AUTOMATION AND COMPUTER-INTEGRATED TECHNOLOGIES

UDC 519.7:519.85(045)
DOI:10.18372/1990-5548.66.15229

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AGGREGATIVE-DECOMPOSITION APPROACH FOR OPTIMAL CONTROL OF A HIERARCHICAL ERGATIC ELECTRIC POWER SYSTEM

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Abstract—*This article discusses the optimization problems of energy associated with the optimal management of a complex ergatic electric power system. The search for solutions to these problems is proposed to be carried out on the basis of extremization of the target functional specified using the statistical model. In order to analyze the control process of a complex ergatic electric power system, it is proposed to apply the aggregative - decomposition approach, according to which models of complex power supply systems are described by compositions of interconnected units. When searching for a solution to the optimization problem of controlling a complex electric power system, it is proposed to apply the method of stochastic programming, as well as the method of stochastic quasigradients. From the point of view of the object-oriented approach, it is proposed to consider complex ergatic electric power systems as a class of multi-level multi-purpose systems, which are the subject of cybernetics research. Moreover, the adequacy of algorithmic models for managing these systems is ensured by the implementation of compromise methods. To implement control functions at the highest hierarchical levels of complex electric power systems, it is proposed to create aggregated models of these systems using the descriptive aggregation procedure. The principles of coordination of mathematical programming problems of electric power systems are also considered, according to which local admissibility and consistency predetermines global admissibility.*

Index Terms—Electric power system; mathematical programming.

I. INTRODUCTION

In the process of finding solutions for optimal control of a complex ergatic electric power system (EPS), situations are possible in which the quality indicators and parameters of the limitations of the optimization problem can be random or uncertain. If the study of the power consumption process allows us to identify the stochastic characteristics of its parameters, then the optimization control problem is a risk problem. If it is not possible to determine the statistical laws of the process in the analysis of control actions in the system, then it is necessary to solve the optimization control problem in the face of uncertainty. These tasks should be solved using stochastic programming methods, as well as fuzzy mathematical programming methods.

Markov programming is a method for solving problems that represent dynamic stochastic optimization models that describe Markov random processes. The modeling of the control process in power supply systems (PSS) based on linear models of Markov sequences in solving extreme problems is based on solving optimization problems of linear programming.

II. PROBLEM STATEMENT

It is proposed to carry out a search for a solution to the problem of optimal control of an ergatic complex EPS based on the optimization of the functional specified using the statistical model. To analyze the management process of a complex EPS, it is advisable to apply the aggregative – decomposition approach, in accordance with which models of complex PSSs are defined as compositions of interconnected aggregates.

An aggregate as a model of a dynamic system can be defined by a combination of sets *T*, *X*, *Z*, *Y* and random operators *V*, *U*, *G*, where *T* are many points in time; *Z* is the set of states of the unit at each moment of time; *X* is the set of input signals; *Y* is the set of output signals [1].

The set of operators *V*, *U* can be considered as the operator of transitions of the unit to a new state:

$$z(t_n+0)=V\left[t_n,z(t_n),x_n\right],$$
$$z(t)=U\left[t,t_n,z(t_n+0)\right],$$

where *G* is the exit operator:

$$y=G\left[t^*,z(t^*)\right].$$

Unit dynamic properties and multiple input signals $\{x(t)\}\in X$ determine the transition of the unit $z(t_i)\to z(t_j)$ out of state $z(t_i)$ to state $z(t_j)$. The field of solving optimization problems of Markov programming is the class of piecewise linear units, the mathematical model of which are Markov random processes.

According to the aggregative – decompositional approach to the analysis of complex EPSs, it is necessary to convert a multi-level hierarchical PSS into an analyzed hierarchical system with fewer levels, which is necessary to solve the problems of composition of complex aggregates, as well as the analysis of their structure.

The composition of a complex PSS includes a control unit, the purpose of which is the distribution in time of the functions connecting the units of this system. The algorithm for the functioning of the EPS is determined by the set $\{x_i\}, i=\overline{1,n},$ generated as a result of power consumption by the control unit. Given set $\{x_i\}, i=\overline{1,n}$ is a plan that determines the functioning of a complex EPS, including state functions $z_i(t)$, as well as stochastic parameters of the system, which characterize the indicators of quality and reliability of the power consumption process.

The effectiveness of the search for a solution to the optimization problem of controlling an ergatic EPS is determined by the quality of the initial information, the adequacy of the control algorithms, the speed of the control system, and the reliability of the elements of the PSS. At the same time, the functional purpose of the control algorithms implemented by the units is to optimize the target functionals of the optimization task of EPS control. Models implemented in control algorithms should be adequate to the completeness and accuracy of the initial information on the stochastic process.

