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Research paper

A model for power shortage minimization in electric power systems given constraints on controlled sections

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ABSTRACT

This paper considers the problem of modifying the mathematical models of power shortage minimization as used in the adequacy assessment of electric power systems. A review and analysis of existing software packages were conducted, in particular, the power shortage minimization mathematical models that are part of them were considered. The mathematical models were modified to correctly account for the maximum allowable active power flow in the controlled sections. In the experimental part of this study we tested the proposed modifications. As a result, it was determined that the most appropriate results from the standpoint of the physical laws of operation of electric power systems are yielded by the model of power shortage minimization with quadratic losses, which takes into account the constraints of power transmission through the controlled sections.

1. Introduction

Nowadays energy industry is faced with an urgent task to ensure the required level of adequacy of electric power systems (EPS) which is needed for economic development and well-being in a modern society. This task becomes especially challenging due to constant changes, enlargement and growing complexity of the EPS. The main tasks to ensure adequacy include early planning, timely correction of changes, and redundancy of EPS elements. The combination of all measures helps to reduce the damage caused by failures of power equipment and, consequently, the constraints of power supply to consumers. However, the measures associated with provision of additional power reserves and the replacement of system elements, which are obsolete or in critical condition, are costly and require a qualified assessment and unbiased justification for their implementation. The implementation of these measures requires an assessment of the adequacy of prospective EPS schemes and adjustment of development plans on its basis. The result of such assessment should be a set of adequacy metrics (AM) of EPS.

The AM include the following elements:

– Probability of shortage-free operation
– Expected value (EV) of a power shortage
– EV of unserved electric power in adequacy zones (AZ)
– Elements of the calculation model of the EPS, which represent a part of the EPS with a set of generating units and load that have no capacity constraints for power transmission lines within them, as well as the system in general
– Probabilistic weighted dual estimates of the sufficiency of generating capacities and network infrastructure.

Internationally, similar AMs are adopted, such as: (a) Expected Unserved Energy (EUE), (b) Loss of Load Probability (LOLP), (c) Loss of Load Expectation (LOLE) and (d) Loss of Load Hours (LOLH).

Currently, the method of statistical tests (Monte Carlo method) is the most frequently used method for adequacy assessment (Kovalev and Lebedeva, 2019; Iakubovskii et al., 2018; Kovalev and Lebedeva, 2000; Chukreev, 1995; Billinton and Li, 1994; Wenyuan, 2011; Oboskalov, 2020; Working Group 601, 2010; Poncela et al., 2016; Krupenev et al., 2020; Singh et al., 2018). The Monte Carlo method consists of three main stages. The first stage is to define a set of pseudorandom states of the system. Then, at the second stage, for each defined pseudorandom state of the system, each such state is modeled and power shortages at the consumer's side are calculate. Also events which affect the power shortage, such as the maximum load of generating sources in adequacy zones and power transmission lines included in the inter-zone links, are recorded. Random events occurring at adjacent points of time can be either dependent or independent. At the third stage, the results of statistical processing determine the adequacy and other characteristics that are relevant for further analysis.

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Domestic and foreign software packages for adequacy assessment of EPSs (Kovalev and Lebedeva, 2000; Chukreev, 1995; Working Group 601, 2010; Fernandez Blanco Carramolino et al., 2017; Antonopoulos et al., 2017; Bertoldi et al., 1991; Working Group 15, 1991; Antares, 2021, 2018; Gaikwad et al., 2015; Lilliam, 2016; Papic, 2011; Hong and Lee, 2009; Siemens, 2020, 2014b,a; OPTGEN, 2019; ENTSO-E, 2018; PLEXOS, 2021; Chu, 2014; Jirutitijaroen and Singh, 2006; Poncela et al., 2016; Bera et al., 2019; Krupenev et al., 2020; Belyaev et al., 2020; Dmitriy, 2018; Antares, 2016) that operate based on the Monte Carlo method make use of different mathematical models and pursue different goals, both technical and economic. That being said, most of them apply linear models or those linearized in the process of analysis that are based on the transportation problem of flow distribution. However, it should be noted that the existing linear models introduce a fairly significant error in determining the power shortage. In Kovalev and Lebedeva (2019), it was demonstrated that the most appropriate method was the statement in the nonlinear form, where losses in power transmission lines have a quadratic dependence on the transmitted power. Some of the existing domestic solutions already use nonlinear models that factor in quadratic losses, but these models have deficiencies and are characterized by an excessive set of variables and constraints, which can lead to distortion of the result and unreasonably high counting time for the analyzed schemes of large dimensionality.

Another disadvantage of existing power shortage minimization (PSM) models is that they require that constraints on power flows are set with respect to inter-zone links. Typically, data on the capacity of each inter-zone link is not available, and controlled sections with a given characteristic of maximum allowable active power flows (APF) are used for analysis and control. In practice, it is difficult to obtain a full correspondence between the inter-zone links and controlled sections. This circumstance must be considered when developing mathematical PSM models.

Therefore, this paper has the following research goals:

- To consider various models, their benefits and deficiencies,
- To evaluate these models according to their appropriateness to include the above-mentioned elements and to overcome deficiencies,
- To provide recommendations on modifications of the models to suit modern conditions of EPS.

The article consists of three sections. The first section reviews and analyzes the existing PSM problem statements. The second section presents a modification of the PSM model, which takes into account the specifics of accounting for the controlled sections of the EPS. The third section presents the results of experimental studies of the proposed modification of the PSM model of the EPS.

2. Modeling of electric power system states for adequacy assessment

The second stage of the Monte Carlo based EPS adequacy assessment technique is to simulate the random states of the EPS. Usually, in the context of the adequacy assessment, the transportation problem is solved, which consists of finding the flow distribution for given parameters of the grid, generating capacities, and levels of power consumption in the adequacy zones. Both domestic and foreign software packages use a number of different statements of the PSM problem. It should be taken into account that in terms of calculating AMs, the problem of minimizing the power shortage with an optimal and physically appropriate distribution of generation between sources and consumers should be considered in the first place. However, almost all foreign software packages consider the problem of minimizing various costs to be the main one, i.e., the emphasis is placed on economic criteria, which also affects the subsequent flow distribution.

