

A Comprehensive Review of AI-Based Methods for Modern Power Systems

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Abstract

During the last years, modern power systems have been extensively transformed due to rapid integration of renewable energy sources, distributed energy generation and technologies. Such developments result in operational challenges, such as uncertainty of power generation sources, increases the complexity of the system and necessitates intelligent decision-making mechanisms. Recently, some of these issues could be solved by different artificial Intelligence (AI) techniques which are used for advanced analysis, prediction and optimizing the system. AI-based approaches have the potential to process vast datasets collected from sensors, smart meters and monitoring devices to optimize system reliability and operational performance. Machine learning, neural networks and fuzzy logic (among generative tools) are some of the different AI methods that have been extensively used in power system analysis and control. Along with it, the increased access to computational power and enormous datasets boosted the integration of AI technologies in energy management and smart grid applications. Recent researches show that AI based models can greatly enhance and increase the forecasting accuracy, fault detection capability, and stability analysis of modern power systems. To address the above challenge, this paper provides a systematic review of AI techniques used in contemporary power engineering applications such as: load forecasting, fault diagnosis, stability analysis, renewable energy integration and finally smart grid.

Keywords: Artificial Intelligence, Power Systems, Smart Grid, Machine Learning, Deep Learning, Load Forecasting, Fault Detection, Power System Stability, Renewable Energy Integration, Energy Management Systems.

I. Introduction

Power system has been the backbone of both modern industrial and social infrastructure. For example, power systems were traditionally designed to accommodate for centralized electricity generation and a one-directional flow of power from generation plants to consumers. But with the increased proliferation of distributed generation, renewable energy sources, and smart grid technologies, a new paradigm shift has taken place in terms of the way modern power systems are structured and operated. The increasing penetration of these developments led to a multitude of operational challenges such as uncertainty in energy generation, dynamic

demand variations, and stability concerns among others. One of the scopes that came up as an important technical solution to overcome these challenges is Artificial Intelligence. AI technologies allow computers to sift through hundreds of data points, identify trends and even make informed decisions with little human input. AI applications in Power systems were initially used for more research purposes, where intelligent algorithms helped with manufacturing improved system monitoring, control and protection mechanism [1]. As machine learning and computational technologies continue to advance, AI approaches have demonstrated greater success at addressing complex power system challenges. Figure 1. Demonstrate the A.I. approaches for contemporary power systems.

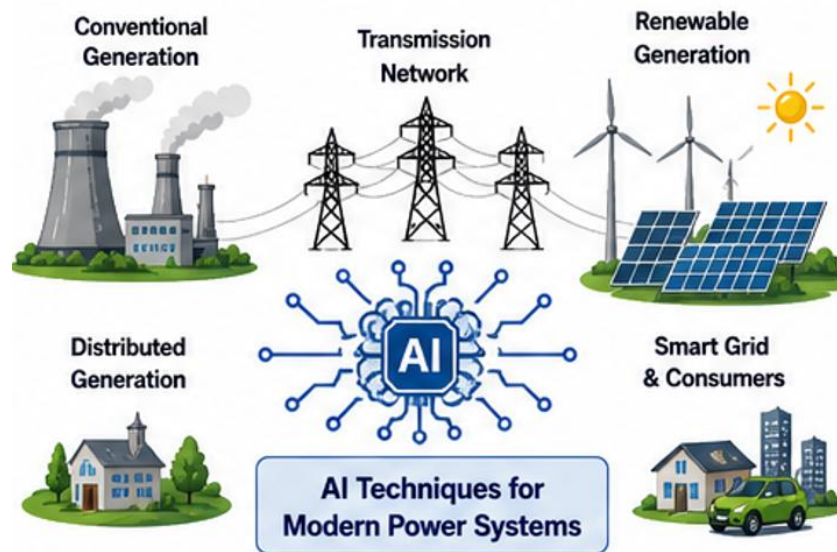


Fig. 1. AI techniques used in modern power systems.

