Models for the Determination of Reliability Criteria in the Planning of a Liberalized Electric Power System

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***Abstract*—The determination of reliability criteria is an essential part of the work to establish the future power reserves in territorial areas of the United Power System of Russia. This task has been thoroughly studied. In this article, the main features of long term planning are discussed, and methods and models for the determination of reliability criteria are proposed.**

***Index Terms*--Power system reliability, power system analysis computing, power generation, parallel architectures, reliability theory.**

I. INTRODUCTION *(HEADING 1)*

The development of the electrical power system is of major importance for the economic growth of a country. The United Power System (UPS) of Russia delivers energy to more than 95% of the consumers and covers almost the entire territory of the country. Nowadays, more than 640 power plants of different kind and size are connected to the network by 2 millions of kilometers of transmission lines, making the UPS a complex and interdependent critical infrastructure. The development of the UPS of Russia, as a united technological complex, needs to fulfill reliability and safety requirements at all time and in all territorial areas. The territorial areas are already indicated by the system operator (SO). In this paper, we are interested in the short term (up to 3 years) and long term (5 to 15 years) planning of the power system under reliability and safety constraints.

According to the Federal law on electrical power systems [1], the "SO-UPS" is responsibile for making the various development routes meet the safety and reliability requirements during power system planning. The determination of reliability criteria for the UPS of Russia is considered a cornerstone of the decision making process [2]. The above mentioned law and the Decree of the Russian Federation[1] have a strong impact on the technological rules of power system operation[2]. In this document, it is demonstrated that the determination of reliability criteria for long term planning should be performed for each year according to the UPS development program of the coming 5 to 7 years.

The determination of reliability criteria constitutes an essential task when establishing the power reserves necessary to keep the balance during a contingency. Fulfilling the long term planning requirements of the UPS of Russia requires development efforts in multiple directions: modeling of the UPS; building a database with information about the UPS network; developing methods for the determination of reliability criteria and their programming (taking into account the available data for variations in load, the occurrence of planned and emergency maintenance, the distribution of power reserves during long term outage of the power system). The first of these assignments (modeling) is taken care of by "STC UPS". In this work, the main features of long term planning are discussed, and methods and models for the determination of reliability criteria are proposed. In the rest of this paper, by the term "reliability" will be meant the ability of the UPS to satisfy the demand under given restrictions on the access to power resources considering planned and emergency outage of the power system components.

II. BRIEF ANALYSIS OF EXISTING MATHEMATICAL MODELS AND PROGRAMMING TOOLS FOR THE DETERMINATION OF RELIABILITY CRITERIA

Problems related to the development of mathematical models based on a probabilistic analysis of the power system reliability are investigated in [4]-[12]. Solutions to these problems require the estimation of the demand in the different territorial areas, the random choice of the state of power generators and transmission lines (due to unplanned outages), as well as the analysis of the quality of power supply for the given system state. The development of mathematical models for the determination of reliability criteria is based on analytical methods or combinatorial and statistical models.

Models based on analytical methods rely on the probabilities of over- or under- production and of restricted

[1] Decree of the Russian Federation dated October 17, 2009 № 823 "On the schemes and programs of perspective development of electric power industry

[2] Approved at a joint meeting of the Scientific Council on the problems of reliability and safety of large-scale power systems and scientific-technical board of NP "STC UPS" 16.05.2011.

transmission capacity between two neighboring areas. The analysis is performed sequentially from one node to another, thereby propagating across the entire network. The following models were developed using this method: AMON/D [4], AMON/N [5], TRELSS (EPRI), TPLAN (Siemens) [10], [11]. On the one hand determination of reliability criteria of the power system by analytical methods significantly increases the computational efficiency; on the other hand it can be implemented only on a radial power system.

Models based on statistical modeling are more flexible and universal and have therefore found wide application for the determination of reliability criteria in complex power systems [6]-[8]. The determination of reliability criteria can be performed through the analysis of random events (models «Orion» [7], [8], Jantar' [6], JeNINa [4], MECORE [11], etc.) and of random processes (GE MARS, GridView, etc. [11]). The main drawback of these models lies in their poor computational efficiency. Nevertheless, the recent improvements in computational power of personal computers allow the determination of a wide range of reliability criteria, making it a method of choice for the analysis of complex power systems.

In practice, most of the programming tools used for the determination of reliability criteria are based on statistical modeling methods. In the following, issues with the development of technical guidelines and methods for the determination of reliability criteria in the long term planning of the UPS of Russia are discussed.

