Reconfiguration of intelligent electrical distribution networks of railways

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Abstract. The Digitalization of the power supply system and the introduction of sources of distributed generation based on renewable energy create new conditions for improving the efficiency of transport and distribution of electric energy. In normal operation, the 35/10 (6) kV distribution electric networks of railways have an open-ended structure and are partitioned in such a way as to be able to connect a group of substations to another power source in emergency or repair modes. existing technologies for managing modes in these electrical networks do not imply the possibility of changing their topology to ensure the tasks of reducing overload and electricity losses in the pace of processes of change in demand for electricity in normal modes. As a rule, at present, the task of reconfiguring the electrical network arises when normal conditions are restored after accidents, when lines are overloaded, and if necessary, electrical equipment needs to be repaired according to the n-1 criterion, while optimizing the modes. The most important task of increasing the transmission capacity of distribution grids can be solved by reconfiguring them at the pace of changing the demand for electricity in normal conditions, without resorting to expensive reconstruction and increasing the installed capacity of electrical installations and lines. An algorithm for reconfiguring the electrical network has been developed to increase its capacity based on solving problems of optimizing normal modes (static reconfiguration) and minimizing power consumption without calculating steady-state modes in the pace of electricity demand changes (dynamic reconfiguration). To ensure the admissibility of the modes of distribution electric networks, approaches to managing the supply of active (based on renewable sources) and reactive capacities and the demand of active consumers have been proposed. There are the results of the implementation of dynamic reconfiguration for the test circuitry without taking into account the power supply and demand management of active consumers, indicating the validity of the proposed approaches to improving the capacity of the electrical network.

1. Introduction

At present a digitalization of railway electric power supply system opens new opportunities for transport efficiency increase and electric energy distribution.

In normal work mode distributive railways electric networks 35/10(6) kV have an open structure and are segmented so, that they have a connection opportunity of one group of substations to another power supply in emergency or repair modes.

Existing technologies of modes control in the specified electric networks do not assume change opportunities of their topology for tasks providing for overload and electric energy losses reduction at a pace of demand change processes for electricity in normal modes. As a rule, a task of an optimal electric
network configuration appears during restoration of normal mode after accidents, by lines overload, by necessity of electrics output in repair by criterion \( n-1 \), by modes optimizations.

In this research we will consider an approaches realization to electric schemes reconfiguration in a railways electric power supply system of non-traction and outside consumers for tasks providing for voltages stabilization, overload and electric energy losses reduction at a pace of demand change processes for electricity in normal modes. An optimization task of electric network structure by change of active and reactive capacities in last years is widely studied in foreign and domestic scientific circles.

As a whole the given task can be considered as an optimization nonlinear of mixed integer programming [1].

A part of researchers follow heuristic task solution methods of an optimal electric network reconfiguration [2-5], which allow substantially reducing computing and \( n \) temporary resources, and finding approximate solutions. An optimization task of combinatorial type can be solved by some authors with the help of salute (fireworks) algorithms, neural networks, fuzzy sets [6-9] mainly in the conditions of limited initial information.

Heuristic solution methods of combinatorial optimization tasks showed its high efficiency in comparison with classic enumeration methods by significant number of objective function arguments, when accuracy isn’t defining, and speed of calculations is defining. Optimization methods, which are bond with search on graphs, are also used by search task solutions of optimal electric network topology first because of unambiguous solvability [10].

Although a problem of minimum tree in graphs theory is well studied [11], solution of given task isn’t simple due to the fact, that for creation of an optimal topology it is necessary not only to minimize resistance of distributive network lines, but also electric energy losses, to determine capacity flows for all variants of network structure, and also to consider restrictions of mode parameters and exploitation, electric power supply reliability and other.

In this study it is proposed to solve the task of an optimal radial electric schemes reconfiguration for overload restriction and electric energy losses reduction in a perspective system of railways electric power supply. Herewith as an optimization criterion of electric network topology there is minimum electric energy consumption by operational restrictions by electric power supply schemes, permissible mode parameters, lines overloads etc.