2.1. Models for power shortage minimization in electric power systems in foreign and domestic software packages

The ANTARES model (Fernandez Blanco Carramolino et al., 2017; Antonopoulos et al., 2017; Antares, 2021, 2018, 2016) is a linear model that takes into account a number of different parameters, and an undirected graph is used to handle the EPS. The objective function aims to minimize the sum of the costs of different types of power. The balance constraints of this model are based on Kirchhoff's first law, which takes into account consumer load, power generation, and power flows. The above model also includes an economic component, i.e., the costs of power generation and transmission are considered in determining the power shortage.

The Transmission Reliability Evaluation of Large-Scale Systems (TRELSS) model used in the software package with the same name has now been fully transferred to the Transmission Contingency Analysis Reliability Evaluation (TransCARE) software package (Working Group 601, 2010; Gaikwad et al., 2015; Lilliam, 2016; Papic, 2011). It is based on modeling using Markov processes, and the calculation of adequacy indicators is performed in several different ways. One of them is based on measures that focus exclusively on system-wide issues of grid components, such as overloads, voltage violations or deviations, and grid separation. This approach is called the "approach to system-wide issues" and provides information on the frequency, duration, and severity of system-wide issues. It is worth noting that this approach fails to take into account the possibility of rectifying the issues through system response and/or operator action. Consequently, this approach provides a pessimistic view of adequacy and is an indicator of the worst-case scenario. Another approach, called the "possibility approach", provides a set of load rejection metrics as an indicator of the inadequacy of the EPS. The purpose of this approach is to estimate the amount of load which must be disconnected if problems in the EPS persist even after corrective actions are taken following a power equipment failure. All adequacy metrics used, such as expected unserved energy (EUE), probability, frequency, and duration of load rejection, are calculated for each load node as well as for the system as a whole. The approach fails to consider the response time of corrective actions.

The Siemens PTI PSS/E TPLAN model (Working Group 601, 2010; Fernandez Blanco Carramolino et al., 2017; Hong and Lee, 2009; Siemens, 2020, 2014b,a) provides the possibility to calculate several objective functions, such as minimizing fuel costs, minimizing active power losses, minimizing reactive power losses, minimizing or maximizing active power transmission, etc. Due to the fact that the software is proprietary, it is not possible to fully familiarize with the model unlike with, as with other models such as the Antares software package. However, the existing brochures and references to the package make it clear that it partly uses a linear model, and the above objectives can be combined by the user themselves.

The software package CORAL (Working Group 601, 2010; Fernandez Blanco Carramolino et al., 2017; OPTGEN, 2019) developed by PSR includes such models as SDDP, OPTGEN/NETPLAN. The latter is responsible for calculations related to production/ transmission expansion planning with supply reliability constraints. The Coral add-on is responsible for modeling the system operation and the objective is set as Expected Power Not Supplied (EPNS), i.e. as the maximum expected power shortage. The OptGen model, as well as the Antares model, considers hydropower and thermal power units of the EPS, including the operating costs of these units.

The Grid Reliability and Adequacy Risk Evaluator (GRARE) software package (ENTSO-E, 2018) evaluates adequacy and economic performance using the Monte Carlo method. This tool is designed to analyze a complete system model (lines, generators, transformers, etc.). The mathematical model, like most of the composite models described above, takes into account the operating costs for the hydro and thermal generating units of the EPS. Models up to 5000 nodes are supported, and the Sauer algorithm is used to calculate power flows and estimate voltage levels using the DC model. The modeling considers the need of meeting energy demand at minimum cost, maximizing revenues from power generation, and optimal flow distribution, while factoring in the capacity of the links. Flow or NTC approaches are used to solve the flow distribution problem. The adequacy level of the EPS is determined by the following metrics: ENS, LOLE, and LOLP. Renewables production is calculated by random selection, based on statistically processed data on the performance of these plants.

The PLEXOS software package (ENTSO-E, 2018; PLEXOS, 2021) developed by Energy Exemplar is a sophisticated power system modeling tool. It uses mixed-integer optimization methods to determine minimum costs and solve dispatch problems to meet demand while meeting technical and economic constraints on generating units. Extended mixed-integer programming (MIP) is the main modeling and optimization algorithm. The problems of meeting energy demand at minimum cost, maximizing revenues from energy production, and optimal flow distribution are stated in the linear form (after linearization) with integer variables revealing the state of the generator in the grid.

The software package Multi-Area Reliability Simulation (MARS) (Working Group 601, 2010; Chu, 2014; Jirutitijaroen and Singh, 2006) was developed by General Electric. In MARS the level of adequacy of the system being assessed is determined by LOLE and LOEE metrics, frequency and duration of emergency shutdowns, the need to initiate procedures in case of emergencies. To solve the problems stated, a transportation model is used as a means to analyze the power flows that connect the power zones of the system. This package was developed in the form of another model, which is Multi-Area Power System (MAPS) (Jirutitijaroen and Singh, 2006). This model was designed to solve the problem of determining the least cost, considered in the other aforementioned packages as well.

Both linear and non-linear flow distribution models are used in domestic software packages. Of the linear ones, one can highlight the PSM model presented in Chukreev (1995). The objective function is aimed at minimizing the difference between the load demand power and that of covering the demand while taking into account the coefficient reflecting the cost parameters of consumer constraints. In the balance constraints, the difference between the covered demand and utilized generating power for each zone of adequacy is taken into account, where the sum of flows associated with the given zone is also factored in, while power losses are not taken into account. At the same time, such a linear statement has the disadvantage of ambiguity arising with respect to distributing the power shortage over individual adequacy zones. The elimination of ambiguity requires a second step in solving the problem of minimizing the system power shortage. For the second step, the objective function changes, the cost factor does not apply, and the balance constraints do not change. The values of the variables for power shortages varying in their depth for the divided parts of the EPS interconnection are determined according to the principle of proportional consumer limitation (the proportionality principle).