The deployment of smart grid technology accelerates the demand for intelligent analytical tools that can process data on a large scale in real time. Smart meters, sensors and monitoring devices generate tremendous amounts of data in conventions of a smart grid like never seen before. These datasets can be analyzed through AI algorithms to identify anomalies, predict electricity demands and optimize power flow operation [2]. In addition, AI-based solutions facilitate the development of adaptive learning systems that can constantly enhance their own performance by training on new data. AI-based techniques have been shown to not only improve operational efficiency, but also reduce power loss and system reliability [3]. Consequently, AI has earned an integral part in next-generation intelligence power systems.

II. Overview of Artificial Intelligence Techniques for Power Systems

Artificial intelligence is a field that deals with computational agents and creating computational methods to mimic human intelligence in machines. This category of techniques enables systems to learn from data, detect patterns and make decisions in an automatic fashion. AI has been applied for forecasting, optimization, fault detection and control applications in modern power systems. Fig. The AI techniques for the power systems is shown in Fig. 2.

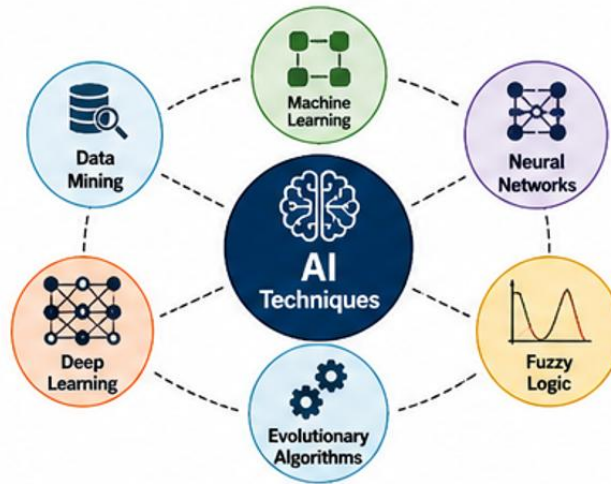


Fig. 2. overview of the AI techniques for power systems.

Machine Learning (ML) is among the most widely applied AI methods in power system applications. ML algorithms are trained on historical data to identify patterns and predict future system performance. Statistical learning methods are mostly focused on load forecasting and fault classification, that is supervised [4]. These algorithms continuously learn from operational data, improving the performance of the system. Artificial Neural Networks (ANN) are method based on biological neural networks of the human brain. They are made of interconnected nodes that compute weighted inputs. These non-linear relationships between input and output variables are very common in modeling of power systems, for which ANNs have been shown to outperform them. Compared with classical methods, neural networks can considerably improve the accuracy of prediction works in power system analysis & forecasting tasks [5].

Fuzzy logic: Fuzzy logic is another AI method for reasoning with uncertain information and making decisions under uncertainty. Fuzzy logic is different from the common binary system of logic operation where a variable can only have values that are 0 and/or 1 (e.g. This allows for more effective modeling of complicated and uncertain power system environments. This framework has successfully been shown to be applicable for voltage control and power system stabilization using fuzzy-based controllers [6]. In summary, AI approaches seem to be effective methods in solving complicated dispatching problems and details most of the areas that can enhance techniques of operation.

III. AI-Based Load Forecasting in Power Systems

Load forecasting is an important task in power system planning and operation. By predicting electricity demand accurately, utilities are able to balance supply and demand of the electricity as well as reduced operational costs. Conventional forecasting methodology are based on statistical methods that regularly fail to detect nonlinear affiliations in electricity consumption data. Fig. 3. Demonstrates AI based load forecasting in Power systems. Artificial Intelligence (AI) methods have a lot advanced wisdom of load forecasting fashions since the 1970s. Among such methods, forecasting models that are based on neural networks can learn the complex relationship between electricity demand and other influencing factors involving weather

information and economic activities [7]. It has been leveraged for short duration load forecasting applications. With this capability provided by deep learning techniques, forecasting performance has been improved as large and complex datasets can be analyzed. Time-series forecasting problems, such as electricity demand prediction [8], are one of the most applicable tasks to recurrent neural networks and long short-term memory (LSTM) networks. These models are used to identify temporal dependencies in consumption patterns, producing more accurate forecasts.