2. Materials and methods.

Distributive railways electric networks 6-10 kV are performed open (fig. 1), as a rule, by loop or combined schemes, therefore the variants number of their reconfiguration is enough limited, as well as by operational modes.

The task is to define, which of switches must be open to provide the largest electricity consumption reduction in the electric network with specified loads.

If for all combinational switches variants we will perform a full current distribution calculation and/or solve an optimization nonlinear task of integer programming, then it will be unacceptable for operational control of electric network reconfiguration by overload and/or for electric energy losses reduction.

Therefore the purpose of this work is creation of more effective calculations ways of electric network spanning graph creation in terms of speed and calculations correctness by considered reconfiguration.

For this purpose we proposed a configuration task of an open distributive electric network to divide into two subtasks, as a dynamic and static reconfiguration, and to solve them by different methods.

An electric network reconfiguration for fast removal of elements overload is performed on base of an agent approach by method of branches and borders using the recurrent relations for electric energy losses determination for all areas without a full calculation of a fixed mode (in contrast to [12]).

In normal mode for choose of an electric network topology with minimum electric energy consumption (with minimum electric energy losses) a nonlinear task of fixed modes optimization is solved, which imitate a reconfiguration, subject to prognostic loads values.
The given in fig. 1 distributive electric network we denote as a graph \( G(N; E) \), where \( N \) – bus bars: \( N = \{1,2,...,m\} \), and \( (i,j),(i,j) \in E \) – lines (arcs, running from bus bar \( j \) to bus bur \( j \)). This graph can be divided into four sub graphs (by the number of feeding centers of an open electric network): \( G_1(N_1; E_1), G_2(N_2; E_2), G_3(N_3; E_3), G_4(N_4; E_4) \). Herewith \( N_1(i) = \{j|(i,j) \in E\}, \) \( N_2(i) = \{j|(j,i) \in E\} \) etc.

A model of capacity flows for the radial electric network can be presented as:

\[
P = \sum_{i \in N} \sum_{j \in N(i)} \delta_{ij}(P_{Lj} - P_{Gj}) + \sum_{i \in N} \sum_{j \in N(i)} \delta_{ij}(\Delta P_{ij});
\]

\[
Q = \sum_{i \in N} \sum_{j \in N(i)} \delta_{ij}(Q_{Lj} - Q_{Gj}) + \sum_{i \in N} \sum_{j \in N(i)} \delta_{ij}(\Delta Q_{ij}),
\]

where \( P_{Lj}, P_{Gj} \) u \( Q_{Lj}, Q_{Gj} \) – active and reactive load capacities and injections on bus bur \( j \);

\( \Delta P_{ij} = \frac{P_{ij}^2 + Q_{ij}^2}{U_j^2} r_{ij}; \Delta Q_{ij} = \frac{P_{ij}^2 + Q_{ij}^2}{U_j^2} x_{ij} \) – active and reactive capacity losses in lines \( ij \); \( P_{ij}, Q_{ij} \) – active and reactive capacity overflows in lines \( ij \); \( r_{ij}, x_{ij} \) – active and inductive lines resistances \( ij \); \( \delta_{ij} \) – binary variable (\( \delta_{ij} = 0,1 \ (i,j) \in E \)).

For considered open electric network (fig. 1) with four feeding centers an optimization task of dynamic reconfiguration based on (1) can be written as:

\[
\sum_{k=1}^{4} P_k(\delta_{ij}) \rightarrow \min,
\]

\( \delta_{ij} = 0,1 \ (i,j) \in E \)
The solution of given optimization task (2) using the method of branches and borders will allow getting values of a binary variable, which describe an electric network graph branches condition: 0 – line is open, 1 – line is closed.