In Oboskalov (2020) several models with the aim to minimize the power shortage are presented. The author considers the model of the minimum of the total costs across all zones of the electric power system associated with load limitation and the costs of electricity generation. This model is characterized by constraints on the current value of load and generation, power transmitted to the zone through the power grid (grid injections), as well as on power flows through interconnection lines. The observed power balance corresponds to Kirchhoff's first law and is determined by the condition of the zero sum of injections and power losses. The power flows are proportional to injections, which partially accounts for Kirchhoff's second law, and the model also uses a diagonal conductivity matrix. The effect of varying variables, those of generation and load in some particular zone, on the total power balance in the system is carried out through grid injections. The solution to the problem of the optimal distribution of the nodal power imbalance between generation and load limitation, which can be considered as the additional generation, does not pose any problems and is known as the distribution with respect to the criterion of equality of relative increases in the costs of electricity generation. The quadratic programming is one of the options for solving this problem, which results in a need for a linear form of representation of all the constraints. This is how the author states a linear problem. The author also considers a variant of this model which takes into account the costs of generation and indicates the possibility of adjusting the way of calculation of economic performance indicators.

Another more model makes use of grid injections as control variables and implements the criterion of minimum total operating costs so that the objective function takes the form of a quadratic one. The author of this model also considers a version of the linear model and takes into account the proportionality of the forced load and generation constraints, where the criterion of optimality of distributing the power shortage in proportion to the loads is factored in. This model takes into account the criterion of the minimum of the sum of squares of deviations from the ideal coefficient. This coefficient is the same for all zones and is obtained without taking into account the grid constraints, thus the problem is stated as non-linear. Another version of this model development is the application of the criterion of minimum deviation from ideal values, which eventually allows using the sum of weighted squares of residuals as the objective function.

For a long time, the Melentiev ESI SB RAS has been developing software packages for adequacy assessment, such as "CORAL", "POTOK-3", and "YANTAR" (Kovalev and Lebedeva, 2000). These packages incorporate original mathematical models aimed at identifying the minimum power shortage. Currently, the "Nadezhnost" software package is used for adequacy assessment and is continuously under improvement.

Initially, a model based on flow algorithms which included balance equations, as well as a model based on the grid equations in the direct current idealization, was used in the developed software packages. Later, a two-criteria model for estimating the power shortage in the EPS was adopted. EPS was reduced to the classical problem of maximum flow in the grids and was defined as linear. The objective function was denoted as the minimum of the power shortage, and the balance constraints included the power difference in the zone itself, as well as the incoming and outgoing power flow. In this model, only Kirchhoff's first law was taken into account, and losses were not taken into account.

To distribute the shortage over all adequacy zones potentially affected by the shortage in a way approximately proportional to loads of these adequacy zones, the second stage of optimization was implemented using a different objective function. Thus, a two-stage model was formed, which subsequently received two modified objective functions.

As the next step, the models were formed to take into account the power losses at the inter-nodal links. This is how the model with power transmission line losses, expressed as a linear function of the amount of transmitted power, was developed. This model was further modified, namely, the balance linear constraints were changed to nonlinear equality constraints.

A similar model was formed which is however different from the above-mentioned models as it takes into account the specifics of EPS operation in the wholesale market environment. Despite the abundance of models, they all operated given the flow distribution and the availability of input information about the capacity of the links. At the moment, such information may not be fully available or not available at all, and APFs of controlled sections (CS) are used to account for grid constraints.

Based on the performed analysis of mathematical models for minimizing the power shortage, as used in domestic and foreign software packages to assess the adequacy of the EPS, we can conclude that the relevant task for the development of the model is to consider the specifics of setting the correct grid constraints corresponding to the controlled sections of the EPS.

2.2. A model for minimizing the power shortage of electric power systems with linear losses

The "Nadezhnost" software package (Iakubovskii et al., 2018; Krupenev et al., 2020; Dmitriy, 2018), which is currently being developed at the Melentiev ESI SB RAS, uses linear and nonlinear models of power shortage minimization. The problem of PSM is stated as following:

for known values of operable generating power, required levels of power consumption, constraints on power transmission through inter-zone links, and power loss factors in power transmission lines, to determine the minimum value of the power shortage in the EPS.

In mathematical terms, the linear problem is stated as follows:

$$\sum_{i=1}^{n}(\bar{y}_i - y_i) \to \min_{y,x,z}, \tag{1}$$

given that the following balance constraints are respected:

$$x_i - y_i + \sum_{j=1}^{n}(1 - a_{ji})z_{ji} - \sum_{j=1}^{n} z_{ij} = 0, \tag{2}$$

As well as the constraints on optimized variables:

$$0 \le y_i \le \bar{y}_i, i = 1, \ldots, n, \tag{3}$$

$$0 \le x_i \le \bar{x}_i, i = 1, \ldots, n, \tag{4}$$

$$0 \le z_{ij} \le \bar{z}_{ij}, i = 1, \ldots, n, j = 1, \ldots, n, i \ne j, \tag{5}$$

where: x_i - utilized power in adequacy zone i (MW); $\bar{x}_i$ - available power in adequacy zone i (MW); y_i - actually consumed power in adequacy zone i (MW); $\bar{y}_i$ - maximum consumed power in adequacy zone i (MW); z_{ij} - power flow from adequacy zone i to j (MW); $\bar{z}_i j$ - total transmission capacity of power transmission lines between adequacy zones i and j (MW); z_{ji} - power flow from adequacy zone j to i (MW); $\bar{z}_j i$ - total transmission capacity of power transmission lines between adequacy zones j and i (MW); a_{ji} - specific power loss ratios during its transmission from adequacy zone j to i, $j \ne i$, $i = 1, \ldots, n$, $j = 1, \ldots, n$.

Model (1), (2), (3), (4), (5) is a common flow distribution model in the field of adequacy assessment. This model is a transportation problem. To solve the presented optimization problem, due to its relative simplicity, the simplex method and the dual simplex method in their different variations are used most often.