The criterion of efficiency of the task of optimization of complex ergatic EPS is improvement of the global quality function. The effectiveness of the control system of a complex EPS is also predetermined by its reliability. The algorithm for the operation of a complex EPS is based on the Boolean concept of reliability. In this case, the condition for reliable operation of the system is modeled on the basis of a logical function that reflects the functioning process, or based on an analysis of the EES graph. Reservation of EES elements is a Markov process with discrete states and continuous time. Complex ergatic EPSs are recoverable systems, the criterion of effectiveness of which is the probability of normal functioning.

III. Problem Solution. Control Modeling of Complex Ergatic EPS Based on the Method of Stochastic Programming

The search for a solution to the optimization problem of controlling a complex EPS can be implemented based on the analysis of the stochastic programming problem, which can be presented as a two-stage [2]. The mathematical model of the stochastic programming problem is:

$$M_\omega(\mathbf{X},\mathbf{Y},\omega)\to \min,$$

under random restrictions:

$$P\{g_i(\mathbf{X},\mathbf{Y},\omega)\le b_i\}\ge 1-\varepsilon,\ i=\overline{1,m},$$

where M_ω is the expected value; ω are disturbances; $\mathbf{X}$ is the vector of control variables; $\mathbf{Y}$ is the vector of output variables; $g_i(\mathbf{X},\mathbf{Y},\omega)$ is the loss function of the ith resource; b_i is the value of the ith resource; $P\{g_i(\mathbf{X},\mathbf{Y},\omega)\le b_i\}$ is the probability of model constraints.

In stochastic programming problems, the stochastic quasigradient method is used. In this case, the problem of stochastic programming is presented as a two-stage one. The method of stochastic quasigradients is also used to solve non-linear programming problems in the conditions of inaccurate information, which is characteristic of ergatic complex systems.

The method of designing stochastic quasigradients is implemented based on the procedure [2]:

$$x_{s+1}=\pi_x\left(x_s-\rho_s\gamma_s\xi_s\right),$$

where π_x is the set mapping operator $R(x)$; x_0 is the arbitrary starting point of space; ρ_s is the step; γ_s is the normalization factor; ξ_s is the stochastic quasigradient; s = 0, 1, … .

Using stochastic programming methods, extreme problems of mathematical statistics are also solved, namely, problems of estimating the distribution parameters of random variables and processes when searching for unbiased and effective estimates. The algorithm of stochastic quasigradients is used.

Ergatic complex EPSs are hierarchical technical and organizational systems, the peculiarity of which is that these systems are a hierarchy of control systems. The governing body is a hierarchical system [3]. Electric power system control bodies of various levels of the hierarchy are systems parallel to the main linear hierarchy, their functions are: planning, decision making, forecasting.

From the point of view of the object-oriented approach, hierarchical systems are a class of multi-level multi-purpose systems that are the subject of cybernetics research. The decision made in these systems is the choice of one of the alternative strategies that are aimed at implementing the target functionality. The purpose of planning in EPS is to identify the model of the process of the operation.

The process of forming the target management functions, as well as the tasks of the activity – the implementation of decision-making is a system analysis of the management process. The modeling of ergatic complex EPS control based on the adoption of multicriteria decisions involves the use of an aggregated – decomposition approach to the analysis of information about ongoing processes. The need for planning EPS is due to the desire of the control system to improve its condition. The system of goals and objectives aimed at neutralizing the effects of the external environment determines the plan of the control operation, the task of which is to maintain a favorable situation for the control system.

Ergatic EPS is a combination of hardware, mathematics, software. The adequacy of algorithmic control models of complex EPS is ensured by the use of compromise methods. The class of compromise tasks determines the following: based on a combination of control actions, it is advisable to implement changes in the parameters of the mathematical model of the system taking into account the energy balance in the EPS. The architecture of the ergatic EPS should be adaptive, that is, it must allow the implementation of variations and the expansion of the functions of the system at the stage of its operation.

In the process of managing a complex EPS, extremization of management efficiency criteria is carried out. For forecasting at different hierarchical levels of EPS, it is advisable to design a hierarchy of models of control objects based on the aggregated – decomposition approach. The adequacy of mathematical models of EPS is achieved by choosing their structure and identifying the parameters of the models. The choice of the target functional for finding the optimal solution is carried out by a person; this solves the problem of heuristic programming.

The implementation of management functions at the highest hierarchical levels of a complex EPS determines the feasibility of constructing aggregated models of this system. The correlation analysis of variables, as well as the parameters of the EPS model is significantly simplified by reducing the dimension of the aggregated model, which simplifies, accordingly, the procedure for finding the optimal solution to the optimization problem.

The optimization approach applied to the search for the optimal solution to a complex EES provides for the construction of an aggregated model. The aggregated model corresponds to the minimum of the loss function for a certain region of variation of the arguments. If the arguments are random variables with known probability distribution functions, the mathematical expectation of the loss function should be minimized.

