Fusion Engineering and Design 129 (2018) 58–67

Contents lists available at ScienceDirect

Fusion Engineering and Design

journal homepage: www.elsevier.com/locate/fusengdes

Estimation of ECH power deposition based on neural networks and fuzzy logic in plasma fusion Tokamaks

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ARTICLE INFO

Keywords:
Fusion
Self-organizing maps
Neural networks
Bayesian filter
Plasma diagnosis
Tokamak

ABSTRACT

In order to stabilize magnetic hydro dynamics (MHD) activity in a Tokamaks, the measurement data acquired by different sensors along with prior information obtained from predictive plasma models are used. Suppression of plasma instabilities is a key issue to improve the confinement time of controlled thermonuclear fusion with Tokamaks. This paper proposes a method based on Self Organizing Maps (SOM) type Neural Network to estimate the Electron Cyclotron Heating (ECH) power deposition radius (r_{DEP}) during plasma confinement. The proposed approach that is a part of the control system to stabilize MHD instability, has been compared to the Bayesian filter approach which has been proposed previously. The Bayesian approach uses on-line information acquired from Electron Cyclotron Emission (ECE) sensors and prior information got from ray-tracing code to compute the mean and standard deviation of the estimated deposition channel. The SOM approach mostly relies on ECE sensors data instead of prior information and tries to estimate the power deposition channel in real-time with less computations. A fuzzy system is also designed to reduce the uncertainty of the SOM algorithm. These algorithms have been fully compared in different aspects too. The algorithms have been tested on off-line ECE channels data, obtained from an experimental shot at Frascati Tokamak Upgrade (FTU), Frascati, Italy.

1. Introduction

In nuclear fusion Tokamaks, the methods of plasma instability control that use electron cyclotron (EC) resonance heating and current drive such as control of Neoclassical Tearing Modes (NTM) require real-time control of EC deposition location [1]. Active control of Magneto Hydro Dynamics (MHD) instabilities is important in order to improve the tokamaks performance in nuclear fusion systems. Localized heating by Electron Cyclotron Current Drive is a promising tool for active control of the MHD. With this technique, it is possible to drive a localized current exactly in the narrow region of the plasma where the instabilities occur. The simulations and preliminary experiments have shown the feasibility of real-time diagnosis and control and estimation of EC power deposition radius in order to reduce the growth of magnetic islands in the plasma [2–4]. Recent experiments on plasma stability control in tokamaks like TCV have focused on developing and testing several new methods of MHD control based on steering antennas [5]. Due to the less advancement of the hardware (the DSP boards connected through VME bus [2,6] not using the FPGAs as the parallel processing units and a small Linux high performance computing system) used for real-time diagnosis and control, the results have not yet reached to the expected level of reliability [7,8].

For heating the plasma, there are different ways that include ECH system. This system consists of high power ECH lines and each one can be controlled independently. The generated power must be conveyed in the way that it deposits exactly on the expected region. The system for eliminating the instabilities should firstly detect the deposition channel and then detect the target channels [9]. It is possible to measure the uncertainty and evidence of each ECH power line by some diagnostic instruments for example ECE signals radiometers, or *soft X-ray emission*. The uncertainty and evidence can be forecasted using plasma models for the *ray tracing code* of the ECH line paths by having the steering angles of the ECH antennas [9–12].

This paper proposes a new method to determine the EC power deposition radius as a promising feedback to be used in the real time MHD control system. This method only uses the 12 channel ECE offline data stored in the database as the measured sensory information. The present technique's success relies on real-time beam tracing based on real-time measurement of density and magnetic equilibrium, without considering a direct measure of the actual deposition location of the EC power. This has been abandoned in the past years, due to the great uncertainty of ECE measurements used to determine the EC power

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https://doi.org/10.1016/j.fusengdes.2018.02.027
Received 21 May 2017; Received in revised form 28 December 2017; Accepted 7 February 2018

deposition. The possibility to use the proposed technique will open again this field, at least as a benchmark for the real-time beam tracing. The proposed method provides a real-time estimation of deposition radius (r_{DEP}) because the uncertainty and evidence of measurements are significant in the procedure of plasma control.

The general configuration of the Bayesian theory-based algorithm can be found in [9,13,14]. The Bayesian Assimilation inputs are ECE channels and ECH power signals along with the prior information (Ray tracing code) and the outputs are Evidence and Posterior probability density function (PDF). The prior information is a function of time in reality but in the simulation that are performed in this paper for Bayesian approach, the prior information is considered to be constant for simplicity.

A Self-Organizing Map (SOM) [15] is a type of Artificial Neural Network (ANN) that is trained using unsupervised learning to produce a low dimensional (typically two-dimensional), discretized representation of the input space of the training samples, called a map. Self-organizing maps differ from other artificial neural networks as they apply competitive learning as opposed to error-correction learning (such as *back propagation* with *gradient descent*), and in the sense that they use a neighborhood function to preserve the topological properties of the input space. This makes SOMs useful for visualizing low-dimensional views of high-dimensional data [16]. SOMs have different applications in several predictor modules of tokamaks, for example, an adaptive neural system has been proposed and then improved to predict the risk of disruption at ASDEX Upgrade [17–19]. SOMs have also been implemented to integrate the neural disruption predictor that is proposed for JET [20].

