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Conceptual design of cogeneration plants under a resilient design perspective: Resilience metrics and case study

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HIGHLIGHTS

- Resilience of cogeneration plant conceptual design is analyzed through complex network theory.
- A novel resilient design framework based on Monte Carlo simulations is developed.
- New metrics of resilience are proposed based on the resilient design framework.
- Results from the framework are more consistent than those from complex network theory.

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ABSTRACT

The conceptual design phase is the first step in the design process of an engineering system. Most engineering systems, including cogeneration plants, may and likely will experience some malfunctions during its life cycle. The metrics typically considered in the conceptual design phase (and for analysis and optimization) of energy systems are cost, efficiency and environmental impacts. Quite rarely are operational considerations about malfunctions integrated during the conceptual design phase. Resilient design, or design for resilience, addresses this gap as illustrated here in the area of energy conversion and conservation of energy processes by examining the conceptual design of a cogeneration plant. Resilient design is a relatively new research field where the engineering system is designed such that it can optimally recover from failures. The main challenge is to quantify the resilience in early design phases, since there is not much detailed information about system components available at this point. To address these challenges, this paper introduces a novel resilient design framework that uses new metrics within a Monte Carlo-based assessment approach. The framework is exercised on conceptual designs of cogeneration plants. Results from this framework are compared against those from a methodology based on complex networks theory that has been previously suggested in the literature. The former presented more consistent results than the latter and we discuss the differences. Results also show that the concept with higher efficiency was not the one with higher resilience. Finally, we discuss how to integrate specific failure probabilities information into the framework (should that information be available), and deliberate on relations between resilience, fault handling strategies and design requirements.

1. Introduction

Cogeneration is one of the most attractive alternatives realization of power plants that promote the rational use of energy resources. A cogeneration plant simultaneously generates power and useful heat from the same fuel and can be seen as a thermal system, i.e., a collection of components with interrelated performance on which fluids, heat and work are transported and converted. Gas turbines and reciprocating internal combustion engines are the most used prime movers in natural gas-fired cogeneration plants. Fuel cells fed by hydrogen obtained from natural gas reforming are state-of-the-art technologies for cogeneration, but they are still not enough mature to be commercially competitive [1].

Design teams of cogeneration plants often seek a conceptual solution for high efficiency, low capital cost and low emissions, as reported in [2–5]. However, a fault-tolerance analysis is rarely carried out during conceptual design because detailed knowledge of system components and their performance criteria are not yet available [6],

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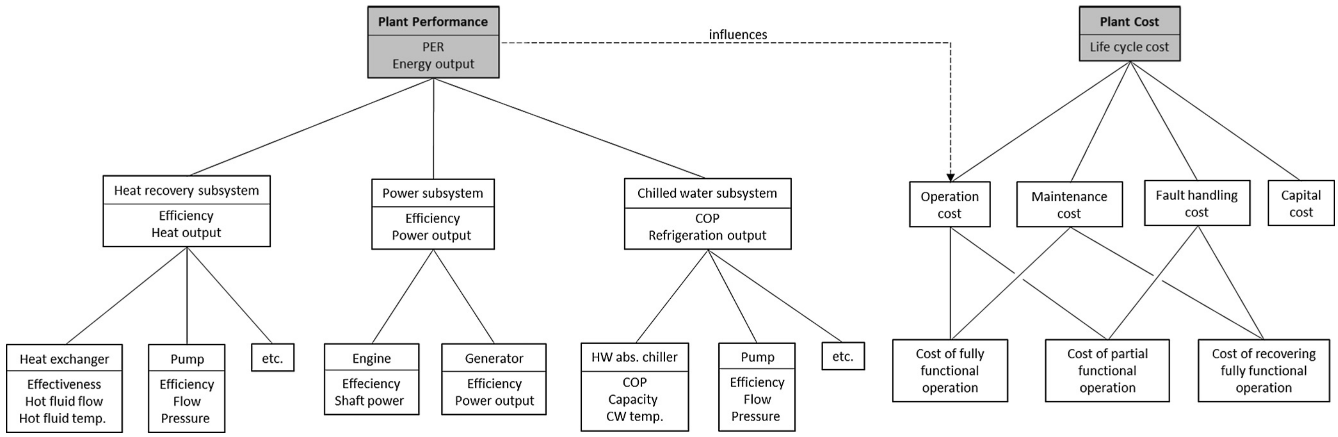

Fig. 1. Requirements flow-down.