III. Development of Methodology and Methods for the Determination of Reliability Criteria in the Planning of the UPS of Russia

In addtion to unplanned events, the following factors have an important impact on reliability criteria of a multiarea electric power system:

- available power in the different territorial areas;
- structure of the generating units;
- planned equipment maintenance;
- load variation diagrams in the territorial areas per day and year;
- irregular fluctuations in the load and forecast errors in the demand;
- reduction of generation power in the territorial areas due to outage of generating units and transmission lines;
- transmission capacity reserves in the normal and emergency states;
- network model of the UPS of Russia.

The determination of reliability criteria for complex power systems using statistical modeling methods involves the constitution of a range of random states for the generating units and network components based on their fault clearing ability, and the evaluation of the consumer satisfaction for these system states. In the models developed prior to the liberalization of the power system [3], [4], [7], [9], [10], the determination of reliability criteria was performed sequentially for all time interval during which the input data remains unchanged. These contributions were thereafter summed up taking into account the probability of existence of the corresponding time interval. In this regard, the liberalization of the electricity market didn't require any modification in the methods of determination of reliability criteria. The main components of programming tools remained (Fig. 1):

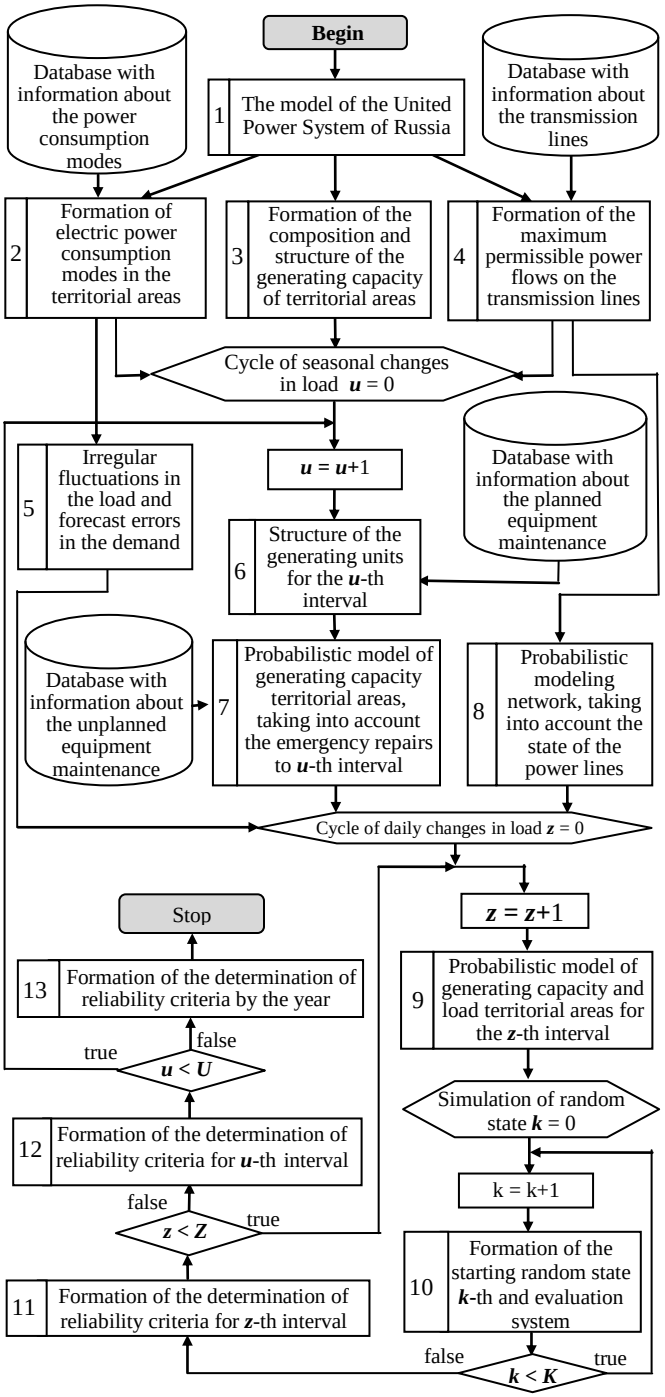

Figure 1. Outline flowchart for estimating reliability parameters of a power system

- the constitution of random states for the generating units and network components, based on their fault clearing ability;

- the evaluation of consumer satisfaction in the different territorial areas for the give system states.

A. *Evaluation of random states of the power system (block 10)*

The task is to evaluate the over- and under- generation in the territorial areas, taking into account the network parameters (derived from the chosen probabilistic model). From the reliability point of view, only random states for which under generation is probable are considered. In contrast to the traditional steady state determination, the parameters of active and reactive power are not strictly defined in the determination of reliability criteria.