2.3. A model for minimizing the power shortage of electric power systems with quadratic losses

The PSM model of the EPS with linear losses has assumptions concerning the incomplete accounting for power flow losses, so in Kovalev and Lebedeva (2019) there is a reasonable conclusion that the model where power losses depend on the square of the transmitted power is a more appropriate model and is close to the physical meaning of the real-life operation of the EPS. For this purpose, the model (1)–(5) uses modified balance constraints, where the constraints of the form (2) are replaced by the constraints presented below:

$$x_i - y_i + \sum_{j=1}^{n}(1 - a_{ji}z_{ji})z_{ji} - \sum_{j=1}^{n} z_{ij} = 0. \tag{6}$$

Thus, the PSM problem can be presented as a nonlinear programming problem. The study of models (1)–(5) and (1), (3)–(6) revealed that these models have a number of shortcomings, in particular, incorrect flow distribution as manifested in simultaneous power counterflows over a single inter-zone link.

2.4. Power shortage minimization model with quadratic power losses and variable constraints

As an improvement to the existing quadratic loss PSM problem statement, we consider the model presented in Zorkaltsev and Perzhabinsky (2010), where improvements have been made to reduce the number of variables to be optimized with respect to power flows. For example, instead of using two variables denoting the power flows in the inter-zone links for each direction, one variable is used. This eliminates the problem of the presence of power flows in different directions over the same link. (1) is used as the objective function, and the constraints (3) take the following form:

$$\underline{z}_j \le z_j \le \bar{z}_j, i = 1, \ldots, n, j = 1, \ldots, n, i \ne j \tag{7}$$

the balance constraints take the following form:

$$x_i - y_i + \sum_{j=1}^{m} t_{ij}z_j - \sum_{j=1}^{m}[\tilde{a}_{ij}(z_j)](z_j)^2 \ge 0, i = 1, \ldots, n. \tag{8}$$

where m – the number of links between nodes, t_{ij} – elements of the links matrix of size $n \times m$,

$$t_{ij} = \begin{cases} -1, & \text{if the link begins in the EPS zone } j \\ 1, & \text{if the link ends in the EPS zone } j \\ 0, & \text{if the link with EPS zone is missing.} \end{cases} \tag{9}$$

And functions $\tilde{a}_{ij}(z_j)$ are defined as follows:

$$\tilde{a}_{ij}(z_j) = \begin{cases} a_{ij}, \text{ if } t_{ij}z_j > 0 \\ 0, \text{ if } t_{ij}z_j \le 0 \end{cases} \quad i = 1, \ldots, n, j = 1, \ldots, n, \tag{10}$$

$$\underline{z}_j = -\bar{z}_j, \text{ for all } j. \tag{11}$$

In those cases where the value obtained as a result of optimization is $z_j < 0$, it is necessary to assume that the flow is directed in the opposite direction with respect to the direction specified in matrix t. However, this model (1), (7), (8), (9), (10), (11), cannot be fully utilized for calculations due to the constraint (11), where the link capacity is specified with the same value for the forward and reverse directions. This way of specifying flows is not quite correct because of the different constraints in the forward and reverse directions. Thus, it is necessary to get rid of the constraint (11), thereby allowing to use the excellent capacities of links in the reverse directions. Constraint (8) because of the transition from equality to inequality fails to match the physics of the process and leads to unnaturally large values of the generator power value, which is actually impossible in the real-life EPS. However, in spite of these shortcomings, it should be noted that reducing the number of optimized variables has a positive effect on the speed and volume of calculations.

3. Modification of the electric power systems power minimization model with quadratic losses

3.1. Solving the problem of inter-zone power flows

The optimal values obtained by models (1)–(5), and (1), (3)–(6) do not have the required adequacy from the standpoint of the physics of the flow distribution process. The solution to this problem may involve power counterflows over the inter-zone links. It is also difficult to find a unique solution because of the presence of a plateau or a number of optimal solutions.

The results yielded by models (1)–(5), and (1), (3)–(6) in the process of adequacy assessment can lead to distortion of adequacy metrics. To eliminate this problem, an additional constraint for power flows, commonly known in optimization as "variable zeroing", was stated. In our case, the constraint is represented as follows:

$$z_{ij} * z_{ji} = 0, i = 1, \dots, n, j = 1, \dots, n. \quad (12)$$

Thus, constraint (12) transforms the given problem into the correct one from the point of view of modeling the operation of power flows between adequacy zones and changes the model behavior into a more correct one from the point of view of the physics of the flow distribution process and forms the model of minimization of the power shortage with square losses (1), (3)–(6), (12), referred to as (PSM_1) in what follows.

3.2. Solving the problem of incorrect power flow distribution

Experimental studies have shown that despite the modification of the nonlinear model and its presentation in the form (1), (3)–(7), there is an incorrect power flow distribution due to the presence of a set of optimal solutions. In other words, the flow distribution is not optimal, but based on the conceptual statement of the problem, one needs to find not only the minimum power shortage but also the correct flow distribution. An incorrect flow distribution consists in the appearance of circular power flows.

To solve this problem, a number of modifications of the model described in Iakubovskii et al. (2018) and Krupenev et al. (2020) were proposed, first of all based on changing balance constraints (6) from equality-type constraints to inequality-type constraints. This constraint provided for the transition of the power shortage assessment model to the form of a convex programming problem.

$$x_i - y_i + \sum_{j=1}^{n}(1 - a_{ji}z_{ji})z_{ji} - \sum_{j=1}^{n} z_{ij} \geq 0, i = 1, \dots, n. \quad (13)$$

Experimental studies were conducted relying on this modification of the model. As a result, it was found that the minimum of the power shortage coincides with the value of the PSM_1 model. At the same time, the physically incorrect distribution of power flows remains, but the utilization of generator power has increased, which is physically impossible because the excess generator power is locked in and there are no consumers to meet such a supply.

