sensitivity of relative growth of losses and capacities in the linearized type. Herewith relationship between active power losses in the network and the loads of separate units is close to the quadratic, and relationship between relative growth of losses and capacities is close to linear [19].

During operational voltage control in electrical network we proposed to use linearization of the control task, since the relationship between relative power gains and loads of individual nodes is almost linear, i.e. to use the sensitivity matrix (Jacobi), which can be previously calculated. That allows performing the calculations with the necessary speed for one-three iterations within 100 ms, i.e. in the mode of operational measurements of actual regime information. The actual regime information includes physical parameters: current, voltage, angular shifts among them, active and reactive capacities, and positions of regulatory and switching units in devices and equipment. The dynamic assessment is provided taking into account the date from the previous points of time and prediction.
The mode optimization is usually implemented according to the minimum of electrical energy losses in the electrical network and under the condition of voltage stabilization.

The issue of coordinated voltage control in the distributed electrical network can be decomposed into some subtasks for separate distributed (local) controllers of the transformer stations (TS).

The law of voltage control in each area (within the local controller) of the electrical network includes the state vector $z_a(k)$ and the vector of controllable variables $u_a(k)$ in the k-th point of time:

$$\tilde{y}_a(k) = [z_a(k), u_a(k)]^T.$$  \hspace{1cm} (1)

For example, for the local controller TS 4 (Figure 1) the state vector and controllable variables vector for the time step k are:

$$z_4(k) = [U_4(k), \delta_4(k), P_4(k), Q_4(k)]^T;$$
$$u_4(k) = [\Delta P_4(k), \Delta Q_4(k)]^T.$$ \hspace{1cm} (2)

![Figure 1. The calculation scheme.](image)

Every local controller has its own control purpose.

The common problem of voltage optimization, which is solved by the managing controller-moderator as an issue of minimization of additional control actions by active and reactive capacity, can be presented as follows:

$$F = \sum_{i=1}^{n} \left[ \sum_{j=1}^{m} \left( k_P \Delta P_j + k_Q \Delta Q_j \right) \right] \rightarrow \min,$$
$$\begin{cases} 
\sum_{i=1}^{n} \sum_{j=1}^{m} \left( a_{ij} \Delta P_j + b_{ij} \Delta Q_j \right) = \Delta U_k; \\
P_j^{\min} \leq P_j^0 + \Delta P_j \leq P_j^{\max}; \\
Q_j^{\min} \leq Q_j^0 + \Delta Q_j \leq Q_j^{\max}; \\
\forall j = 1, \ldots, m.
\end{cases}$$ \hspace{1cm} (3)

n is the number of points (buses) of the electrical network; m is the number of connected in the i-th point $P_j^0, Q_j^0$ are weighing coefficients by active and reactive capacity (“cost” of regulation); $P_j^0, Q_j^0$ is active and reactive capacity (generation and (or) consumption); $a_{ij}, b_{ij}$ is voltage-sensitivity coefficients for active and reactive capacity.

The proposed algorithm of coordinated voltage control in a distribution electrical network using local regulators based on the agent approach is as follows.
When a voltage deviation occurs on buses, the corresponding agent sends an informational message to the agent-coordinator. The agent-coordinator prepares a message for each agent in form of a request with the necessary voltage change $\Delta U$.

After receiving the message every local agent of TS updates the sensitivity values of their factors $a_{jk}$ and $b_{jk}$. The agent-mediator determines control action of the local agents of the TS basing on ranking of relations between weighing coefficients to the sensitivity factors ($k_p/a_{jk}, k_q/b_{jk}$) and solution of the optimization task (3). The chosen agents accept the instruction and inform the agent-mediator. If one of the agents is faulty, then the others agents update the sensitivity values of their factors again without taking into account the failed agent etc.

4. Results
We consider a segment of the 6 kV distribution network of power supply system of the third-party consumers of railways (Figure 1) in normal mode. The simulation modeling of the electrical network was performed using Matlab Simulink.

Table 1 and Figure 2 present the imposed restrictions, the results of simulation and mathematical modeling of voltage coordinated control in accordance with the proposed algorithm for the voltage deviation $\Delta U_3$ at TS 3.

| Bus number in Figure 1 | Weighting coefficients for active and reactive capacity | Voltage sensitivity coefficients for active and reactive capacity | Reserve by active and reactive capacity, kW and kvar respectively |
|------------------------|-------------------------------------------------------|---------------------------------------------------------------|---------------------------------------------------------------|
|                        | $k_{p3}$                                               | $k_{q3}$                                                      | $a_{j3}$  $b_{j3}$                                           | $p_{i}^{max}$  $Q_{i}^{max}$ |
| 1                      | –                                                     | –                                                            | 0.01  0.06                                                  | –  – |
| 2                      | – 0.70                                                | 0.2                                                         | 0.08  0.30                                                  | –  8.8  –  500 |
| 3                      | – 0.90                                                | 0.04                                                        | 0.30  –                                                     | –  3.0  –  0 |
| 4                      | 2.1 0.70                                              | 0.03                                                        | 0.22  70.0                                                  | 3.2  200  300 |
| 5                      | – 0.65                                                | 0.02                                                        | 0.20  –                                                     | 3.3  –  400 |

After ranking the relations ($k_{p3}/a_{j3}$) and ($k_{q3}/b_{j3}$) in descending order and solution of the optimization task (3) we determined the most efficient sources and values of reactive capacity sources (SVC) on buses TS 2, 4 and 5 and active capacity on the TS 4 (it is equal to zero) for achievement of control at voltage deviation $\Delta U_3$ (Figure 2).

Since the solution of the optimization task (3) depends on lots of restrictions and variables of some local controllers, then it is decided iteratively, i.e. on each step of iteration the controllers exchange the updated values of the variables. In this case the calculation was performed for three iterations and 0.2 s.

From Table 1 it follows that the sources of active and reactive capacity with the minimal relation $k_{p3}/a_{j3}$ and $k_{q3}/b_{j3}$ in the range of the available stock primarily take part in voltage stabilization on bus 3.

Herewith for the given example, if $\Delta U_3 > 190V$, then voltage stabilization on bus 3 up to the specified deviation $\varepsilon$ is not provided using the local linear regulators, so it is necessary to perform the coordinated voltage control with the voltage regulator under load transformer in PS I. The used methods of voltage regulation in PS often can’t provide the necessary voltage on buses of all TS (the
curve 1 in Figure 3). The coordinated agent control better copes with the task of voltage stabilization in the nodes of electrical network.

Figure 2. Reactive capacity of SVC, connected to bus TS 4, TS 5 and TS 2, fed from PS I.

Figure 3 presents voltages on TS buses, fed from PS I, with regulation in main substation (1), with coordinated control (2), in the original mode (3), which were received as results of simulation modeling.

Figure 3. Voltage on TS buses, fed from the PS I, with regulation in main substation (1), with coordinated control (2), in the original mode (3).

5. Conclusions
Consequently, the research results showed the practical feasibility and efficiency of the developed algorithm for coordinated voltage control in distribution electrical networks of railways. The use of linearized equations for determination the control actions in small increments are justified by high speed of data analysis and allows performing solution of the optimization task for voltage stabilization in real time. The importance of the given algorithm of the coordinated voltage control in the distributed electrical networks of railways is that it allows achieving the electrical power quality by voltage in all specified nodes of electrical network unlike the existent ways. It can become a base of a multi-agent control system for electrical power system within the framework of active-adaptive electrical networks concept.
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