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ADORE-GA: Genetic algorithm variant of the ADORE algorithm for ROP detector layout optimization in CANDU reactors

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ABSTRACT

The regional overpower protection (ROP) systems protect CANDU® reactors against overpower in the fuel that could reduce the safety margin-to-dryout. The overpower could originate from a localized power peaking within the core or a general increase in the global core power level. The design of the detector layout for ROP systems is a challenging discrete optimization problem. In recent years, two algorithms have been developed to find a quasi optimal solution to this detector layout optimization problem. Both of these algorithms utilize the simulated annealing (SA) algorithm as their optimization engine. In the present paper, an alternative optimization algorithm, namely the genetic algorithm (GA), has been implemented as the optimization engine. The implementation is done within the ADORE algorithm. Results from evaluating the effects of using various mutation rates and crossover parameters are presented in this paper. It has been demonstrated that the algorithm is sufficiently robust in producing similar quality solutions.

1. Introduction

The regional overpower protection (ROP) systems in the CANada Deuterium Uranium (CANDU®) reactor (see Fig. 1) protect the reactor against overpower in the fuel which could originate from either a localized power peaking within the core (for example, due to certain reactivity device configurations) or from a bulk power increase during a slow-loss-of-regulation (SLOR) event. The overpower could lead to fuel sheath dryout[1] which, if uncontrolled or undetected, could lead to fuel failures.

To protect the core from this fuel failure event, the CANDU 600 MW (CANDU 6) reactors are equipped with two ROP systems. Each of these systems consists of three independent safety channels and is connected to a fast-acting shutdown system. These two systems use different mechanisms to shutdown the reactor and are physically separated (see Fig. 2). More detailed descriptions of the ROP systems can be found in (Kastanya and Caxaj, 2011).

The placement of the ROP detectors in the core is a challenging discrete optimization problem. The design of the current CANDU 6 plants was determined using a method called the detector layout optimization or DLO (Pitre, 1998). Unfortunately, when the design process involves thousands of potential detectors and hundreds of flux shapes,[2] the DLO methodology does not perform well. To circumvent this issue, in recent years the DETPLASA (Kastanya and Caxaj, 2011) and ADORE (Kastanya, 2011) algorithms have been developed. Both of these new algorithms employ the simulated annealing (SA) stochastic optimization technique (Kirkpatrik et al., 1983) to come up with an optimized detector layout solution for the ROP system. It has been shown that both algorithms can produce a solution for a design problem where more than 500 flux shapes and more than 2000 candidate detectors are involved.

An alternative optimization technique, namely the genetic algorithm (GA), has been implemented within the ADORE algorithm to assess the performance of GA in solving the ROP detector layout optimization problem. For discussion within this paper, this version of ADORE will be called ADORE-GA. The GA method is chosen for this evaluation since this method has been widely used in analysis for various reactor design such as the pressurized water reactor (PWR) (Yamamoto and Hashimoto, 2002; Pereira and Lapa, 2003; Alim et al., 2009); the boiling water reactor (BWR) (Carmona et al., 2009; Kobayashi and Aiyoshi, 2001); the Canada Deuterium

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[1] Dryout is a condition where the fuel is operating at temperatures higher than the desired temperature. During a dryout event the coolant around the fuel sheath surface produces many small bubbles that could eventually coalesce into a vapor film enveloping the fuel element. This reduces the heat transfer from fuel to the coolant and in turn further elevates the fuel temperature.

[2] "Flux shapes" are various flux and power distributions caused by changes to device configuration (including zone controller fills) or xenon distribution from the nominal distribution. The term "nominal" refers to normal, operating core configuration where the average zone controller level is around 50%, the adjusters are fully inserted, and the mechanical control absorber rods as well as the shutoff rods are fully withdrawn. This configuration is defined as the nominal case since this is expected to be a representative average over the life of the reactor.