As a solution to the problem encountered, it was proposed to use the second stage of optimization. Thus, the first stage is to optimize the above model (1), (3)–(6), (12)–(13), this approach will provide a convex set of feasible solutions. Next, the obtained optimal solutions with respect to variable y_i should be fixed with the new variable denoted as $\tilde{y}_i$. Then one proceeds to the second stage of the solution, forming a new objective function, which involves minimizing the sum of the squares of power flows:

$$\sum_{j=1}^{n} z_{ji}^2 \to \min z, \quad (14)$$

and also modifies the current balance constraints (13), to match the balance constraints below:

$$x_i - \tilde{y}_i + \sum_{j=1}^{n}(1 - a_{ji}z_{ji})z_{ji} - \sum_{j=1}^{n} z_{ij} = 0, i = 1, \dots, n. \quad (15)$$

The effectiveness of this approach of successive two-stage optimization and interaction of the PSM model with balance constraints of inequalities (1), (3)–(6), (12)–(13) and the minimization model of the Euclidean norm by flows (14), (3)–(6), (12)–(15) was experimentally tested and the results proved this approach effective (Iakubovskii et al., 2018).

3.3. Modeling of controlled sections

Under the current conditions of operation and development of the EPS, data on the capacity of inter-zone connections are often completely or partially unavailable. At the same time, to control the power transmission between EPS adequacy zones, controlled sections with a given APF characteristic are used. Such CSs include up to several branches (power transmission lines) with a designated direction of power flow. Thus, it becomes impossible to use the models presented above without introducing additional changes, and therefore it is proposed to consider the necessary adjustments and additions for stating the mathematical problem with quadratic losses.

The authors carried out improvements (modification) of the existing model for minimizing the power shortage, which was used in adequacy assessment of EPS. This modification includes the controlled sections and the maximum permissible active power flows, which makes it possible to correctly use the network restrictions while adequacy assessment and obtain more accurate power shortage value and other reliability indicators of the EPS compared to previous models.

First of all, it is necessary to designate matrix S of the controlled sections, in which the presence of branches in the CS is denoted with their directions taken into account. The dimension of matrix $l \times m$, where l - the number of CSs, and m - the number of branches, the elements of the matrix are denoted as cs_{kf}:

$$cs_{kf} = \begin{cases} 1, \text{ if a branch is present in the monitored section} \\ 0, \text{ if a branch is absent in the monitored section.} \end{cases} \quad (16)$$

Each controlled section has its APF in the forward and reverse directions, to store them one needs matrix M of dimension $l \times 2$, where the first element (md_{k1}) in the row contains the values of the forward APF, the second element (md_{k2}) contains the values of the reverse APF. For this model to operate one has also to introduce CS constraints, for forward and reverse APFs.

$$\sum_{f=1}^{m} cs_{kf} z_f^{\text{forward}} \leq md_{k1}; k = 1, \dots, l, \quad (17)$$

$$\sum_{f=1}^{m} cs_{kf} z_f^{\text{backward}} \leq md_{k2}; k = 1, \dots, l, \quad (18)$$

where z_f^{forward} - forward power flow z_{ij} (MW), and z_f^{backward} - reverse power flow (MW), i.e., z_{ji} that are determined when forming matrix S. Thus, the existing model (1), (3)–(6), (12)–(13) should be transformed into the model (1), (3)–(6), (12), (16), (17), (18) to eliminate the problem of bidirectional loading of controlled sections. This problem was solved by introducing additional constraints on the controlled sections:

$$(\sum_{f=1}^{m} cs_{kf} z_f^{\text{forward}})(\sum_{f=1}^{m} cs_{kf} z_f^{\text{backward}}) = 0; i = 1, \ldots, n, j = 1, \ldots, n, \tag{19}$$

This constraint, in addition to physically correct distribution of power flows over sections in one of the directions, also allows eliminating constraint (1.12) from the model thanks to the doubling of actions with respect to the direction of power flows. The result of the above additions and modifications is the following power shortage minimization model with quadratic losses and factoring in of controlled sections: (1), (3)–(6), (16)–(19), referred to as (PSM_2) in what follows.

3.4. Modified statement of the power shortage minimization problem

Given that the statement (1), (7)–(11) has a number of advantages, namely the absence of counterflows and reduction of the number of variables, it is proposed to make changes that allow dealing with the likely ambiguity of the solution and making it possible to employ this model in the calculations that use real-life data and constraints on the controlled sections. It is proposed to consider the following statement of the mathematical problem: the objective function (1), as well as the upper and lower constraints on the generation and load variables (3)–(4), the matrix defining the direction of power flows through the links (9), as well as the loss factor determination functions $\tilde{a}_{ij}(z_j)$–(10) remain unchanged. To rule out the possibility of locked in generation, the balance constraints (8) are replaced by the following equality-type constraints:

$$x_i - y_i + \sum_{j=1}^{m} t_{ij} z_j - \sum_{j=1}^{m} [\tilde{a}_{ij}(z_j)](z_j)^2 = 0, i = 1, \ldots, n. \tag{20}$$

The constraint (11) does not allow the use of different capacities of power flows in the forward and reverse directions and contradicts the physics of the EPS operation process. Thus, a modified power shortage minimization model of the following form is formed: (1), (3)–(4), (9)–(10), (20), referred to as (PSM_3) in what follows, which is identical to model (1), (3)–(6), (12). To take into account the controlled sections in the resulting model, it is necessary to use the CS matrix S, the elements of which has to be changed, so instead of the elements of (16) one should use the following:

$$cs_{kf} = \begin{cases} 1, \text{ if the direct link refers to a CS} \\ -1, \text{ if the reverse directional link relates to the CS} \\ 0, \text{ if there is no communication in the monitored section.} \end{cases} \tag{21}$$

In addition to transformations of the matrix S elements, it is also necessary to change the constraints of the controlled sections given in (17)–(18) to constraints of the form:

$$\sum_{f=1}^{m} \text{if } z_f \geq 0, \text{then}(cs_{kf} z_f) \leq md_{k1}; k = 1, \ldots, l, \tag{22}$$

$$\sum_{f=1}^{m} \text{if } z_f < 0, \text{then}(cs_{kf} z_f) \geq md_{k2}; k = 1, \ldots, l, \tag{23}$$

where z_f - power flow z_j, and its direction is defined in matrix S. Thus, the modified model of power shortage minimization taking into account the controlled sections is formed, which will take the following form: (1), (3)–(4), (9)–(10), (20), (21), (22), (23), referred to as PSM_4 in what follows.

