Applying the Computational Intelligence Paradigm to Nuclear Power Plant Operation:
A Review (1990-2015)

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ABSTRACT

In the guise of artificial neural networks (ANNs), genetic/evolutionary computation algorithms (GAs/ECAs), fuzzy logic (FL) inference systems (FLIS) and their variants as well as combinations, the computational intelligence (CI) paradigm has been applied to nuclear energy (NE) since the late 1980s as a set of efficient and accurate, non-parametric, robust-to-noise as well as to-missing-information, non-invasive on-line tools for monitoring, predicting and overall controlling nuclear (power) plant (N(P)P) operation. Since then, the resulting CI-based implementations have afforded increasingly reliable as well as robust performance, demonstrating their potential as either stand-alone tools, or - whenever more advantageous - combined with each other as well as with traditional signal processing techniques. The present review is focused upon the application of CI methodologies to the - generally acknowledged as - key-issues of N(P)P operation, namely: control, diagnostics and fault detection, monitoring, N(P)P operations, proliferation and resistance applications, sensor and component reliability, spectroscopy, fusion supporting operations, as these have been reported in the relevant primary literature for the period 1990-2015. At one end, 1990 constitutes the beginning of the actual implementation of innovative, and – at the same time – robust as well as practical, directly implementable in H/W, CI-based solutions/tools which have proved to be significantly superior to the traditional as well as the artificial-intelligence-(AI)derived methodologies in terms of operation efficiency as well as robustness-to-noise and/or otherwise distorted/missing information. At the other end, 2015 marks a paradigm shift in terms of the emergent (and, swiftly, ubiquitous) use of deep neural networks (DNNs) over existing ANN architectures and FL problem representations, thus dovetailing the increasing requirements of the era of complex - as well as Big - Data and forever changing the means of ANN/neuro-fuzzy construction and application/performance. By exposing the prevalent CI-based tools for each key-issue of N(P)P operation, overall as well as over time for the given 1990-2015 period, the applicability and optimal use of CI tools to NE problems is revealed, thus providing the necessary know-how concerning crucial decisions that need to be made for the increasingly efficient as well as safe exploitation of NE.

1. INTRODUCTION

Nuclear energy (NE, Weinberg, 1994) amounts to the energy that is required in order for an atom to retain its stability, i.e. for the protons and neutrons that comprise the nucleus of the atom to remain bound to each other. NE is released when

(1) the nucleus of an atom is split into smaller nuclei (nuclear fission, NFi),
(2) the nuclei of two or more atoms are integrated into a larger nucleus (nuclear fusion, NFu),

where, in both cases, the released neutrons of the nuclei of the atom(s) involved in the process are vital not only for producing NE, but also for sustaining the chain reaction. In a nutshell:

(1) the difference in mass (and, thus, energy) between the original and resulting nuclei causes the release of significant amounts of NE (especially when compared to the size of the interacting elements), which - following collection and conversion - can be used for turning turbines, and consequently driving generators to produce electricity [1];
(2) the neutrons released from these nuclei sustain the NFi/NFu phenomena.

The practical exploitation of NE has become of particular interest since the last century[2], with - to date - NFi constituting the main means of energy production. The last 20 years have further brought about a shift in nuclear (power) plant (N(P)P) construction and operation, with the focus moving away from building new and towards maintaining existing N(P)Ps. Consequently, special emphasis has been placed upon the need for (i) comprehensive plant life management (PLiM) and (ii) cost-effective as well as reliable instrumentation & control (I&C), both of which are crucial not only for avoiding a forced shut-down due to unavailability, but also for maintaining optimal functionality of the ageing N(P)Ps.

Control, diagnostics and fault detection, monitoring, N(P)P operations, proliferation and resistance applications, sensor and component reliability, spectroscopy and – finally - fusion supporting operations have been established as key-issues of safe, maximally efficient real-time adjustable N(P)P operation (Ma & Jiang, 2011). Complementary to the traditional signal and image/sound processing techniques that have been applied to these key-issues, the computational intelligence (CI) (Pedrycz, 1997) paradigm - which was put forward in the early 1990s as a set of computationally effective, adaptive, resistant-to-noise as well as to missing and/or partly erroneous information - has provided alternative on-line/real-time, robust, non-invasive methodologies for monitoring, controlling and predicting N(P)P operation. For the last 25 years, the resulting CI-based implementations and applications have afforded prompt, reliable as well as robust response to these key-issues, thus demonstrating the potential of CI either as a superior stand-alone tool, or - whenever advantageous - in combination with traditional signal and/or image processing/analysis techniques.

The present review communicates the application of CI methodologies to the aforementioned N(P)P key-issues, as reported in the relevant primary literature of the major publication and dissemination media (listed in alphabetical order):

(1) Annals of Nuclear Energy (ANE), published by Elsevier,
(2) Fusion Science and Technology (FST), Nuclear Science & Engineering (NSE) and Nuclear Technology (NT), all three published by the American Nuclear Society (ANS), and
(3) Progress in Nuclear Energy (PNE), also published by Elsevier

journals for the period 1990-2015. A crucial decision has been made not to extend the present review beyond 2015 as the transition from 2015 to 2016 brought about an important paradigm shift

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