With such a formulation of the problem, several questions arise: how to model the state of the system in case of under-generation? how to define the steady state disregarding reactive power? etc. For these reasons, in the early works on the determination of reliability criteria for the planning of multiarea power systems, it was decided to neglect the reactive power and to implement simplified models for the evaluation of the steady state. Under these assumptions, it is necessary to introduce maximum allowed levels of power flow that need to be calculated beforehand (using traditional methods). Nowadays their determination in the context of the complex network model of the UPS of Russia is the main problem for building the database used in the determination of reliability criteria. Implementation of the above described algorithms for a liberalized power system can be found in the work of [8], [12].

B. *Determination of random states for the generating power and load in the territorial areas*

The reform of the Russian electricity market has made the determination of reliability criteria an even more complicated task, with an increased size of the system from 15-20 nodes (united and concentrated power systems) with 20-30 lines [3], [4], [6], [7] to 100-150 nodes (territorial areas) with 200-300 lines. The reason is the evolution towards a more detailed network model for the UPS with the introduction of territorial areas. The fragmentation of the united power systems into territorial areas has an influence first on the composition of generating structures in the territorial areas (blocks 3, 4, 9) and on the probability density function of generating power variations (block 7); second on the constitution of randoms states of the system using statistical modeling methods. The authors of [12] estimate the influence of the use of statistical modeling methods on the functions describing generating power variations in the territorial areas, and their effect on the results of the reliability criteria determination.

IV. THE USE OF PARALLEL COMPUTING

The flowchart in Fig. 1 shows that boxes from 2 to 8 are aimed at defining a set of power system states, boxes 9 and 10 evaluate the consequences caused by these system states for the consumers, boxes 11, 12 and 13 determine the annual parameters for the determination of reliability criteria. To improve the proposed algorithm for determination of the adequate parameters, it is necessary to develop methods that would speed up the simulation process with the use of computer hardware for parallel computations.

A current trend of the modern compact computer hardware development is to increase performance by increasing the number of computational elements (cores, threads, etc.). The most available elements for use in desktop systems, namely personal computers, include multi-core central processing units (CPU) and graphics processing units (GPU). The latter, despite their name, can do general-purpose computations and include RAM with a size comparable with that of a central processor (CP). It is important that these units are independent computational elements which can operate asynchronous with respect to other personal computer (PC) components. In addition, the number of GPUs in the PC configuration can be increased up to at least two and even more in some cases.

Consider splitting a cycle with respect to the hours of the day. A flowchart of the simplified version of such algorithm is given in Fig. 2. The parallel computations is done with respect to a set $I=\{I_1, I_2, \ldots, I_i\}$, which is a number of hours in a day. An important feature of this algorithm is that there is a cycle inside the parallel procedure. This feature, first, reduces the requirement to the available RAM size, second, requires that the computer hardware architecture incorporates a more complex memory access system, an interim cache-memory, etc.

Let consider the issues related to practical implementation, for example, the implementation of the algorithm given in Fig. 2 to a multi-core CPU. To estimate the effectiveness of the algorithm paralleling, the computation speed-up is used as a criterion, which can be estimated according to the Amdahl's law in the following way:

$$\eta = \frac{T_{comp}^{S}}{T_{seq} + \frac{T_{par}}{p} + T_{comm} + T_{wait}} < \frac{T_{comp}^{S}}{T_{seq} + T_{comm} + T_{wait}},$$

where T_{comp}^{S} is total time of computations $T_{seq} + T_{par}$, T_{seq} is run time of the sequential algorithm section, T_{par} is run time of the parallel algorithm section, T_{comm} is data communication time, T_{wait} is waiting time at synchronization, p is a number of processors. In the case of the problem under consideration T_{par} in percentage shall exceed T_{seq}, and T_{comm} and T_{wait} shall be insignificant if multi-core CPUs are used. For the modern multi-core CP, $p = 2 \div 12$ and in the near future will grow even higher. Due to this, it is possible to preliminary estimate η as equal to 1,7-7,5 (at $p = 2 \div 8$).