Determination of capacity flows is performed without calculation of fixed mode by given injections in nodes and topology of electric network. Permissible mode parameters of electric network by voltage are estimated by module in the line end on bus bur from date at the line start on bus bur as [13]:

\[
U_j = \sqrt{\left(U_i - \frac{r_j p_i + x_{ij} q_i}{U_i}\right)^2 + \left(\frac{x_{ij} p_i - r_j q_i}{U_i}\right)^2},
\]

Electric network reconfiguration for lines overload exception must provide a permissible new mode, if it is possible, otherwise to resort to demand control, up to loads shutdown.

Reconfiguration criteria:
- capacity balance provision, including reserve;
- exception of electric equipment overloads;
- exception of voltage and frequency unacceptable levels;
- provision of required electric power supply reliability level;
- provision of required reconfiguration frequency (threshold).

Proposed algorithm of considered electric network reconfiguration is given in fig. 2.

Reconfiguration control system provides a continuous control and network condition assessment, and in case of overload absence of electric network elements performs an optimization of electric network new topology and mode parameters subject to demand prognostic values and capacity proposals (statistic reconfiguration), for example, as it’s shown in works [14, 15].

As a rule, an electric network reconfiguration for mode parameters optimization and electric energy losses reduction has a practical meaning with periodicity up to twice a day and isn’t always justified from an economic point of view, what cannot be said about reconfiguration for electric equipment overload to except normal mode recovery in case of emergency disturbances.

Determination of electric network new topology by dynamic reconfiguration is performed on base of task solution (2) by method of branches and borders by keeping the conditions of mode admissibility (3). Method of branches and borders is based on following procedures: setting an original plenty of enumeration variants, choice of the most perspective lots by an original plenty partitioning, perspective lots branching into enumeration subsets [16]. For each border there is determined a low border of a target function, and for a final top there is an exact value of a minimized target function. Branching principle consists of an obligatory participation or non-participation in a tree of any branch that means that the original plenty of permissible solutions is divided in two no overlapping subsets: vectors with a fixed value 1 and 0. Herewith for each electric network tree branching capacity losses are calculated recursively by given in (1) formulas without a nonlinear equations calculation of fixed modes.
Some authors by search of electric network flow partition point use an approach based on sign determination of capacity flow in schemas branches [16, 17] with all their enumeration. Herewith a need arises of additional electric network schema transformation for exception of blind branches branching.

According to the given in figure 2 algorithm, if an overload exception because of reconfiguration is impossible on the conditions of mode admissibility (3), then there is performed a demand control and a capacity proposal in the electric network up to the load shutdown.

As a capacity proposal there are considered sources of reactive capacity and distributive generation (in case of availability).

In this case the lines overload means an excess of not limit current load for specific wires types, but limit current values subject to provision of static stability and minimum necessary capacity reserve [13].

Along with a restriction of consumers’ capacity emergency modes by appropriate automatic equipment (shutdown) there is proposed an approach with more thorough consumers’ ranking in terms of a possible damage (cost) of their shutdown in real time and their flexibility in the demand control.

Let’s consider more detailed approaches to the elements overload reduction of a distributive electric network by active capacity, as a reactive capacity balance can be provided with fixed compensation equipment of reactive capacity (a separate task outside of this research).

The main ways of lines overload reduction:
- regulation of an active capacity generator (in case of availability);
- regulation of a phase angle (by technical capability);
- setting of a capacity transit graph (import/export);
- change of an electric network topology;

**Figure 2. Electric network reconfiguration algorithm**
– consumers’ load reset;
– control of an active consumers’ demand.

The load reset is the last variant, when the lines overload cannot be reduced using another methods. Within a distributed agent control realization of capacity flows in the electric network [19, 20] by overload there are proposed the following steps of this problem solution:
– warning (availability of potential conditions for an overload appearance subject to prognostic values, structures of capacity balances and other factors);
– notification (excess of established dynamic threshold values);
– emergency mode;
– overload exception.

3. Practical part
Let us consider a realization of given approaches to the electric network reconfiguration 10 kV (fig. 1).

The main line parameters and calculated loads are given in table 1.1, 1.2.

