Genetic algorithms applied to turbine extraction optimization of a pressurized-water reactor

Wagner F. Sacco\textsuperscript{a}, Cláudio M.N.A. Pereira\textsuperscript{a,b,*}, Pius P.M. Soares\textsuperscript{a}, Roberto Schirru\textsuperscript{a}

\textsuperscript{a}Universidade Federal do Rio de Janeiro, PEN/LMP, COPPE/UFRJ, PO Box 68 513, Rio de Janeiro, 21945-970, RJ, Brazil
\textsuperscript{b}Comissão Nacional de Energia Nuclear, IEN/CNEN, PO Box 68 550, Rio de Janeiro, 21945-970, RJ, Brazil

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Abstract

In this work, we propose the use of a genetic algorithm (GA) for the determination of the optimal fraction of mass flow rate to be extracted from each stage of the turbines of a typical pressurized-water reactor (PWR) secondary side, in order to increase cycle efficiency. Here, we show some preliminary results obtained in a case study in which the PEPSE\textsuperscript{\textregistered} system was used as simulation tool.

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1. Introduction

In nuclear and fossil-power plants, an increase in thermodynamic efficiency of only 0.1% can be worth hundreds of thousand dollars per year. In the Brazilian Angra 2 PWR, for instance, this efficiency gain would mean US$ 512,460/year. (1.300 MW is generated at US$ 45/MWh). Consequently, there is a continued quest for higher efficiencies in thermal power plants, which has resulted in some innovative modifications to the basic steam-power cycle [1]. Among these, there is the regenerative

* Corresponding author. Fax: +55-21-25604113x2146.
\textit{E-mail address:} cmnap@ien.gov.br (C.M.N.A. Pereira).

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cycle, where the temperature of the feedwater is raised from that on leaving the condenser to the final feedwater temperature using steam extracted from various stages of the turbines. The determination of the optimal fraction of mass flow rate to be extracted from each stage of the turbines is a complex optimization problem. In this study, this problem has been solved by means of an evolutionary computation technique called genetic algorithm (GA) [2,3], which is a powerful global optimization technique inspired in the principles of evolution and natural selection. Such algorithms have been successfully used in many complex optimization problems found in nuclear-reactor physics and engineering, such as the nuclear reactor reload [4] and design [5] problems; maintenance [6] and surveillance [7] policy optimization; and transient identification systems design [8]. The use of GAs in cycle efficiency optimization by finding an optimal combination of turbine extractions is introduced in this article.

2. Problem description

An examination of the Rankine cycle reveals that heat is added to the working fluid during isentropic compression in a pump, at a relatively low temperature. This lowers the average temperature at which heat is added and thus the cycle efficiency. To remedy this shortcoming, there would be ways to raise the temperature of the feedwater before it enters the boiler. One such possibility would be to compress the feedwater isentropically to a high temperature. This, however, would involve extremely high pressure and is therefore impractical.

Another possibility is to transfer heat to the feedwater from the expanding steam in a counterflow heat-exchanger built into the turbine, that is, to use regeneration. This solution is also impractical because it is difficult to design such a heat exchanger and because it would increase the moisture content of the steam at the final stages of the turbine.

A practical regeneration process is accomplished by extracting, or “bleeding”, steam from the turbine at various points. This steam, which could have produced more work by expanding further in the turbine, is used to heat the feedwater instead. The device where the feedwater is heated by regeneration, is called a regenerator, or a feedwater heater. Regeneration not only improves cycle efficiency, but also provides a convenient means of deaerating the feedwater (removing the air that leaks in at the condenser) to prevent corrosion in the boiler [9].

As mentioned above, in the regenerative cycle, a fraction of the steam that could have been used to produce work in the turbine is used to heat the feedwater instead. There is a gain of efficiency by one side, there is loss by the other. So, a question arises: how much steam should be extracted from each turbine in order to achieve an optimal heat efficiency? As in thermal power plants, there are trains of turbines (high pressure and low pressure), the more the heat is extracted from one turbine, less energy is available for the subsequent turbines. It is a difficult task to achieve an optimal set of extractions from the turbines.
This is how genetic algorithms came about. They have been used to solve problems as complex as the above mentioned one. There is, therefore, a great potential to apply this technique to optimize the extraction of steam from the turbines in order to increase the cycle thermal efficiency.

3. The optimization system

The system used to find the optimal combination of turbine extractions consists of the PWR secondary side simulator, the genetic algorithm and an interface so that both can communicate.

To simulate a PWR secondary side, we employed PEPSE®, which is a modeling tool used to perform integrated heat balances for power plants. It permits the modeling of fossil-fired plants, BWR or PWR nuclear plants, cogeneration plants and combined cycles. PEPSE® has been widely employed by the thermal plant community for more than 20 years. The optimization tool is the genetic algorithm, which is a searching method based upon the biological principles of natural selection and survival of the fittest individuals. They were rigorously introduced by Holland [10]. GAs consist of the evolution of a population of individuals that are candidates to the problem solution. Each individual receives a reward, known as the fitness, that quantifies its suitability to solve the problem. Individuals with better than average fitness receive greater opportunities to survive and recombine generating offspring (new solution candidates). On the other hand, low fitness individuals will have less chance to reproduce until they are extinguished. Consequently, the good features of the best individuals are disseminated over the generations. In other words, the most promising areas of the search space are explored, making the GA converge to the optimal or near optimal solution.

As GAs are black-box methods that use fitness information exclusively, not requiring any internal knowledge of the problem, they are the ideal means of solving our problem.

We have used the GENESIS [11] package, one of the most GA disseminated in the Artificial Intelligence community. The chromosome is formed by the values of extraction from each turbine encoded into binary strings of 60 bits and these values are limited in range, so that operational values are not violated. The fitness to be maximized is quite simple, being the thermal efficiency itself.

4. Method application

To test the effectiveness of our system, we modeled a typical PWR secondary side, consisting of a high pressure train with two stages, a low-pressure train with six stages, reheat and regeneration. Fig. 1 shows the PEPSE model of this secondary with the description of the symbols and main components. The connectors are used to simplify the diagram layout. The extractions were allowed to change about 10% over the original design value.
To prevent biased results, we executed the system with 10 different GA seeds. The GA parameters were set up to values within their typical ranges [2]. It is interesting to mention that, with the genetic coding we adopted, there are $1.1529 \times 10^{18}$ possible solutions, and it would take more than 30 billion years to evaluate all these possibilities using the computer that we used in this study.
The GA could quickly evolve solution candidates until an efficiency of 35.12% is reached (i.e. about the 8th generation). From this point on, the evolution slowed down, and, finally, after 50 generations it has reached the mark of 35.13%. For terms of comparison, according to the Babcock & Wilcox Company [9], a typical PWR cycle efficiency ranges from 34.0 to 34.5%. The original efficiency of the plant used here, which is a PEPSE® add-in, is 34.93%. Hence the gain in efficiency is 0.2%, representing an earning of about US$1,000,000/year.

5. Conclusion

In this paper, we have introduced the application of genetic algorithms in the solution of an important optimization problem, commonly found in thermal power installations.

Our tests reveal the robustness and efficacy of the proposed GA in finding an optimal combination of turbine extractions that maximizes the thermal efficiency in a typical PWR. The case study has shown that such an application is quite promising, giving a means to possible changes in existing plants turbine extractions (within allowed variation ranges) or to its optimal design of new plants, both considering the objectives of finding the best thermal efficiency and, consequently, reducing the costs of energy generation.

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