4. Experimental studies of different models of power shortage minimization

Experimental calculations were performed for systems of different configurations with different initial parameters. We analyzed the results of the previously considered models: PSM_1, PSM_2, and PSM_3. The modified PSM_4 model was omitted from the experiment due to the impossibility of reproducing fully constraints (22) and (23) and performing the calculations because the objective function and its gradient cannot be calculated while taking into account the penalty function method. Attempts to define formalized constraints have not been successful, due to the presence of different signs in the flow variables, as well as overlapping and contradictory constraints for different controlled sections. Thus, the modified PSM_4 model cannot operate correctly with the controlled sections without introducing additional variables to control the direction of flows.

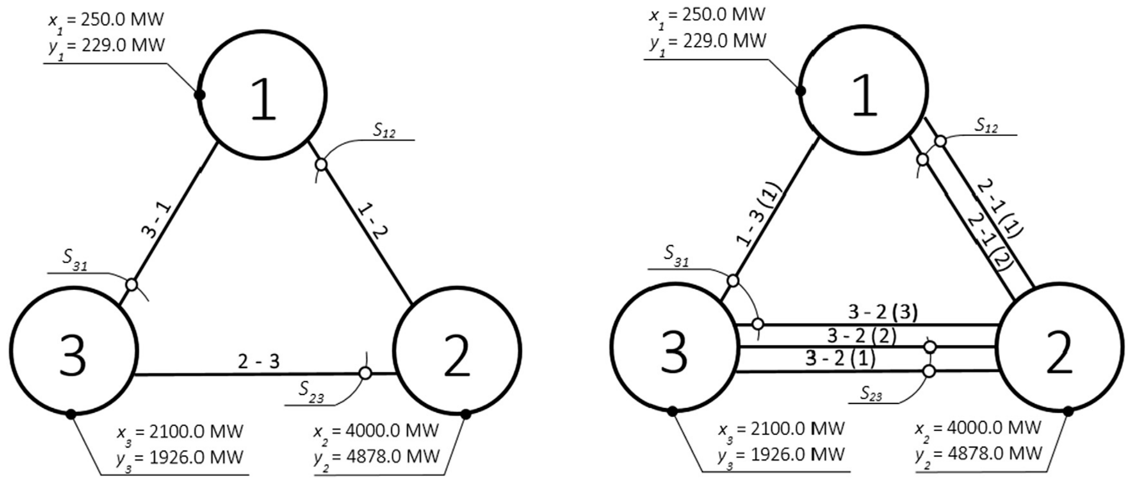
A total of four stages of experiments were conducted, where three different types of calculations were prepared for the purposes of the study:

- Calculation 1: calculation for the specified input data;
- Calculation 2: of all input data only specific loss factors at the power transmission line are changed, all of them are assigned the value of 0.1;
- Calculation 3: the input data with the changed characteristics of the APF of the CS were used.

It is important that the proposed mathematical models for minimizing the power shortage can be used for systems of any dimension. At the first stage, the experimental studies were conducted for the three-zone systems shown in Fig. 1. TS_1 scheme is made up of three adequacy zones and three power transmission lines. The TS_2 scheme is made up of three adequacy zones and six power transmission lines distributed over three different controlled sections. The calculations were performed in the GAMS software package that is used in some domestic and foreign packages for adequacy assessment.

At the first stage, a series of calculations was performed for TS_1, the initial parameters for which are shown in Fig. 1, as well as in Table 1. In this case, each CS includes one power transmission line, and the value of the CS APF coincides with the capacity of the power transmission line included in the CS. Based on the results obtained in Calculation 1, the operation of PSM_1 and PSM_3 models has an identical logic of distribution of generation by adequacy zones and loading of controlled sections. The main result is assumed to be the found power shortage, in this case for the model PSM_1 the minimum power shortage is 718.734 MW, for the model PSM_3 it is 718.543 MW. The difference was 0.191 MW, which is within the margin of error of the input data of up to 5 MW, but the PSM_3 model used large amounts of adequacy zone 3 generating power and larger S_{31} section loading to achieve a smaller shortage. To confirm the effectiveness of the PSM_3 model in terms of the found power shortage, we performed Calculation 2 where the specific loss factors for each of the links were set at 0.1. As a result, the minimum power shortage for the calculation by the PSM_1 model was 873.0 MW, and for the PSM_3 model it was 838.192 MW, thus the solution difference is 31.808 MW. Calculation 3 involved the use of the original input data with modified sectional capacity specifications, where identical power shortages with a difference of 0.001 MW were found as a result.

As a result of the operation of the PSM_1 and PSM_3 models, the PSM_3 model showed the advantage in finding the smallest



Scheme TS_1 Scheme TS_2

Fig. 1. Schemes of the analyzed systems with 3 adequacy zones and the different number of power transmission lines in the controlled sections, where S is the controlled section.

Table 1
Additional input data for TS_1.

Power transmission lines designation		1-2	2-3	3-1
Specific loss factor of power transmission lines		0.0006033	0.0000113	0.0001729
CS APF (MW)	Forward	30	150	20
	Backward	45	130	40

Table 2
Results of substitution of the obtained values into the balance constraints.

	Calculation 1		Calculation 2	
	PSM_1	PSM_3	PSM_1	PSM_3
BC - Node 1	$-5.7E-05$	0	0.0479	0
BC - Node 2	0.0004	0.0003	4.9846	2.4849
BC - Node 3	$1.24E-13$	$8.22E-05$	$-8.72635E-14$	141.6724

power shortage values. Since both models are identical, additional calculations were performed to determine the factors that influence the difference in the final results. The PSM_1 model uses the balance constraints of equality (1.6), where incoming and outgoing power flows are used, this includes taking into account the quadratic losses for all power transmission lines adjacent to the adequacy zone, which in turn affects the minimization result. In the PSM_3 model, quadratic losses are taken into account only for power transmission lines directed to a specific adequacy zone, so the losses in the process of minimization are factored in differently. To confirm this conclusion, the objective function of the PSM_3 model was replaced by the following objective function:

$$\sum_{i=1}^{n}(\bar{y}_i - y_i) + \sum_{j=1}^{m}[\tilde{a}_{ij}(z_j)](z_j)^2 \rightarrow \min_{y,z}, \tag{24}$$

As a result, model (24), (3)–(4), (9)–(10), (16)–(19) was obtained, for which Calculations 1, 2, and 3 were performed, which resulted in completely identical calculation results as compared to the PSM_1 model. The latter may indicate that quadratic losses in the PSM_3 model are factored in incorrectly.