Table 1. Lines resistances

| Line | 1-1 | 2-3 | 3-14 | 4-5 | 6-7 | 8-9 | 9-2* |
|------|-----|-----|------|-----|-----|-----|------|
| r, Ohm | 0.329 | 0.266 | 1.119 | 0.419 | 0.464 | 0.354 | 0.291 |
| x, Ohm | 0.099 | 0.080 | 0.144 | 0.102 | 0.113 | 0.064 | 0.087 |

Table 2. Calculated loads

| Load | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|------|---|---|---|---|---|---|---|---|---|----|
| P, kW | 1200 | 930 | 1270 | 1100 | 820 | 910 | 830 | 560 | 780 | 860 |
| Q, kVar | 1100 | 870 | 1140 | 930 | 620 | 820 | 730 | 420 | 650 | 760 |
| Load | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | – |
| P, kW | 760 | 370 | 1200 | 1270 | 560 | 715 | 810 | 1100 | 390 | – |
| Q, kVar | 650 | 290 | 1150 | 1100 | 430 | 550 | 725 | 970 | 300 | – |
| Generation | 3 | 4 | 5 | 6 | 7 | 8 | 12 | 13 | 14 | 15 |
| P, kW | – | – | – | – | – | – | – | – | – | – |
| Q, kVar | 400 | 400 | – | – | – | – | – | – | – | 200 |

According to the given in fig. 2 algorithm for electric scheme with four feeding centers in the solution result of an optimization reconfiguration task (2) there were received optimal places of lines disconnection and quantitative assessments of mode parameters (table 3).

Reconfiguration purpose is a lines 1’-1 and 9-2’ overload exception.

Table 3. Capacity consumption in the electric network before and after reconfiguration

| Electric network mode | Type | FC 1 | FC 2 | FC 3 | FC 4 | In total |
|-----------------------|------|------|------|------|------|---------|
| Initial               | P, mW | 6.225 | 5.391 | 2.343 | 4.134 | 18.093  |
| δ34, δ1213, δ1415 = 0 | Q, mVar | 6.12 | 4.808 | 2.011 | 3.527 | 16.466  |
| After reconfiguration  | P, mW | 5.017 | 4.064 | 4.688 | 3.809 | 17.578  |
| δ45, δ314, δ1415 = 0 | Q, mVar | 4.447 | 3.59 | 4.463 | 3.344 | 15.844  |
Electric network reconfiguration for the fast removal of elements overloads is performed on the basis of an agent approach (more detailed in [18]) by method of branches and borders using the recurrent relations for determination of electric energy losses for all areas without a calculation of a steady mode. From the given in table 3 date it follows that after reconfiguration the consumed capacity in the electric network decreased by 2.9 %.

In fig. 3 there are the simulation modeling results of capacities on electric network bus bars, in fig. 4 and 5 there are lines load and capacity losses in them.

**Figure 3.** Capacity on electric network bus bars before (line 1) and after (line 2) reconfiguration

**Figure 4.** Active capacity losses in electric network lines before (left column) and after (right column) reconfiguration

**Figure 5.** Load of electric network lines before (left column) and after (right column) reconfiguration
Total load losses of active capacity in electric network line are: 798,08 kW before reconfiguration and 541,9 kW after.

As it was mentioned earlier lines load is determined subject to reserve for provision of a static статической stability (it's accepted 10 %) and a minimally necessary capacity reserve (if necessary, also on condition n-1).

Thus, the optimal reconfiguration for the examined case provided as mode admissibility by voltage (fig.5), so as lines overload exception. Therefore in this case there is no need to resort to loads capacity restriction and demand control of active consumers that is subject of authors' research in other works.

4. Conclusions.
Research results showed validity of the proposed approach to the electric network dynamic reconfiguration for overload restriction and electric energy loss reduction without a calculation of steady modes nonlinear equations for every variant of a topology network change. Herewith as an optimization criterion of electric energy topology there is minimum electric energy consumption by operational restrictions by electric power supply schemes, acceptable modes parameters, line overloads, etc.

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