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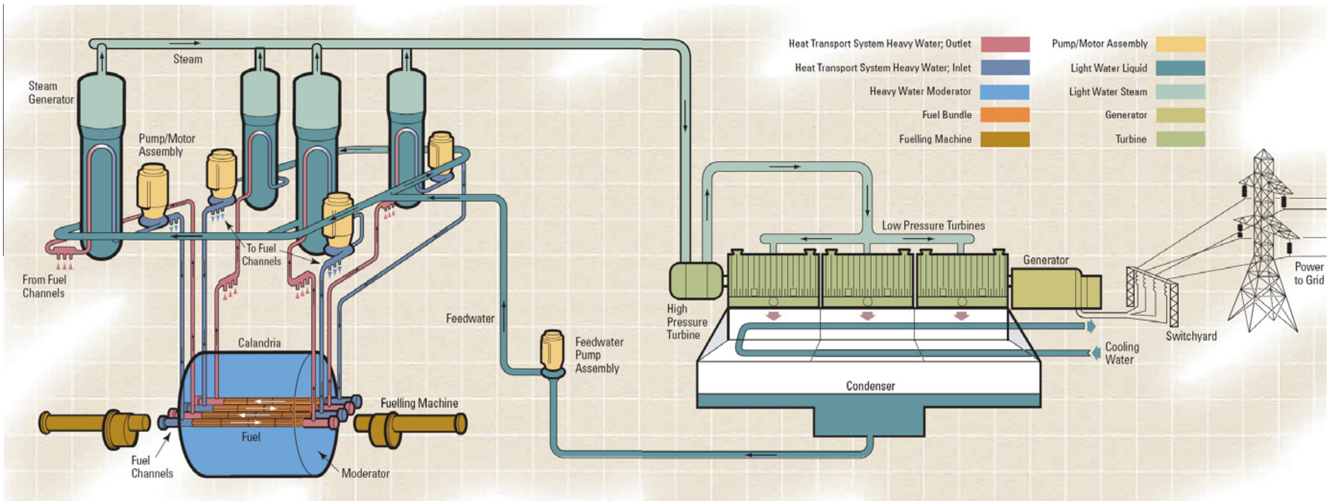

Fig. 1. CANDU station flow diagram.

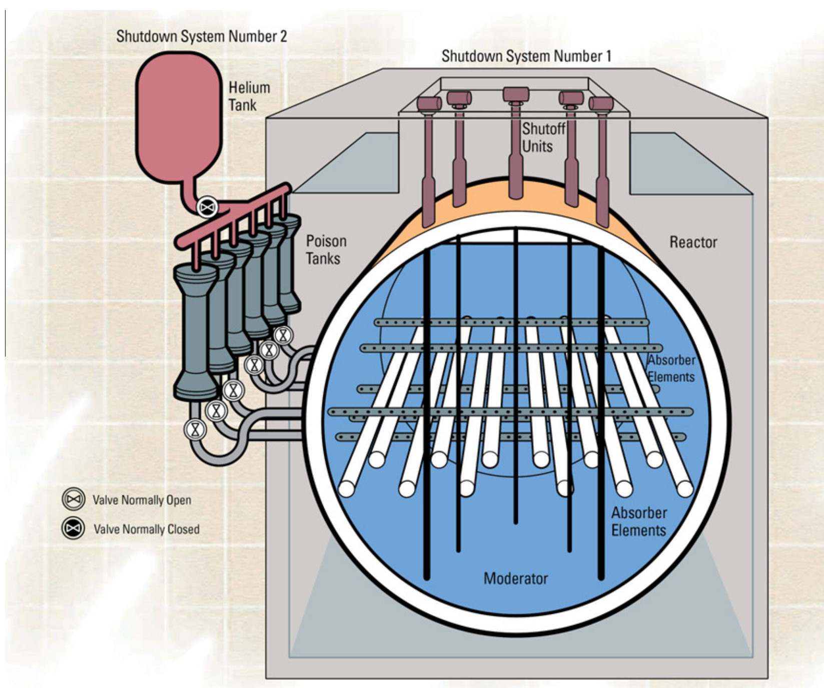

Fig. 2. CANDU 6 shutdown system.

Uranium (CANDU) (Lee et al., 2011; Huo and Xie, 2005; Do et al., 2006); VVER (Guller et al., 2004); and Liquid Metal Fast Breeder Reactor (LMFBR) (Toshinsky et al., 2000).

In executing the GA methodology, there are several optimization parameters which can be tuned to improve the performance of the algorithm. Two of them are the mutation rate in each generation and the length of the chromosome segment for two-point crossover. The effects of varying these parameters are evaluated in this paper. The following is how this paper is structured. A brief overview of the ROP trip set point (TSP) calculation using the ROVER-F code (Kastanya and Caxaj, 2010), a brief overview of the GA algorithm, and the current implementation of GA within the ADORE-GA algorithm are presented in Section 2. The methodology for quantifying the effects of varying these GA parameters is described in Section 3. Section 4 presents some numerical results from this evaluation and, finally, Section 5 closes the paper with some conclusions.

2. Methodology

2.1. ROP TSP calculations

The current safety requirement of an ROP system is that it must actuate a reactor trip before the onset of intermittent dryout (OID) in any fuel channel. It is physically prohibitive to detect the dryout of a fuel bundle among 4560 fuel bundles in a 380-channel CANDU 6 reactor. Instead of monitoring the OID directly, the ROP analyses