When solving energy optimization problems, it is advisable to perform descriptive aggregation. The descriptive aggregation procedure provides for the construction of an aggregate mapping that associates a set of valid aggregated plans with a solution to the aggregated problem [3]. The solution to this problem is the set of optimal aggregated plans that satisfy the compatibility condition for the optimization problem.

For linear systems, the descriptive aggregation procedure assumes that the linear system is described by convex polyhedral sets in space E^n, wherein the set of control variables X satisfies the condition $X = \{x \to Ax \le b\}$, the search for the optimal solution is carried out by extremizing a linear functional:

$$Y = F(X) = \operatorname{Arg}\max_{x \in X} cx.$$

In this case, the optimization problem is solved by the linear programming method.

The process of human interaction with the automated control system of an ergatic EPS is iterative. Iterative algorithms should be applied to ensure the stability of the solution of optimization problems in the energy sector. According to the studies, the convergence of optimization problems determines the convergence of their solutions in such a way that the solution of mathematical programming problems in a fuzzy formulation converges to the set of solutions of the limiting optimization problem [3]. A study of the convergence of a sequence of sets defined by a system of constraints – functional inequalities – is not a study of the convergence of sequences of functions defining these sets. In the case of finding a solution to a mathematical programming problem with linear constraints, the set of feasible solutions to the limiting optimization problem is the set X defined by a consistent system of linear inequalities. The limiting problems of mathematical programming with mixed constraints have similar convergence.

Thus, when considering the stability of energy optimization problems, it is advisable to study how changes in the problem parameters affect the optimal value of the target functional, as well as the set of feasible and optimal solutions. If the stability conditions for an admissible set of optimization problems are fulfilled, then, with changes in the system of constraints, the continuity of changes in the optimal value of the target functional is predetermined. During the operation of the human – machine interface of the ergatic EPS, the interrelation between the stability of the optimization tasks of the energy industry and the conditions of convergence of their sequences is manifested.

In the formulation of mathematical programming problems, constraints are a system of inequalities and equalities. Restricted optimization problems are also local problems. A means of coordination in mathematical programming problems is the specification of the applied restrictions. The principles of coordination should be applied to certain sets of admissible local solutions. Between the sets of admissible local solutions and the set of globally admissible control actions there is a dependence based on the principles of coordination. According to these principles, local acceptability and consistency predetermine global acceptability [4].

Aggregate-decompositional approach to finding a solution to the optimization problems of energy in the case of linear systems involves the application of the decomposition of complex linear programming problems into interconnected subproblems, which are also linear programming problems. The optimal feasible solutions of linear programming subtasks determine the optimal feasible solution to the global linear programming problem. Moreover, the decomposition of the global additive linear objective function and the constraint system is determined in such a way that the coordination of the control process is predetermined by the modification of the objective functions of the linear programming subtasks. The decompositional subproblems of linear programming can be coordinated based on the principle of coordination of interactions if the global optimization energy problem has an optimal feasible solution.

The main global mathematical programming problem has an optimal feasible solution if and only if the dual problem also has an optimal feasible solution [4]. The following is true: if a global problem, which is dual to the main one, has an optimal feasible solution, then the subtasks obtained as a result of decomposition are coordinated based on the principle of coordination of interactions. Moreover, it is characteristic for a dual problem that the optimal coordinating signal can be expressed through the optimal solution of the dual problem, namely:

$$\overline{\beta}_i = \mathbf{B}_{ii}{}^T y_i,\ i = \overline{1, n},$$

where $\overline{\beta}_i$ coordinating signal; y is the admissible solution of the dual global problem; $\mathbf{B}$ is the matrix of coefficients.

In the event that the coordinating signal is given by the vector $\overline{\beta}$, then each decompositional subproblem of linear programming has an optimal admissible solution if the global linear programming problem has an optimal admissible solution. The search for solutions to the optimization problems of complex energy systems predetermines the application of decomposition procedures. When solving linear programming problems, the Danzig–Wolf decomposition method and the method of consistent constraints are used [4]. In this case, to implement the principles of coordination, one should formulate local optimization problems in such a formulation that the optimal local solutions determine the optimal solution to the global optimization problem with an optimal coordinating signal. An acceptable optimal solution to a global problem in decomposition according to the Danzig–Wolf method is a convex combination of solutions of decomposition subproblems, that is, the implementation of this method does not provide an acceptable optimal solution to a global optimization problem.

Decision making in the analysis of hierarchical energy systems shows that strict global optimality of control actions and local decisions is not always feasible due to incompleteness of information. The incompleteness of information is manifested in the lack of information about factors affecting the results of certain decisions, as well as control actions. The search for solutions to poorly structured problems in the face of uncertainty is based on optimization algorithms. A strict optimal solution to the global problem of optimizing a complex ergatic EPS can be unrealizable due to time constraints. The criterion of effectiveness in this case is the improvement of the global quality function.

