Accuracy Improvement of Fault Diagnosis Methods for Small Modular Pressurized Water Reactors Based on Machine Learning Methods

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Abstract: The paper proposes a fault diagnosis method for small modular pressurized water reactors (SMPWR). Due to the compactness and complexity of SMPWR, for general fault diagnosis methods, it is difficult to extract the corresponding special complex fault characteristics, resulting in a great increase in the difficulty of diagnosis. Therefore, this paper intends to propose a more applicable diagnosis method in close combination with the characteristics of SMPWR. Traditional machine learning methods based on feature selection and feature extraction work well in other research areas, but when it comes to SMPWR, it is difficult to determine the features that should be extracted, and different feature selection can cause great interference in the diagnosis results. Therefore, this project proposes to use advanced deep learning algorithms to automatically learn fault features of complex systems, reduce human interference, and build up more reasonable and accurate intelligent diagnostic models.

Keywords: Fault Diagnosis; Machine Learning; Small Modular Pressurized Water Reactors

Introduction

Under the circumstances of global warming, with the progress of science and technology and productivity further released, demands for energy, especially the low carbon energy will be more and more vigorous. Compared with other new energy sources, nuclear energy starts earlier and develops longer, has the advantages of long design service life, low comprehensive cost, and small land occupation space, and has become an important part of the global energy source.

Since 2000, the United States and Russia have all carried out researches on small modular reactors (SMR) with innovative technological characteristics. Compared with traditional nuclear water reactors, the small modular reactor (SMR) has the characteristics of high inherent safety, diverse applications, flexible deployment, low investment, short construction period, etc. According to statistics from the International Atomic Energy Agency (IAEA), there are currently more than 50 types of small modular reactors at different research and development stages worldwide.[1] While in China, the small modular pressurized water reactor named as NHR200-II adopts the design concept of integrated layout, full power natural circulation, self stabilization, passive safety, and is equipped with an intermediate isolation circuit, which can actually eliminate large-scale radioactive release. [2]

But it is a pity that due to the nuclear accident in Fukushima Daiichi, researches on nuclear power have been stagnant all over the world. From my perspectives, what we should learn from nuclear accidents is that we ought to import more automation application and reduce human intervention, when in emergency, instead of overthrowing the whole nuclear industry.

On the other hand, in order to make the progress of nuclear industry sustainable, we should pay attention to fault diagnosis. From my perspectives, designing an automation system, which detects faults accurately and on time and even proposes some workable methods for operators to act, are significantly important to research on in nuclear industry.

Literature Review

Fault diagnosis technology can monitor the system operation condition, determine whether faults occur, and also determine the time, location, size and type of the fault, complete fault detection, separation and estimation, which plays an important role in improving the operation reliability of complex industrial systems and reduce the system operation risks.[3] In present, the fault diagnosis methods for closed-loop systems mainly contain model-based methods, signal processing-based methods and knowledge-based methods. For complex systems such as the Small Modular Pressurized Water Reactor (SMPWR), which are complex in structure, large in scale, and difficult to model accurately, knowledge-based intelligent fault diagnosis methods have good application effect. SMPWR has a serious fault issue due to its complicated compact structure, variable operating conditions and extreme external disturbance in the application scenes, which poses a significant threat to the system operational safety.

Research methods

SMPFR has compact and complex structure, large time delay, non-linearity and high correlation between modules, and there is a complex mapping relationship between fault signs and fault categories. The actual fault sample data of SMPWR is scarce, so this paper intends to generate one-dimensional time series fault data of SMPWR through virtual simulation, which is based on MARLAB/Simulink for the nuclear steam supply system. On top of that, its accuracy and reliability are well-verified.[12]

The deep learning technology has strong feature recognition capabilities and can automatically learn the fault representation in the original data, which is suitable for complex fault diagnosis of SMPWR. Therefore, it is proposed to use transfer learning technology to migrate the excellent Convolution Neural Network (CNN) as a feature extractor to small-sample SMPWR fault diagnosis. To achieve this, we ought to measure the parameters at the same time step and input in time order to transform 12 measured time-varying parameters like temperature, pressure and water level into matrix (one row). Every input into the network is a 12plus12 matrix, then goes with padding layer to make sure every input value are treated equal, convolution layer to extract the characteristics of data, and fully connected layer with a function that produce an output. With the output, we know whether there are faults with the pile or not. If there are, which fault happens could be distinguished by different output value. All above are the ways how to use CNN to do fault diagnosis.

