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Modeling and recognition of smart grid faults by a combined approach of dissimilarity learning and one-class classification

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ABSTRACT

Detecting faults in electrical power grids is of paramount importance, both from the electricity operator and consumer point of view. Modern electric power grids (smart grids) are equipped with smart sensors that allow to gather real-time information regarding the physical status of all components belonging to the whole infrastructure (e.g., cables and related insulation, transformers, and breakers). In real-world smart grid systems, usually, additional information that are related to the operational status of the grid are collected, such as meteorological information. Designing an efficient recognition model to discriminate faults in real-world smart grid system is hence a challenging task. This follows from the heterogeneity of the information that actually determine a typical fault condition. In this paper, we deal with the problem of modeling and recognizing faults in a real-world smart grid system, which supplies the entire city of Rome, Italy. Recognition of faults is addressed by following a combined approach of dissimilarity measures learning and one-class classification techniques. We provide here an in-depth study related to the available data and to the models based on the proposed one-class classification approach. Furthermore, we perform a comprehensive analysis of the fault recognition results by exploiting a fuzzy set based decision rule.

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1. Introduction

There are many possible definitions for a Smart Grid (SG). The SG European Technology Platform defines [4] a SG as an “electricity network that can intelligently integrate the actions of all the connected users, generators, consumers and those that do both, in order to efficiently deliver sustainable economic and secure electricity supply.” A SG employs innovative products and services together with intelligent monitoring, control, communication, and self-healing technologies in order to (i) facilitate the connection and operation of generators of all sizes and technologies; (ii) allow consumers to play an active role in optimizing the operation of the system; (iii) significantly reduce the environmental impact of the whole electricity supply system; (iv) preserve or improve the level of system reliability, quality of service, and security. SGs can be considered as an “evolution” rather than a “revolution” of the existing energy networks [3]. This evolution is leaded by the symbiotic exchange between power grid technologies and the Information and Communication Technologies (ICT). ICT provide instruments, such as *Smart Sensors* (SS), to monitor the network status, wired and wireless communication network to collect and transport data, and powerful computational architectures for data processing. A SG can be considered as a complex non-linear and time-varying system [9,20,35,39,41,66], where heterogeneous elements, including exogenous factors, are highly interconnected through the exchange of both energy and information. Computational Intelligence (CI) techniques offer sound modeling and algorithmic solutions in the SG context [7,67,71]. Well-known CI techniques adopted in the SG context include approximate dynamic programming [10], neural networks and fuzzy inference systems for prediction and control [11,43], as well as swarm intelligence and evolutionary computation for optimization problems [6,16,52,54,61].

An important key issue of SGs is the design of a Decision Support System (DSS), which is an expert system that provides decision support for the commanding and dispatching systems of the power grid. Such a system analyzes the risk for damage of crucial equipments, assesses the power grid security, forecasts and provides warnings about the magnitude and location of possible faults, and timely broadcasts the early-warning signals through suitable communication networks [41]. The information provided by the DSS can be used for Condition Based Maintenance (CBM) in

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the power grid [53]. CBM is defined as “a philosophy that posits repair or replacement decisions on the current or future condition of assets”. The objective of CBM is thus to minimize the total cost of inspection and repair by collecting and interpreting (heterogeneous) data related to the operating condition of critical components. Through the use of CBM, advanced SS technology has the potential to help utilities to improve the power grid reliability by avoiding unexpected outages. A discussion on how the changes in modern power grids have affected the maintenance procedures can be found in [72]; the importance of modern diagnostic techniques is treated in [62].

Collecting heterogeneous measurements in modern SG systems is of paramount importance. For instance, the available measurements can be used to deal with various important pattern recognition and data mining problems on SGs, such as fault recognition [8,56,74]. On the basis of the data at hand, different problem types could be formulated. In [23] the authors have established a relationship between environmental features and fault causes. A fault cause classifier based on the linear discriminant analysis (LDA) is proposed in [15]. Information regarding weather conditions, longitude-latitude information, and measurements of physical quantities (e.g., currents and voltages) related to the power grid have been taken into account. In [73], the authors proposed a system based on LDA, which processes phasor measurement unit data, with the aim of recognizing and locating faults on power lines. As concerns fault diagnosis in power grids, in [70] is proposed a Support Vector Machine (SVM) based method to perform the recognition of faults related to high-voltage transmission lines. The One-Class Quarter-Sphere SVM algorithm is proposed [59] for faults classification in the power grid. The reported experimental evaluation is however performed on synthetically generated data only.

