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An enhanced singleton type-2 fuzzy logic system for fault classification in a railroad switch machine

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ABSTRACT

A switch machine is an electromechanical device that allows railway trains to be guided from one track to another. Among all possible faults that can occur in a switch machine, the three mains ones are: lack of lubrication, lack of adjustment and malfunction of a component. Aiming to classify these faults, an important contribution of this work is to address the height type-reduction and to propose a modified version of interval singleton type-2 fuzzy logic system, so-called upper and lower singleton type-2 fuzzy logic system, thereby reducing the complexity of the training phase. The computational simulations are performed with real data set provided by a Brazilian company of the railway sector. The obtained results are compared with other models reported in the literature (Bayes theory, multilayer perceptron neural network and type-1 fuzzy logic system), demonstrating the effectiveness of the proposed classifiers and revealing that the proposals are able to properly handle with uncertainties associated with the measurements and with the data that are used to tune the parameters of the model. In addition, the convergence speed and performance analysis show that the proposed singleton type-2 fuzzy logic system is attractive for classifying faults in a switch machine.

1. Introduction

A railroad switch is an electromechanical equipment that guides railway trains from one track to another, such as at a railway junction, while a switch machine is an equipment used for handling railroad switches. The increase of Brazilian railroad sector, which results in greater usage of switch machines, is an important problem to deal with, since real time operation, monitoring, and diagnosis of switch machine are of vital importance, especially with respect to predictive maintenance to avoid accidents and losses [1–3].

Recently, there has been increased interest among both transportation researchers and practitioners in exploiting the feasibility of applying computational intelligence paradigms to address critical problems in order to improve the efficiency, safety, and environmental-compatibility of transportation systems [4–6].

Research on switch machines has been in evidence in recent years, since they are important equipments that must be constantly monitored to avoid accidents. For instance [7], describes a strategy and a technical architecture for prognosis and health management (PHM) of a switch machine. Feature extraction techniques and principal component analysis (PCA) have been used in the assessment of the machines' health. [8] makes use of a support vector machine (SVM) in an online switch machine condition monitoring system based on current measurements to detect faults at their earliest stage or even before they occur. In [9], wavelet transform together with SVM showed that electrical active power can be a parameter for condition monitoring of switch machines. Moreover, [10] applies an expert system for fault identification in a switch machine, when the failure modes are not easily separable. In addition, [11] addresses a technique for detecting gradual failure in a switch machine, in which a Kalman Filter was applied for pre-processing signal signature. Other works such as [12] and [13] present alternative techniques related to unsupervised and semi-

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supervised fault detection and identification in industrial plants based on the analysis of the control and error signals. Among all possible faults that can occur in a switch machine, the three main ones are lack of lubrication, lack of adjustment and malfunction of a component. A common aspect of all previous works (see Refs. [7–13]) is the focus on the detection of the existence of a fault, and not on classifying different types of faults, such as those contemplated in this work. It is important to emphasize that the classification of specific types of faults (lack of lubrication, lack of adjustment and malfunction of a component) and the normal condition by monitoring the motor current of switch machine in the railroad is novel and it was introduced in the literature by the authors in [1,2].

Regarding monitoring and diagnosis [1], discussed and analyzed the performance of techniques for classifying typical faults (lack of lubrication, lack of adjustment and malfunction of a component) that can occur in a switch machine. Combinations of feature extraction technique based on Higher-Order Statistics [14,15], feature selection technique based on Fisher's discriminant ratio [14], and three classifiers (Bayes theory [16], multilayer perceptron neural network [17], and type-1 and singleton fuzzy logic system (FLS) [18,1]) showed performance improvement when applied to a data set, composed of measured current signals. Later [2], discussed a type-1 and singleton FLS trained by the conjugate gradient method (i.e., 2nd-order information) and the reported results show that such FLS can offer higher convergence speed and classification ratio for a limited number of epochs than that one trained by the steepest descent method. The authors in [19] introduce the use of Set-Membership concept, derived from the Adaptive Filter Theory, into the training procedure of type-1 and singleton/nonsingleton FLS, in order to reduce computational complexity and to increase convergence speed.