Besides, there are disturbances when a pile works, and it is unavoidable. Therefore, when we build a nuclear power plant, we also design supporting facilities to help pile work smoothly and sustainably, which implies every parameter are fluctuating rather than constant. As long as they are in the tolerance range of supporting facilities, it would be all right. To monitor and forecast faults, we could use LSTM to do classification for each parameter and learn their safe range. Once detect fault signals the control system could alert operator to take actions.

Thus, to define possible kind of different accidents, we ought to use a LSTM layer for every parameter and a fully-connected layer to connect all. Thus, we could detect the types of faults by distinguishing which parameter deviate from normality. The two methods are based on the build-in app of MATLAB named as deepNetworkDesigner.

Last but not least, we also use another app named ntstool to learn and make predictions. When the output data deprived a lot from predictions, it diagnoses errors. To achieve this, we only need to input normal operation data of nuclear power plant, which is easier to get than fault data.

On top of those, we could train model with fault data of plants in different power levels. At different power levels, parameters show different characteristics and possible accidents are diverse.

Results

In this study, three possible fault diagnosis methods based on machine learning are proposed and discussed, all of which are worth to dig in. The outcome of the third method has proven to have strong capabilities to learn features with the raw time series data of SMPWR as input. The method has been proven to have strong diagnostic capabilities for historical faults in both steady and transient operating conditions of the system with high accuracy. With network goes deeper, the differences between predictions and real data shrink and the network achieve the best outcome in 472 rounds and only takes nearly 3 minutes.

The diagnostic accuracy for the SMPWR. Here, the prediction accuracy is defined as the difference between 1 and the maximum prediction deviation. It is clear that the proposed method achieves high prediction accuracy, which reaches 98%. Thanks to such high accuracy, we could have 98% certainty to commit that there have been faults, when the input data deviates too much from the predictions.

Discussion

With the improvement of fault diagnosis technology, data-driven diagnosis machine learning methods are increasingly welcomed and widely applied. Deep learning can adopt to long-term dependent systems' parameters. The above simulation experiments demonstrate that the deep learning method is a promising fault diagnosis method with high accuracy and efficiency. And it can also contribute to improve the disadvantages of traditional fault diagnosis models by achieving the degree of compatibility. Every method has its own advantages and disadvantages. How to combine different methods, which complement each other to achieve the best output is worthy of been dug in.

The combination between machine learning methods and other traditional fault diagnosis methods could improve the accuracy and efficiency better than any single method. This also inspire us all to pay attention to multi-diagnosis methods for further development of fault diagnosis.

Based on the outcomes of this paper and literature reviews of the research status of fault diagnosis not only in nuclear power plant industry, this paper has a try to import the machine learning methods to nuclear industry system fault diagnosis, and works well. The successful applications of machine learning in supervised learning, image recognition and so on definitely push the area of fault diagnosis for big breakthroughs and benefit the nuclear industry in the end. In the future, nuclear technology will be more safe and well-accepted by public.

Limitations

However, the two other methods are not verified in this paper due to the limitations of time and length of the paper. It only propose possible research ideas based on machine learning methods to detect faults and judge the types of faults corresponding to continuous inputs of time-varying parameters. Besides, the possible environment SMPWR operates in is harsh, thus there are inevitable to be noise or disturbances with measured data in reality. The methods above do not take this into consideration, which could make the outcome deviate from reality. At present, researches to construct a simulation analysis platform to simulate the conditions of accidents of nuclear power plants are plenty and some have achieved a lot, which make up for the data shortages of faults in nuclear industries. With simulation, we can obtain nearly infinite number of data, which paves the way for machine learning to widely used in nuclear industries.

Most importantly, this paper is totally based on MATLAB, thus may have problems to be directly used in the control system of nuclear power plants. It still needs to be modified to fit the environment of actual control system and do tests just in case.

References

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