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Genetic algorithms for nuclear reactor fuel load and reload optimization problems

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Abstract

Approaches are examined in the present paper to the application of genetic algorithms for optimization of initial reactor load and subsequent reloading and reshuffling of fuel assemblies in the nuclear reactor core. The issues associated with selection of the optimization criterion, which was chosen to be the nuclear fuel burnup depth, are discussed. The burnup depth is estimated after the fuel assembly is unloaded from the core, i.e. after residence in the reactor core during 3 fuel irradiation campaigns.

An important aspect determining the efficiency of the use of the genetic algorithm in the problem under examination is that the neutronics calculation of the reactor core is to be performed in sufficient details allowing "feeling" the change in the location of the fuel assemblies relative to each other. The use of low-precision instrument results in the uselessness of the proposed approach to the optimization of reactor core loading. The opposite extreme, i.e. the excessive degree of details, is associated with significant increase of expended computer CPU time. In the presented paper, the TRIGEX [1,2] application software package was used in the analysis of neutronics characteristics of the reactor core providing acceptable degree of details and capable to demonstrate sensitivity of the results to the changes in the reactor load arrangement.

The genetic algorithm incorporates the use of at least two basic procedures—selection and mutation. One of the most important issues in the application of the genetic algorithm is the definition of the basic concepts, namely the concepts of *mutation, crossing,* and *specimen*. The answers to these questions as applicable to the problem under discussion are provided in the present paper. In addition, the main recommendations for the organization of crossing and mutation procedures are also given.

The efficiency of use of the developed model of the genetic algorithm is demonstrated by the test example of a BN type reactor. The results of the test run demonstrated that the use of the proposed approach allows searching for optimal reactor load mapping for each separate core reshuffling operation. The main objective of the performed study was to demonstrate the applicability and efficiency of the new up-to-date approach to solving the problem of fuel loading into a nuclear reactor.

Keywords: Optimization of fuel initial loading and reshuffling; Burnup value; Genetic algorithm; Nuclear reactor.

1. Introduction

One of the determining factors in the field of development of nuclear power generation is the design of new and advancement of already existing nuclear fuel technologies and, in particular, those allowing achieving high values of fuel burnup. Solution of this problem requires the development of both new structural materials and new fuel types, as well as new reactor control systems. One of the methods for achieving deeper fuel burnup is the optimization of reactor core load and fuel reshuffling. Optimization of fuel load is efficient both for newly loaded reactors of new types, and for re-loading already existing reactors. For instance, the study is known on the configuring of fuel loads for VVER-440 reactor cores during their operation at elevated power level for the Kola NPP [3]. The study [4] is dedicated to the opti-

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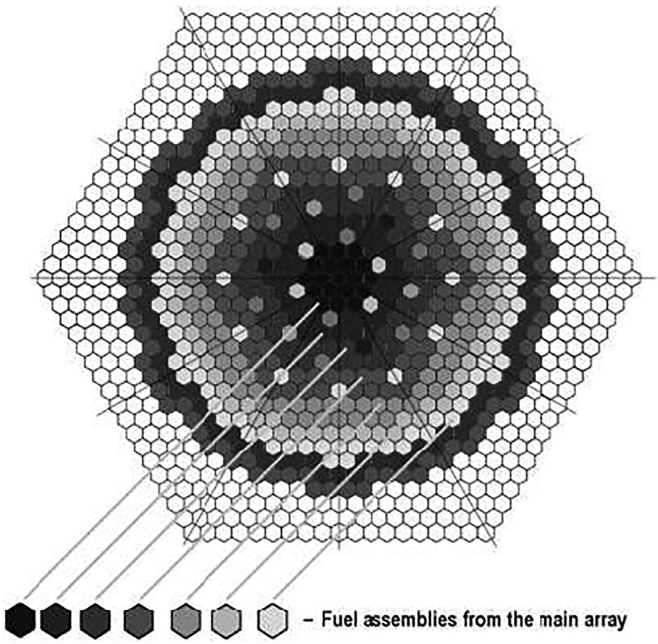

Fig. 1. Map of BN reactor core.

mization of fuel reshuffling in the VVER-440 reactor cores. Approaches to the optimization of reactor core fuel load using evolutionary simulation are presented in Ref. [5]. Example of optimization of fuel loads and reactor core reshuffling using the genetic algorithm is addressed in the present study.