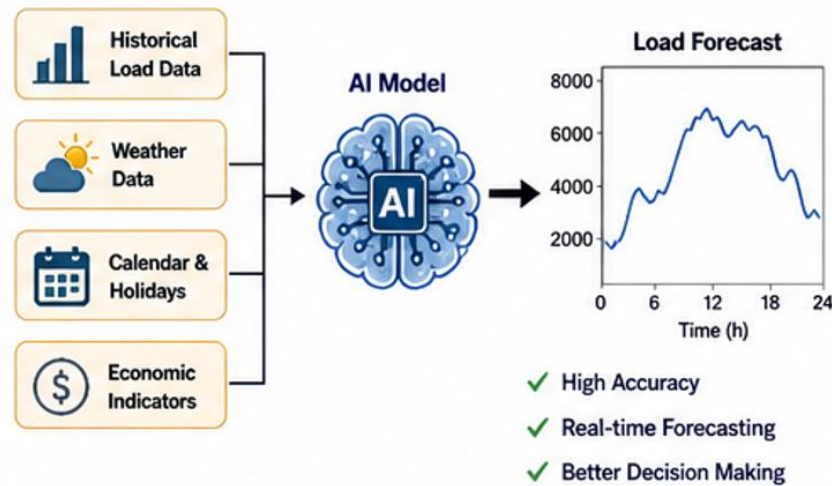


Fig.3. AI based load forecasting in Power systems

Support vectors machine: Another ML technique used for the forecasting of load. You have also recently acquired Models are really good in generalization and also for nonlinear regression problems. Studies show that SVM-based forecasting models reach high accuracy even with small training datasets [9]. Benefits of AI-based Forecasting Models The main benefits of using an AI-based forecasting model include enhanced accuracy, response to changes in demand patterns and the possibility of processing multiple numerical input variables simultaneously.

IV. AI-Based Fault Detection and Diagnosis

Given that reliable operation of any power system relies on the ability to detect faults, fault detection is crucial. Power disruptions, machinery failure, and safety concerns might all occur due to electrical faults. It is important for faults to be detected and classified as soon as possible to minimize disruption in the system. Fig. 4. Illustration of the AI-based fault detection and diagnosis AI techniques have widely been utilized for automatic fault detection and diagnosis. An example of this is the ability to analyze electrical parameters (such as voltage and current signals) using neural networks [5] to locate abnormal patterns associated with faults [10]. It can recognize all kinds of faults such as line to ground or line to line faults. For example, machine learning algorithms have been used for fault detection in the power transmission networks. These algorithms learn to recognize fault conditions with speed and accuracy from large datasets collected from protective relays, monitoring devices etc. [11].

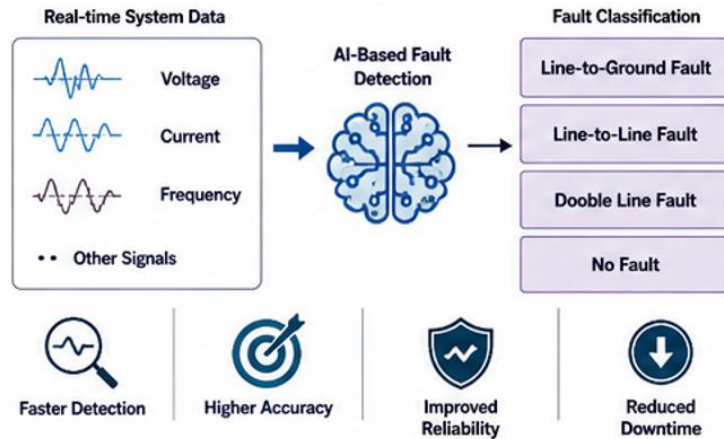


Fig. 4. AI based fault detection and diagnosis.