From a practical point of view, the process of adapting an algorithm to the target architecture consists in developing a code using functions from different support libraries. Nowadays the adaptation procedure, if applied to the multi-core CPU, is most time-effective if it is based on the use of the OpenMP library [13] embedded in a number of compilers or of the more universal library OpenCL [14]. These libraries are universal for different CP brands and do not depend on the CP manufacturer and specifications. Furthermore, OpenCL is a

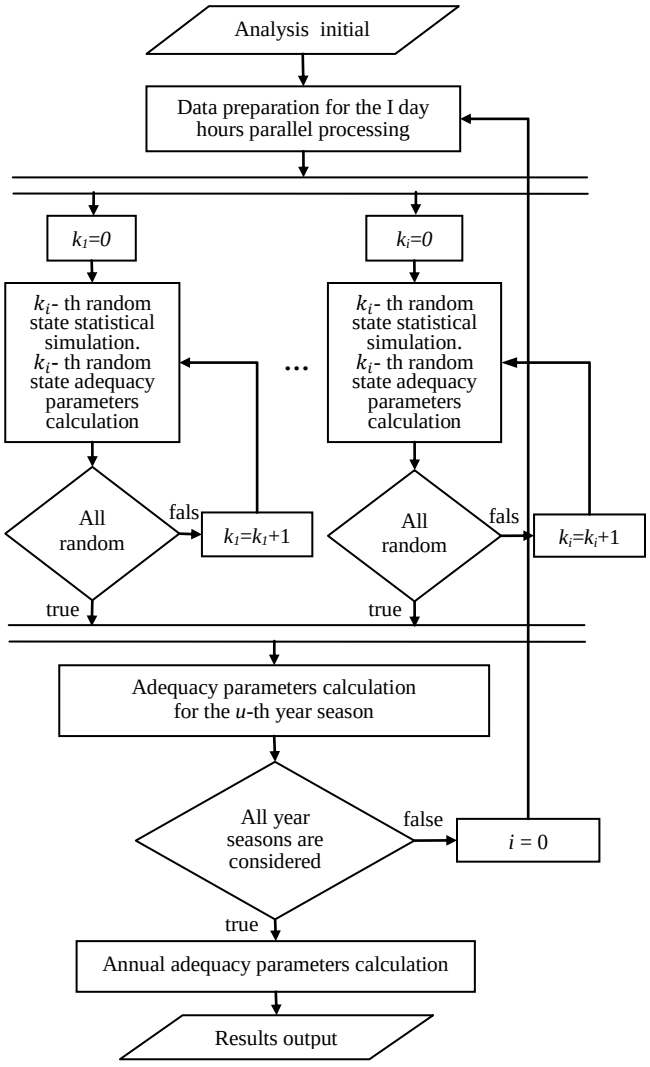

Figure 2. Paralleling a procedure of determining reliability indices at different hours of a day in the algorithm of determining adequacy parameters

new standard for the application development for heterogeneous systems. This standard is used for creating applications to be run on systems with CPUs, GPUs and expansion cards of different architectures. Thanks to this, there is no need to use different algorithms for the systems based on Intel, AMD and other platforms.

To validate the implementation of the algorithm, a number of test problems were computed for test power system systems of various dimensions and configurations. Both OpenCL and OpenMP libraries were used as software for parallel computations. Results obtained with these two libraries are identical in many aspects.

The efficiency of paralleling is close to the theoretically estimated value and almost proportional to the number of simultaneously executed threads, and this makes paralleling the most promising direction for reducing time needed for computations, especially taking into account the current trend of improving computational capabilities by increasing the number of procedures being executed at the same time.

TABLE I. COEFFICIENT OF COMPUTATION ACCELERATION ON DIFFERENT CP FOR THE CONSIDERED TEST POWER SYSTEM PROBLEMS

CPU model	Core frequency, GHz	Cores number/ threads number[3]	Random states number ($^{1000}/_{10000}$)			
			Considered test problems			
			6	10	21	51
Core 2 Duo	3,0	2/2	1,82/1,78	1,85/1,85	1,96/1,96	1,9/1,89
Core i3 540	3,06	2/4	2,42/2,45	2,43/2,42	2,6/2,63	2,4/2,47
Core i5 760	2,8	4/4	3,27/3,48	3,07/3,44	3,25/3,50	3,46/3,39
Core i7-4790	3,6	4/8	3,91/3,86	3,84/4,23	4,26/4,51	4,29/4,49
Xeon w3580	3,33	4/8	2,93/4,21	3,24/4,47	4,45/4,80	4,65/4,78

V. CONCLUSIONS

The analysis of programming tools for the determination of reliability criteria showed the similarities in the base method employed for power systems of different countries. Approaches are proposed for the development of programming tools for the determination of reliability criteria in the UPS of Russia. The system operator of the UPS is responsible for adapting the existing models for the determination of reliability criteria in system planning. For a practical implementation of the model and its application to actual power system planning, it is necessary to:

- create software for the determination of reliability criteria;
- refine the methods and programming tools for the determination of reliability criteria;
- develop the user interface for these programming tools.

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[3] Thread is a process running at one processor. The number of processes done at the same time on one processor can be more than one; their number depends on the process architecture.

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