Combinations of feature extraction technique based on higher-order statistics [14,15], Feature selection technique based on Fisher's discriminant ratio [14], and three classifiers (Bayes theory [16], multilayer perceptron neural network [17], and type-1 and singleton fuzzy logic system (FLS) [18,1]) showed performance improvement when applied to a data set composed of measured current signals. Later [2], using the same data set, showed that the type-1 and singleton FLS trained by the Conjugate Gradient method can offer higher convergence speed and classification ratio than the Steepest Descent method.

Due to the computational complexity of FLSs, we point out that the training phase with high accuracy and convergence speed is of utmost importance because it can result in less hardware resource utilization and, as a consequence, can allow almost real-time training of the classification technique when new patterns need to be covered. Although type-1 FLSs offer improved performance, certain kind of uncertainties associated with the classification problem is something that, unfortunately, type-1 FLS may not properly handle.

In order to deal with the limitation of type-1 FLS and to reduce computational complexity during the training phase, this work proposes a modified version of interval singleton type-2 fuzzy logic system (IST2-FLS) discussed in [3] for classifying the aforementioned types of faults in a railroad switch machine when a reduced set of features is extracted from the current signal (fault signature).

The main contributions of this work are summarized as follows:

- We propose a new FLS-based classifier, called upper and lower type-2 fuzzy logic system (ULST2-FLS), reducing the complexity of the training phase.
- We adopt the steepest descent as training method, the height type-reduction, max-product composition, product implication and adopt the gaussian primary membership function with uncertain mean [18,20,3]. Also, we present the deductions for updating the parameters of ULST2-FLS for the first time in the literature.
- We present performance analyzes in terms of classification ratio and convergence speed by using a real data set constituted by measured signal from several switch machines. After that, we discuss comparative performances analysis among the proposals and previous techniques (Bayes theory, multilayer perceptron neural network, type-1 and singleton FLS trained by steepest descent method, type-1 and singleton FLS trained by the conjugate gradient method and interval and singleton type-2 FLS).

Our major conclusions are as follows:

- Numerical results show that the ULST2-FLS converges faster than those techniques previously discussed in [1–3].
- The ULST2-FLS is easier to implement and yield better results when compared with the classical IST2-FLS discussed in [18,3].
- Comparative analyses show that classification ratios achieved by the ULST2-FLS are higher than those obtained with the previous techniques.

The rest of the paper is organized as follows: Section 2 deals with the problem formulation. Section 3 is devoted to the IST2-FLS background. Section 4 aims to discuss the proposal based on ULST2-FLS. Section 5 discusses the results of computer simulations. Section 6 states the main conclusions regarding the proposals. Finally, (Appendixes A and B) present the deduction of equations responsible for update parameters of IST2-FLS and ULST2-FLS, respectively.

2. Problem formulation

The switch machine is the actuator that drives the switch blade from one position to the opposite position in order to offer different routes to trains. Failure in the actuator has a significant effect on train operations. If this failure occurs, it leads to a less reliable service and causes discredit to the railway company. It can also lead to more disastrous consequences. In 2002 a train derailment accident caused by poor maintenance of a switch machine occurred near Potters Bar railway station in the UK, killing seven people, as shown in Fig. 1. As a result, the railway infrastructure company paid several million GBP as compensation to victims and their families. It is therefore important for all infrastructure companies to minimize the occurrence of failures in switch machine [21,22,9,19].

Britain's railway infrastructure operator, Network Rail (https://www.net-workrail.co.uk/), was responsible for approximately 14 million minutes of train delay in 2002–2003, costing approximately 560 million GBP [23,24]. Switch machine is the main component of railway infrastructure that affects the availability of the system [25]. For example in England, 3.4 million GBP is spent every year for the maintenance of switch machines for 1000 km of railways [23,25]. Consequently, the classification of failures in these equipments is critical for managing and monitoring railway operational conditions. Therefore, the investigation of pattern recognition-based technique, which is capable of automatically identifying failures in switch machines, is of great importance to introduce new generations of solutions to increase system reliability.

The classification of faults in switch machines is one key purpose to assist the railroad company to verify the conditions of this equipment. It is a part of a multi-years project that has the objective of introducing this functionality in 100 of 624 switch machines belonging to the company in the Brazilian railway sector, named MRS Logística S.A. (https://www.mrs.com.br/). The proposed model makes it possible to reduce the impact on trains operation and on preventive maintenance, since interventions shall be carried out only when deviations are observed in the equipment. According to