The results of the use of stochastic programming for energy optimization are:

- construction of an aggregated EPS model based on a descriptive aggregation procedure;
- solution of the optimization problem of the energy sector, which is the set of optimum aggregate plans satisfying the conditions of the combined region;
- solving poorly structured problems under uncertainty is based on optimization algorithms.

Setting optimization problems for the energy sector is of great importance at the design stage of EPS. The goal of solving optimization problems is to find the values of control parameters that extremize the target functional with a certain system of restrictions. To optimize the target functional, mathematical methods of optimization are used; in this case, it is necessary to express the target functional in terms of parameters. Decision-making in complex ergatic EPSs predetermines the extremization of target functionals for given systems of constraints, which are the optimization tasks of the energy sector. Mathematical optimization methods are: the method of Lagrange multipliers, mathematical programming, calculus of variations [2]. Decision making in complex EPS is carried out in conditions of uncertainty. Therefore, mathematical methods for optimizing energy are stochastic programming, fuzzy mathematical programming, heuristic programming.

IV. Conclusion

Finding a solution to the optimization problem of managing a hierarchical complex EPS can be realized by analyzing the method of stochastic programming, with the following positive results.

1. Possibility of solving the problem of estimating parameters of distribution of random values and processes of energy consumption in hierarchical techno-organizational systems.
2. Adaptability of the ergatic EPS architecture at the operational stage.
3. It is advisable to construct aggregated models of complex ergatic EPS for the management functions at the top hierarchical levels of these systems.
4. The possibility of simulating the effect of changing the parameters of the optimization problem of energy on the optimum value of the target functionality, as well as on the set of permissible and optimal solutions, the search for which is carried out on the basis of the aggregate-decomposition approach.

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Received September 10, 2020.

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О. Й. Чуріна. Агрегативно-декомпозиційний підхід при оптимальному керуванні ієрархічною ергатичною електроенергетичною системою

У даній статті розглядаються оптимізаційні задачі енергетики, які пов’язані з оптимальним керуванням складною ергатичною електроенергетичною системою. Пошук розв’язків даних задач пропонується здійснювати на основі екстремізації цільового функціоналу, заданого за допомогою статистичної моделі. З метою аналізу процесу керування складною ергатичною електроенергетичною системою пропонується застосовувати агрегативно-декомпозиційний підхід, згідно якому моделі складних систем електропостачання описуються композиціями взаємозв’язаних агрегатів. При пошуку розв’язку оптимізаційної задачі керування складною електроенергетичною системою пропонується застосовувати метод стохастичного програмування, а також метод стохастичних квазіградієнтів. З позицій об’єктно-орієнтованого підходу складні ергатичні електроенергетичні системи пропонується розглядати як клас багаторівневих багатоцільових систем, що є предметом дослідження кібернетики. При цьому адекватність алгоритмічних моделей керування даними системами забезпечується реалізацією компромісних методів. Щодо реалізації функцій керування на вищих ієрархічних рівнях складних електроенергетичних систем пропонується створення агрегованих моделей даних систем із застосуванням процедури дескриптивного агрегування. Також розглянуто принципи координації задач математичного програмування електроенергетичних систем, згідно яким локальна допустимість і узгодженість визначає глобальну допустимість.

Ключові слова: електроенергетична система; математичне програмування.

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А. И. Чурина. Агрегативно-декомпозиционный подход при оптимальном управлении иерархической эргатической электроэнергетической системой

В данной статье рассматриваются оптимизационные задачи энергетики, связанные с оптимальным управлением сложной эргатической электроэнергетической системой. Поиск решения данных задач предлагается осуществлять на основе экстремизации целевого функционала, заданного с помощью статистической модели. С целью анализа процесса управления сложной эргатической электроэнергетической системой предлагается применить агрегативно-декомпозиционный подход, согласно которому модели сложных систем электроснабжения описываются композициями взаимосвязанных агрегатов. При поиске решения оптимизационной задачи управления сложной электроэнергетической системой предлагается применять метод стохастического программирования, а также метод стохастических квазиградиентов. С позиций объектно-ориентированного подхода, сложные эргатические электроэнергетические системы предлагается рассматривать как класс многоуровневых многоцелевых систем, являющихся предметом исследования кибернетики. При этом адекватность алгоритмических моделей управления данными системами обеспечивается реализацией компромиссных методов. Для реализации функций управления на высших иерархических уровнях сложных электроэнергетических систем предлагается создание агрегированных моделей данных систем с применением процедуры дескриптивного агрегирования. Также рассмотрены принципы координации задач математического программирования электроэнергетических систем, согласно которым локальная допустимость и согласованность предопределяет глобальную допустимость.

Ключевые слова: электроэнергетическая система; математическое программирование.

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