In recent years, deep learning models have received wide attention for fault classification tasks because they can simultaneously extract and analyse features directly from raw electrical signals. Depending on the type of faults, studies showed that deep learning techniques can perform a better or worse fault detection than traditional approaches [12]. The risk of widespread outages is reduced for the network by utilizing AI-based fault detection systems that increase system reliability with quickly responding signals based on abnormal conditions.

V. AI-Based Power System Stability and Control

Power system stability is defined as the ability of a power system to maintain equilibrium under normal processing and recover from any disturbances [5]. However, AI-based approaches have been extensively used to improve the stability analysis and control strategies. Fig. 5. illustrates the stability and control of power systems based on AI. Transient stability assessment with neural network based models In power systems, there have been many approaches for transient stability. We refer with this models to those where system variables such as generator rotor angles and voltages are used to assess the stability of a system in response to disturbances [13]. Power system stabilizers also utilize fuzzy logic controllers relatively popular. These controllers represent versatile decision-making mechanisms that can effectively deal with uncertain and nonlinear system conditions [14].

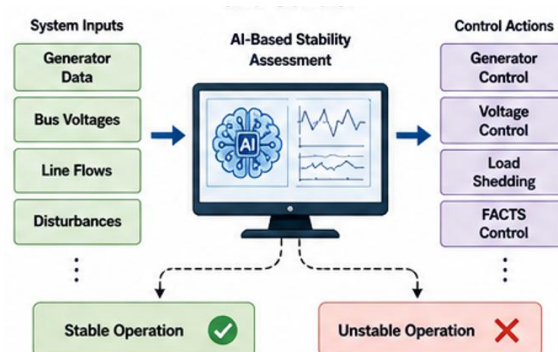


Fig. 5. AI-based power system stability and control.

Recently, adaptive control systems in power networks have been approached by reinforcement learning techniques. By interacting with the environment, these algorithms train

control systems to learn optimal control actions [15]. Compared with traditional control strategies, AI-based stability control mechanisms have shorter response times and are less likely to fail.

VI. AI for Renewable Energy Integration and Smart Grid Management

Renewable energy utilization in the modern power system paradigm includes intermittent nature of renewable generation under integrating into the power grid. AI techniques are important components for addressing these issues by enhancing the accuracy of forecasts and supporting grid optimization. Fig. 6. Demonstrating the AI in other areas of renewable energy integration and smart grid management. Grid with a lot of solar and wind resources are the classical application for machine learning model predictions. These types of models derive renewable energy generation from weather data and analysis patterns of historical generation [16]. Basically, Accurate forecasting allows to schedule the generation resources in a precise way. Smart grids utilize advanced communication and sensing technologies to have real-time monitoring of system conditions. This makes the wide area monitoring control and protection part adaptable to these AI algorithms based on this data collected using number of smart meters and sensors to balance energy related distribution in such as manner considering minimal power loss [17]. This is incorporated deep learning techniques for the prediction of renewable energy. These models are trained on complex environmental data and can allow for very precise generation forecasts [18]-[19]. Artificial Intelligence (AI)-driven energy management systems that provide grid optimisation, cut operational costs and enable large-scale incorporation of RES.

VII. Conclusion

Artificial intelligence (AI) has emerged as a key enabling technology for power systems. An increasing power network complexity (and the integration of renewable sources) requires advance analytic tools, which can handle large amounts of data in dynamic shameless conditions. AI techniques are, in fact, ready-made solutions to these challenges. This review paper serves as a summary of AI-based approaches applicable on load forecasting, fault detection, stability assessment and integration/management of renewable energy/electric vehicle with smart grid. AI algorithms provide system reliability, operational efficiencies and energy management capabilities with significant differences compared to the previous period of returning reliable results. However, few trials remain difficult such as data quality, computational complexity and cyber-security issues. Future works should help direct the research to convergence of artificial intelligence and other emerging technologies, such as Internet of Things (IoT) edge computing to develop more intelligent and resilient power systems.

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