To verify the correctness of the optimized variable values, the obtained results of Calculations 1 and 2 were directly substituted into the PSM_1 and PSM_3 models, after which the values of balance constraints (BC) were calculated.

Due to the specifics of storing numbers in the computer memory, as well as the standard errors of the methods implemented in the GAMS software, the obtained BCs are within 0, but not always equal to it. Table 2 shows how the order of the error changes depending on the calculation, for the PSM_1 model as the largest error one can consider the result of the calculation of the balance constraints of the 2nd adequacy zone in Calculation 2 equal to 4.98456 MW, which is within the error margin of the input data. For the PSM_3 model, the order of the error is exceeded in BC for node 3, the resulting value of 141.6724 MW is not within the margin of the input data error and cannot be considered correct. According to the results of PSM_1 and PSM_3 models we can conclude that using the PSM_3 model we can get more accurate results, at the same time the PSM_3 model yields better values of the power shortage, but with a larger error of calculation that is unacceptable in adequacy assessment.

At the second stage of the experiments, a series of calculations was carried out for TS_2, where the repeating initial parameters are completely the same as in the previous system and are shown in Fig. 1. Table 3 shows additional input data. Calculation 1 for the PSM_2 model resulted in a shortage of 811.148 MW, changes in the input data for Calculation 2 also affected the values of specific loss ratios, they were equated to 0.1. Calculation 2 resulted in shortages of 865.5 MW for PSM_2. We also performed Calculation 3, where the specifications of the sectional capacity were changed, resulting in a value of 822.045 MW for the PSM_2 model.

At the third and fourth stages of experimental studies, we considered a system consisting of 7 adequacy zones and 7 power transmission lines; this scheme has already been used previously in Kovalev and Lebedeva (2019, 2000) and Zorkaltsev and Perzhabinsky (2010). The system was also considered in its two versions: the first used lines included in the same-named CSs, which allowed us to compare the efficiency of finding the minimum power shortage for PSM_1 and PSM_3 models as applied to

Table 3
Additional input data for TS_2.

Power transmission lines designation		2-1 (1); 2-1 (2)	3-2(1); 3-2 (2); 3-2 (3);	1-3
Specific loss factor of power transmission lines		0.0006033	0.0000113	0.0001729
CS APF (MW)	Forward	188	15	40
	Backward	175	10	36

Table 4
Initial parameters of links and controlled sections for TS_3.

Name of the controlled section	Numbers of adequacy zones adjacent to power transmission lines	Specific loss ratios at power transmission lines	Capacities of the sections by direction:	
			Forward (MW)	Reverse (MW)
S12	1–2	0.0004035	360	360
S23	2–3	0.0000216	150	100
S24	2–4	0.0001829	200	200
S25	2–5	0.0002255	800	1000
S45	4–5	0.0000114	1200	1200
S56	5–6	0.0005221	300	300
S57	5–7	0,0003116	150	150

Table 5
Results of Calculation 1 of the PSM_1 and PSM_3 models for TS_3.

Required generation		Load covered		Power transmission line loading		
PSM_1 (MW)	PSM_3 (MW)	PSM_1 (MW)	PSM_3 (MW)	Numbers of adequacy zones adjacent to power transmission lines	PSM_1 (MW)	PSM_3 (MW)
2333.000	2333.000	2451.459	2492.978	1–2	−124.745	−159.978
1775.000	1775.000	1726.000	1726.000	2–3	150.000	150.000
333.000	333.000	482.505	482.505	2–4	−154.514	−178.450
1350.000	1350.000	170.000	170.000	2–5	−76.938	−92.867
509.000	509.000	1549.000	1549.000	4–5	1025.486	995.723
824.000	870.980	524.000	524.000	5–6	−300.000	−300.000
0	0	142.980	142.980	5–7	150.000	150.000

a larger system; the second version used controlled sections that included both one and several lines.

The third stage experiment included calculations performed for TS_3. As can be seen from the diagram in Fig. 2, some of the nodes have redundancy, while others have a shortage in their power balances. The S_{23} and S_{25} controlled sections have different capacities for forward and reverse directions. See Table 4 for a more detailed description:

According to the results of the system calculations with the PSM_1 and PSM_3 models, the direction of flow distribution is completely identical, the same lines are involved, but the loading values of some of them are different. The results of the resulting Calculation 1 are shown below:

Based on the results of Calculation 1 (Table 5), the main difference is present in the value of the minimum power shortage, so for the model PSM_1 it is 523.056 MW, and for PSM_3 - 481.537. In previous calculations, a tangible difference of 31.808 MW of the found minimum power shortage value was present only in calculations with specific loss factors equal to 0.1. In this case, when calculated using specific loss factors not exceeding 0.0001, the difference in the resulting shortages is 41.519 MW, which fails to be within the margin of the input data error of up to 5 MW. According to the results of Calculation 2, the minimum power shortage for PSM_1 was determined to be 1961.5 MW and for PSM_3 it was 1875.128 MW, the difference amounted to 86.372 MW, which is also outside the margin of error. For Calculation 3, the capacity of Line 4–5 was changed to 300 MW, resulting in the following power shortage values: PSM_1 - 1182.003 MW, PSM_3 - 1127.891 MW; the difference amounted to 54.112 MW.

To check the performance of the models, taking into account the controlled sections, a different series of calculations was performed for the fourth stage. In this case, TS_4 included from one to three lines per controlled section, as shown in Fig. 2. This scheme is identical in terms of the level of available generating power and the load covered in the adequacy zones, and the initial parameters for the power transmission lines specified in Table 4 are also used in this calculation. The changes affected the content of the controlled sections and their APF by directions, which are described in Table 6.

