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Systemic health evaluation of RF generators using Gaussian mixture models

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ABSTRACT

We propose an application of specific machine learning techniques capable of evaluating systemic health of a Radio Frequency (RF) power generator. System signatures or *fingerprints* are collected from multivariate time-series data samples of sensor values under typical operational loads. These fingerprints are transformed into feature vectors using standard scaling/translation methods and the Fast Fourier Transform (FFT). The number of features per fingerprint are reduced by banding neighboring features and Principal Component Analysis (PCA). The reduced feature vectors are used with the Expectation Maximization (EM) algorithm to learn parameters for a Gaussian Mixture Model (GMM) to represent normal operation. One-class classification of normal fingerprints is achieved by thresholding the likelihood of a fingerprint feature vectors. Fingerprints were collected from normal operational conditions and seeded *non-normal* conditions. Preprocessing methods and algorithmic parameters have been selected using an iterative grid search. Average robust true positive rate achieved was 94.76% and best specificity reported is 86.56%.

1. Introduction

Modern thin film processing of semiconductor integrated circuits is highly dependent upon reliable and accurate RF (Radio Frequency) power delivery to a plasma source. The RF power controls critical plasma properties, such as an Ion Energy Distribution Function [1], that determine the achievable reaction rate, etch selectivity, and material properties of an etched or deposited film. The operating cost of a state-of-the-art semiconductor fabrication facility dominates the cost of producing the integrated circuit final product. Hence, unscheduled downtime of an RF subsystem can easily exceed the capital equipment cost of the RF system itself. In addition, a significant percentage of RF power generator field returns are classified as “No Trouble Found”, indicating that more accurate diagnosis of these complex systems in the field is needed to reduce the total cost of ownership. Recently, machine learning has been a focus for exploring new diagnosis methods.

In machine learning, the basic assumption is to have a training dataset which adequately represents the parameter/feature space of the system. The RF power generator is a fairly complex system and with such a complex system it may be not practical to collect or artificially seed every possible operational condition. Thus, manufacturers may opt out to seed faults in these complex systems due to difficulty of reproduction and/or cost. Researchers have realized the challenges

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of obtaining data from all operational conditions and suggest a paradigm shift to learn only the normal operational behavior of a system rather than trying to differentiate the non-normal operation from normal. Our proposed method is congruent with learning only the normal operational conditions by using one-class classification and mixture models. This work is an extension to the work presented by Bowen et al. [2] where different preprocessing techniques and experimental data collection and analysis have been explored.

In the next section, we explore the literature in terms of fault detection and previous work in fault detection in RF generators and we present the internal workings of the RF power generators in question. In Section 3, we present our proposed Health Evaluation System to identify faults in RF generators using Gaussian mixtures and a one-class classifier. In this section, we present our processing techniques of raw data collected from RF power generators, feature extraction/creation methods applied to preprocessed generator data, and feature reduction techniques explored. Finally, we present our one-class classifier based on Gaussian mixtures. The performance results of our one-class classifier are presented in Section 4 with some parameter exploration to optimize the one-class classifier for RF power generators. Finally, The conclusion of our work is presented in Section 5.

2. Literature review

In this section, relevant work is presented from a review of current literature. The topics of the related work are focused towards methods that have been applied to fault detection, classification, and health monitoring of systems. Special attention has been placed on fault detection for manufacturing tools such as RF generators in the semiconductor industry.

2.1. Fault detection and health monitoring in industry

Statistical Process Control (SPC) has been conventionally used for detection of out-of-control processes. Current research has extended the use of SPC for fault classification [3]. However, improved fault classification has been suggested by using machine learning techniques. Machine learning has been applied to the detection of faults in semiconductor etch processes [4–7]. The various machine learning methods explored have included Support Vector Machines (SVM) [4], Modular Neural Networks (MNN) [5], Gaussian Mixture Models (GMM) [7], k-NN [6], and Bayesian inference [7]. These methods have focused on primarily on fault detection and classification, which is a subset of a larger problem of health monitoring and analysis of complex systems.

There are a number online health monitoring systems that have been recently published that have used novelty detection techniques [8–13]. Of the these monitoring systems it is seen that they span a range of methodologies including Discrete Wavelet Transforms (DWT) [8], Bayesian networks [9], Mahalanobis distance utilization [10,11], and kernel based algorithms such as SVMs [12]. The kernel based algorithms have shown high classification accuracy but due to the time and memory complexities of these methods they are rarely used in an online manner. However, recently online formulations of SVD have lead to a number of publications with online kernel based model prediction [12,13].

Most of the health monitoring systems are designed with a specific system in mind. A general approach to the problem has been proposed by Filev et al. [14] as a Novelty Detection Framework (NDF). The NDF is capable of updating a decision model continually and autonomously using unsupervised learning methods. The outcome of the NDF is a generic and effective monitoring system capable of detecting novel and/or abnormal equipment conditions prior to the actual event. The NDF uses a Greedy EM for learning model parameters. The standard approach to learning parameters to mixture models is the Expectation Maximization (EM) algorithm. However, some of the well known caveats of the EM algorithm are its sensitivity to initialization and assumption that the number of components within the mixture is known. Numerous well established model selection criteria have been developed to choose the number of components for a mixture model [15]. In lieu of well established model selection criterion, other extensions to the EM algorithm have been proposed. The most common extension is to incorporate greedy search techniques, where Verbeek et al. and Vlassis et al. have provided such greedy approaches to EM [16,17]. The NDF, EM, and other soft-computing techniques have shown promise for application to health evaluation of RF power generators. The next subsection explores our previous work regarding fault detection and classification for a set of RF power generators.

2.2. Prior work on fault detection in RF generators

In collaboration with MKS ENI Products, work has been completed toward developing an in-vivo solution to fault detection for RF power generators. Previous work has been done with SVM and Radial Basis Function Networks (RBFN) [18,19]. Exploration into variable elimination and classification of RF generator data was conducted in [18]. A modified version of NDF and GMM has been applied to offline RF generator data [19]. Preliminary work by Chandrashekar et al. has been implemented in MATLAB and LabVIEW and simulated online classification has showed promising results [19]. Based on literature in fault detection, analysis in semiconductor process, and our previous work with RF generators, we believe there is need for methods that are more accurate than standard statistical controls. However, these new methods must not increase complexity such that an online application is not feasible for real-time monitoring. Therefore, we present extended work with GMMs, where the next section introduces our experimental setup before we present our proposed approach.