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Parameter Identifiability of Boolean Networks with Application to Fault Diagnosis of Nuclear Plants

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Abstract: Fault diagnosis depends critically on the selection of sensors to monitor crucial process variables. A Boolean network (BN) is composed of nodes and directed edges, in which the node state is quantized to the Boolean values of True or False, and is determined by the logical functions of the network parameters and the states of other nodes with edges directed to this node. Since a BN can describe the fault propagation in a sensor network, it can be applied to propose a sensor selection strategy for fault diagnosis. In this paper, a sufficient condition for parameter identifiability of BN is first proposed, based on which the sufficient condition for fault identifiability of a sensor network is given. Then, the fault identifiability condition induces a sensor selection strategy for sensor selection. Finally, the theoretical result is applied to fault diagnosis oriented sensor selection for a nuclear heating reactor (NHR) plant, and both the numerical computation and simulation results verify the feasibility of the newly-built BN-based sensor selection strategy.

Keywords: Fault diagnosis, Boolean network, parameter Identifiability, nuclear heating reactor

1 Introduction

The function of process fault diagnosis is to observe the fault symptoms and identify which fault is the root cause. The efficiency of fault diagnosis depends critically on the selection of sensors to monitor the crucial process variables. There are hundreds of process variables available for measurement in a nuclear plant, and sensor selection for efficient fault diagnosis is an important problem. Since fault propagation in a process system, i.e. the cause-effect behavior, can be qualitatively described by a directed graph (DG), the sensor selection problem has usually been converted to different DG-based optimization problems. In [1-4], sensor selection strategies are given as the solutions of mixed integer linear programming (MILP) problems focusing on optimizing cost or (and) reliability. In [5], the criteria of robustness was added to the MILP problems. In [6, 7], genetic algorithms (GAs) were proposed to solve the optimization problems for sensor selection. The MILP-based approach was applied to sensor selection for fault diagnosis problems of nuclear plant equipment, such as the integral pressurized water reactor (iPWR) and helical-coil once-through steam generator (OTSG) [8, 9]. Moreover, sensor selection has usually served as a basis for developing more advanced fault detection and diagnosis methods for complex process systems [10-12].

The Boolean network (BN) is a network with nodes and directed edges, in which the state of a node is quantized to the values of True or False, and is determined through logical rules by the logical parameters and the states of other nodes with edges directed to this node. It is can be seen that a BN is a coupling of a DG and a set of logical rules or functions defined regarding the logical states of BN nodes, which means that the BN can be applied to describe the fault propagation in a sensor network. In the late 1960s, Kauffman first introduced the BN for modeling and analyzing cellular regulation phenomenon in the field of theoretic biology [13]. It has been proved that the BN can be a proper tool to describe cellular networks [14]. The study of BN from a viewpoint of systems and control begun around 2010. Cheng and Qi gave the state-space model of BN on its linear representation, and then revealed certain features such as fix points, cycles and controllability [15-18]. Therefore, applying BN to solve the problem of sensor selection for fault diagnosis may yield a more advanced and efficient method.

In this paper, the nodes in a sensor network are regarded as the nodes of a BN, the faults are regarded as parameters

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