ACEA is the electricity distribution company managing the electrical network feeding the entire city of Rome. In this paper, we extend our previous work [17] on the problem of modeling and recognizing faults in the real-world SG system of ACEA by introducing several improvements. Initially, we introduce the application's context and the approach followed to implement the One-Class classification system used to recognize conditions of fault. Since the available ACEA data is highly structured (i.e., it is formed by several heterogeneous information), we designed a dedicated One-Class Classifier (OCC) that is suitable for the specific application at hand. The first herein presented improvement consists in equipping the designed OCC with the capability of producing also *soft* output decisions. This is implemented by interpreting the decision regions synthesized by the classifier as fuzzy sets with suitable membership functions [37,38,49]. This fact allows us to provide also a measure of reliability concerning the already implemented hard (Boolean) classification mechanism. As concerns the experiments, we provide (i) a comparison on some well-known UCI datasets [12] with other state of the art OCCs, (ii) several evaluations of the recognition system on ACEA datasets and finally (iii) a more in depth analysis of the informativeness of the solutions found by the proposed OCC on the ACEA data.

The paper is structured as follows. We provide a review of the one-class classification setting in Section 2. In Section 3 a short review of the project is given. The proposed frame work also provides the justification for some design choices concerning the adopted OCC approach. In Section 4, we describe the technical details of the considered SG. Section 5 introduces the fault recognition system that we designed for the specific application at hand. In this section, we describe (i) the representation of a fault pattern and (ii) the computational system as a whole, highlighting also the new contributions introduced here in this paper. In Section 6 we discuss the experiments. Finally, in Section 7 we draw our conclusions.

2. Brief overview of the one-class classification problem

The one-class classification problem can be considered as a particular instance of a standard n-class classification problem, where only patterns belonging to a specific class are available during the training. Such patterns are usually termed *target* or *positive* patterns. This particular scenario covers several interesting real-world situations [17,19,22,29,31,48,65]. Practically, OCCs define a decision rule on the basis of a model that describes suitable boundaries pertaining the target patterns. Such boundaries define the decision regions/surfaces of the classifier. The aim is to synthesize effective models such that target patterns are recognized while non-target patterns are rejected.

Khan and Madden [31] and Pimentel et al. [51] provided recent surveys on the subject of One-Class classification. One important class of OCCs has been derived from the well-known SVM [58,63,69]. Tax and Duin [63] defined well-known system called Support Vector Data Description (SVDD). The classification model is defined in terms of hyper-spheres, which are placed over the training set through an SVM-like optimization problem (the minimization of the sphere radii is enforced). SVDD can be extended to different input domains by defining suitable positive definite kernel functions.

Schölkopf et al. [58] proposed an alternative approach to SVDD that employs a hyperplane similar to that of the conventional SVM case. The hyperplane is constructed to separate the region of the input space containing (target) patterns from the region containing no data. This approach also has the capability of using kernel functions. Other more recent approaches include algorithms based on the minimum spanning tree [28], Gaussian processes [30], and fuzzy sets [24].

3. An overview of the ACEA Smart Grid Project

This study represents a branch of a larger project, namely “ACEA Smart Grid Pilot Project” [1]. The project objective is to develop an automated recognition tool of fault states in the ACEA power grid. In addition, the tool is designed to offer also diagnostic features, allowing the characterization of the power grid status during fault events. The process flow diagram depicted in Fig. 1 shows the overall system and how raw data coming from the Smart Sensors are transformed into meaningful information in order to support business strategies. As related to the on-field functioning, the whole recognition system collects heterogeneous data forming the state of the SG, taking measurements of the considered features on Medium Voltage (MV) backbones of the power grid and queries the diagnostic system about the condition of the collected samples. To obtain the dataset, a preliminary preprocessing stage has been performed with the help of ACEA experts. The dataset is then used as input for the herein presented OCC, which employs an evolutionary strategy to learn typical situations of faults. Clustering techniques are used to define the model of the proposed OCC. The synthesized partition is used also for post-processing purposes, such as data analysis and visualization. Those last two post-processing stages are not discussed in this paper. The one-class classification approach is usually adopted when patterns of a given class are very rare or very expensive to be obtained, as it is the case in the design of a diagnostic system where faulty patterns are only a few, or difficult to obtain. In this case, the OCC is usually trained on “normal working condition” patterns. However, the collection of all faults recorded on the given energy grid in a defined time interval is available together with a sub-sampling of the “normal working condition” patterns. The number of fault patterns is adequate enough, although considerably lower than the set of all the possible non-fault

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