In this paper SOM has been used for a different application. It is employed for EC power deposition radius estimation and a fuzzy system to reduce the uncertainty of the SOM method. The employed SOM method includes two stages of operations: 1) vector absorption of the neurons and 2) fuzzy analysis. Fig. 1 shows the overall structure of SOM and Fuzzy Network ECH power deposition estimation system.

Both algorithms supervise the ECE channels data continuously to estimate the deposition radius (r_{DEP}) and to determine if electron cyclotron heating (ECH) power is correctly deposited on the expected radius in the Frascati Tokamak Upgrade FTU tokamak [21]. FTU is a compact high magnetic field tokamak that is started to operate in 1990 at Frascati, Italy with all the raw and elaborated data archived using two standard header channel descriptions [2]. The simulation results of r_{DEP} Bayesian estimation algorithm and SOM based estimation algorithm have been employed on the FTU off-line data from shot number 21364.

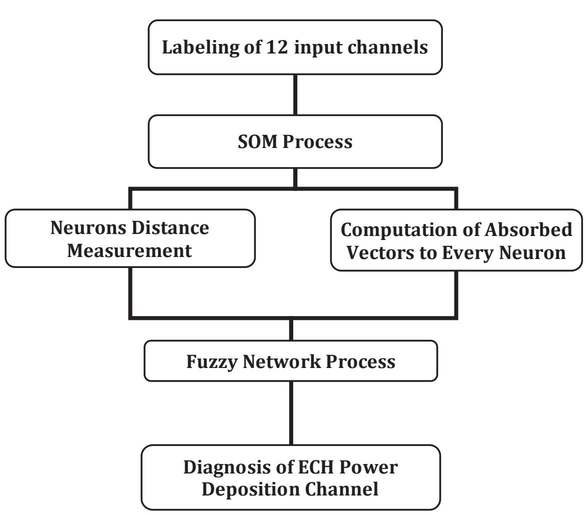

Fig. 1. The overall structure of SOM and Fuzzy Network ECH power deposition estimation system.

An advantage of SOM and fuzzy logic-based approach in addition to its capability to learn is the reduction of the mathematical computations in each iteration. It means that the proposed SOM algorithm is quicker to be implemented in real-time on a simpler and more reliable hardware.

2. Bayesian filter approach

This paper proposes a method based on Self Organizing Maps (SOM) type Neural Network to estimate the Electron Cyclotron Heating (ECH) power deposition radius (r_{DEP}) during flat top phase of plasma discharge. The proposed approach has been compared to the Bayesian algorithm-based approach that has been implemented previously in [9] by the authors of this paper. In this session the Bayesian filter approach will described and then the next session, the Self-Organizing Maps (SOM) approach will be proposed.

In the simulations of this paper, shot number 21364 of the FTU is used to test the Bayesian filter approach along with the proposed innovative algorithm. The illustration of ECE temperature data on all channels versus time for shot #21364 is available in [9]. The data includes 12 ECE channels temperature data and the channels numbers of 5, 6, and 7 are the hottest area in the plasma which are the temperature of the plasma midpoint [4], [10]. In the beginning points of the ECE data, a ramp is added to avoid oscillation while filtering the channels. The 12 channels are then interpolated to 23 channels for better resolution for the following process.

In the control loop, data acquisition, front-end signal processing, data transferring, control algorithm computations and applying the controller output to the motor drives have to be done within 1 ms. The ECE signals are sampled at 40 kHz, the period between each sample is 25 μs [22]. Due to the actuator's dynamic model the actuator's response to the control command cannot be faster than 1 ms. That is why for the current version of the control system hardware the fastest control loop has been fixed at 1 ms. In the next version of the hardware the control loop is upgraded to 20 μs and the actuators are going to be upgraded too [23–26].

It is not our intention to construct precise models for these *sources* of noise; rather it is our intention to propose a generic model for noise and other unwanted effects, and then to examine how robust our algorithm remains in the presence of possibly large amounts of this generic noise. It is our expectation that this robustness will not be particularly sensitive to our choice of noise model. The noise model that is used considers that each attempt to measure experimentally $R_x(\omega, \tau)$ cause pollution by an extraneous signal $\widetilde{R}(\omega, \tau)$ which $R_x(\omega, \tau)$ is the radiation emitted at frequency ω and time τ. Therefore, the following equation is only measured:

$$R_x(\omega, \tau) + \widetilde{R}(\omega, \tau).$$

The noise $\widetilde{R}(\omega, \tau)$ is considered to be Gaussian and uncorrelated all over the discrete measurements that has performed and hence the measurement of the pattern $R_x(\omega, \tau)$ is corrupted by a noise $\widetilde{R}$, with the properties of $<\widetilde{R}> = 0$ and $<\widetilde{R}^2> = \sigma^2$ [21].

In the simulation of the offline data (FTU shot #21364) it has been investigated that an elliptic filter with cut-off frequency of $f_c = 15$ kHz with the order of 12 could reduce significantly $\widetilde{R}(\omega, \tau)$.

To understand the role of uncertainty estimation in the proposed algorithm, it is essential to consider two types of information for deposition radius (r_{DEP}) estimation for each ECH heating line [27,28]:

1) To measure it directly using different diagnostic instruments (radiometers, soft X-ray emission):
The direct measurement approach and prediction using complex mathematical models, have contradictory characteristics regarding sensitivity and uncertainty. The direct measurement approach is described by a lower uncertainty but it has a finite sensitivity