As a result of running the PSM_2 model as part of Calculation 1 a power shortage of 766.137 MW was identified, the distribution of power across power transmission lines was different from the results of running PSM_1 and PSM_3 models: in this case, only 3 lines were fully loaded. Generation in adequacy zone 6 is lower if compared to the calculations for the TS_3 scheme.

As can be seen from Table 7, there are differences observed when the PSM_2 model operates with TS_4, namely, only 3 of the 7 lines are involved, while the generator power of 6 of the 7 adequacy zones is loaded identically, and the load is also covered differently. In this case, the power distribution was affected by the directions of the links within the sections; the lines within cannot be arranged arbitrarily, their directions are determined by expert's judgment.

To confirm this, a separate calculation was performed, where the directions of flows along the power transmission lines were chosen the same as in the obtained solution of Calculation 1 for PSM_1. The shortage obtained using the PSM_2 model and the directions of flows along the lines in the controlled sections, as set based on expert judgment, is 473.171 MW. In turn, identical

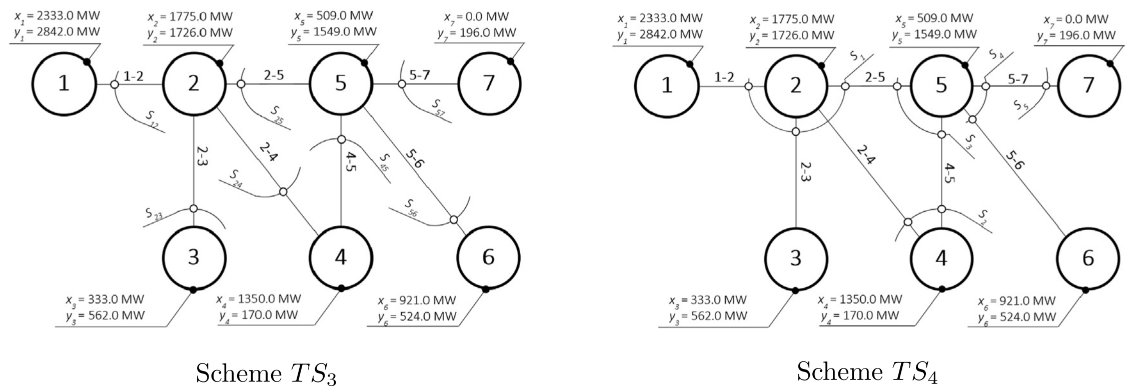


Fig. 2. The schemes of the analyzed systems with 7 adequacy zones and the different number of inter-zone links in the controlled sections.

Table 6
Initial parameters of the controlled sections and links for TS_4.

Name of the controlled section	Numbers of adequacy zones adjacent to power transmission lines	APF of sections by direction:	
		Forward (MW)	Reverse (MW)
S1	1–2 2–3 2–5	1310	1460
S2	2–4 4–5	1400	1400
S3	4–5 2–5	2000	2200
S4	5–7 5–6	450	450
S5	5–7	150	150

Table 7
Results of calculations of models PSM_1 for TS_3 and PSM_2 for TS_4.

Required generation		Load covered		Power transmission line loading		
PSM_1 (MW)	PSM_2 (MW)	PSM_1 (MW)	PSM_2 (MW)	Numbers of adequacy zones adjacent to power transmission lines	PSM_1 (MW)	PSM_2 (MW)
2333.000	2333.000	2451.459	2381.030	1–2	−124.745	−49.000
1775.000	1775.000	1726.000	1726.000	2–3	150.000	0
333.000	333.000	482.505	333.000	2–4	−154.514	0
1350.000	1350.000	170.000	170.000	2–5	−76.938	0
509.000	509.000	1549.000	1549.000	4–5	1025.486	1180.000
824.000	524.000	524.000	524.000	5–6	−300.000	0
0	0	142.980	119.833	5–7	150.000	124.684

power transmission lines were involved in the flow distribution, but with different values.

To summarize, it should be noted that according to the results of the experiments performed, the modified PSM_3 power shortage minimization model proves feasible. This model uses a smaller number of equality constraints and a smaller number of optimized variables, finds better values of the minimum power shortage in the system but has errors that fall outside the margin of the input data error, and, at this stage, this model is unable to account for controlled sections, so it cannot be used for calculations in software packages designed for adequacy assessment. On the other hand, the power shortage minimization model with quadratic losses and controlled sections meets modern requirements for calculating the power shortage with controlled sections factored in.

5. Conclusion

As part of this research work, we analyzed the mathematical models designed for flow distribution calculations and employed in domestic and foreign software packages for adequacy assessment of the EPS. Over the course of the study, we analyzed mathematical models from software packages such as ANTARES, TRELSS, TransCARE, Siemens PTI PSS/E TPLAN, CORAL (including SDDP, OPTGEN/NETPLAN), GRARE, PLEXOS, MARS, MAPS, Orion, Yantar, and Nadezhnost. Some of the above packages use more than one model with a set of different objective functions. Models PSM_1, PSM_2, and PSM_3 were studied experimentally as applied to systems of different dimensionality and topology. The main difference between the analyzed models and the existing statements is the consideration of the grid constraints corresponding to the controlled sections of the EPS, not the power transmission lines. Experimental studies have shown that the PSM_3 model yields better values of the minimum power shortage as compared to PSM_1, however, due to the presence of errors that fall outside the margin of the input data error, as well as the inability to implement additional constraints that form the controlled sections, the PSM_3 model cannot be further used for adequacy assessment. At the same time, the formed PSM_2 model coped with the assigned task of finding the minimum power shortage, while considering the controlled sections with a given APF characteristic.

CRediT authorship contribution statement

Dmitrii Iakubovskii: Conceptualization, Methodology, Investigation, Software, Formal analysis, Writing – original draft. **Dmitry Krupenev:** Conceptualization, Methodology, Supervision, Resources, Formal analysis, Writing – review & editing. **Nadejda Komendantova:** Methodology, Investigation, Visualization, Validation, Writing – review & editing. **Denis Boyarkin:** Methodology, Investigation, Software, Resources, Formal analysis.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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