(notwithstanding the recently proposed methodology for optimization of component reliability of heat supply system [7]). In particular, having accurate failure rates or failure probabilities depends on large amount of historic operational data for all the components, information often difficult to obtain when fleet sizes are small or where no sufficiently long operational history exists. Since fault-tolerance analysis is rarely carried out during the early design phases, resilient design - or design for resilience – covers this gap for system related to energy conversion and conservation of energy processes, including for the conceptual design of energy systems. Resilient design is a relatively new research field where the engineering system is designed such that it can maintain maximally operational states despite the presence of failures. A key aspect is the ability to quantify system resilience in order to support the design team during the conceptual design stage. However, available engineering quantification metrics still exhibit very little standardization and agreement on a general quantifiable measure remains a challenge [8].

There are several definitions of resilience found in the literature. For the purposes of this work, the one presented by Heimes [9] fits best: resilience is the ability of the system i) to withstand a major disruption within acceptable degradation parameters and ii) to recover within an acceptable time and composite costs and risks. The second part of Heimes' resilience definition is closely related to fault handling strategies. It should be noted that integrating specific fault handling strategies during the conceptual design is outside the scope of the present work. We focus here on the assessment of resilience and only discuss the main aspects of fault handling strategies during design phase.

A number of intelligent computational tools for cogeneration plant design including knowledge-based tools [10–14] are found in the literature. Methods based on linear and non-linear programming that support thermal systems design and analysis are well established [15–18]. The goal of the conceptual design of any mechanical system is to generate several alternatives that are able to meet the design requirements [19], which is a very product-oriented point of view. For complex engineering systems, such as cogeneration plants, design requirements should be specified in a verifiable and hierarchical way known as requirements flow-down. Requirements flow-down is a best practice that helps engineers maintain clarity and structure while they perform decomposition of high level system requirements into functional, physical and component design requirements [20].

A simplified requirements flow-down for natural-gas fueled cogeneration plants is shown in Fig. 1. High level requirements pertain to performance and cost. That is, the cogeneration plant should meet energy demands with high efficiency[1] and low cost. The plant performance requirement is split into subsystems performance requirements and each subsystem requirement is split into individual component performance requirements. In a similar way, cost requirement is split into operation cost, maintenance cost and fault handling cost. Depending on how detailed the flow-down should be, each of these lower level requirements can be split into further lower levels. Organizing the requirements as a flow-down diagram can help in understanding the role of some requirements for plant resilience and even lead to establishing new metrics for resilience.

Willis and Loa [22] present several metrics for resilience of energy systems used that can apply to different levels of the requirements flow-down diagram. As a result, some of these metrics have a more global viewpoint, such as knowing how resilience affects economic output stemming from hypothetical disasters that compromise the energy infrastructure of a region, for example. For a local cogeneration plant it may be more important to know how many spare parts are in stock and what options exist for backup power generation [22].

Besides these more management-oriented metrics, resilience can also refer to formal mathematical parameters that quantify the system ability to withstand disruption and its capability to function as required. Providing metrics for resilience has been one of the major research thrusts in computer networks over the last decades. The study of network topology from this area brings some interesting insights into the design of complex engineering systems, as shown by Mehrpouyan et al. [6]. Although resilience has been explored in several engineering domains [23–28], resilient design of energy systems, such as cogenerations plants, is still a somewhat open domain. To address this need, this paper approached the conceptual design of natural gas-fueled cogeneration plants from a resilient design perspective. To do so, we develop an original resilient design framework based on a Monte Carlo approach, from which we propose new metrics to assess the resilience of four different cogeneration plants during the conceptual design phase. The plant designs are generated from an available knowledge-based system. Results obtained from the framework are compared to those obtained from an analytical methodology adapted from complex networks analysis found in the literature. The relationship between resilience and plant requirements is also discussed, as well as integrating more specific failure probability information that might be available, limitations and further development of this research.

2. Methodology

2.1. Concepts generation

Four different cogeneration plant concepts are generated for the present resilience analysis. The concepts are provided by a previously developed knowledge-based system (KBS) [13]. The KBS infers new

[1] In this work, plant efficiency is expressed as Primary Energy Rate (PER), a proper parameter to quantify efficiency of combined power and refrigeration systems [21].