Fuel load configuration of which is close to that of high-power fast breeder reactors (hereinafter referred in the text as the BN reactors) with two reloads was selected as the example. Extraction of fuel assemblies (FAs) irradiated during three fuel residence campaigns, reshuffling of remaining FAs and loading fresh FAs are accomplished in the process of reactor core reload. The type of nuclear reactor in question was selected as the example within the framework of which the approach was worked out to the implementation of optimization using the evolutionary algorithms. The developed approach can be adapted for the cores of reactors of any type.

Since the object of the present investigation is not a specific reactor, the minimum set of nuclear reactor core parameters required for implementation of exploratory studies is presented here. The map of initial load (Fig. 1) and the number of FAs equal to 606 pieces are the most important information [6–8].

It has to be noted that the full list of possible FA reshuffling configurations for the selected problem using the example of BN reactor consists of $606^{3(606-1)/2}$ options. This is the list including practically infinite number of options. This is exactly where the main advantage of the genetic algorithm, i.e. the search for the “sufficiently good” solution within “sufficiently short time”, manifests itself. With high dimensions of the problems and absence of the system in the input data the genetic algorithm possesses unquestionable merits as compared with classical methods (gradient descent method and similar methods) [9].

2. Optimization criterion

Maximum fuel burnup depth was selected as the optimization criterion. In this case optimization is the single-objective optimization and the criterion is sufficiently simple. Transition to multi-criterion optimization can be easily achieved by introducing the value functions or using other known methods.

Other parameters, for instance, effective neutron multiplication factor can serve as the optimization criterion as well [10].

Fuel burnup depth was defined in the optimization of fuel load as the ratio of the difference between the mass of initially loaded heavy elements and the mass of heavy elements unloaded from the reactor core to the mass of initially leaded heavy elements [11]. Since certain integral characteristic for all fuel assemblies irradiated during three reactor fuel residence campaigns is required, the mass of unloaded heavy elements was averaged over the whole FA array after three fuel residence campaigns. In other words, average fuel burnup depth value (in percent) was taken only for those fuel assemblies which resided in the reactor core during three complete fuel irradiation campaigns. Here, each fuel assembly is reshuffled two times, i.e. it has its unique “displacement trajectory” during the interval between the initial loading and final unloading.

Implementation of optimization of core load and fuel assembly displacement trajectories requires taking into account the fuel burnup, the buildup of products of decay of fission fragments and their involvement in the nuclear reactions for each fuel assembly. Notably, the higher is the degree of details for accounting of the above phenomena, the higher the quality of the obtained results will be. Besides that, distribution of neutron flux density over the reactor core must be calculated for each of the options of FA arrangement. Thus, involvement of software complexes allowing calculating the distribution of neutron flux density over the nuclear reactor core and calculating fuel burnup is required for obtaining more or less adequate results. The fact that these software complexes must incorporate the possibility to account for the heterogeneity of the reactor core to the level of FA, is important.

TRIGEX software complex supported with CONSYST neutron data system [12] were used as the software complex for calculating the neutron flux density field and the processes of fuel burnup. The approximation where fuel burnup and accumulation of products of decay of fission fragments is performed for each type of fuel assemblies (total number of FA types is equal to seven) and not for each separate fuel assembly, is used in the accounting of fuel burnup for each separate fuel assembly during three reactor fuel irradiation campaigns. This is explained by the targeting the investigation not at the obtaining the specific result for the examined reactor type, but, instead, at the testing the efficiency of the method allowing significantly reducing the overall time expenditures for computer calculations.