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Review: World experience in the use of artificial intelligence in operation and control of power systems

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Review: World experience in the use of artificial intelligence in operation and control of power systems

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Abstract. The article provides an overview of various artificial intelligence (AI) methods that can be used in the operation and control of power systems. It is shown how artificial intelligence can be used to account for optimal energy consumption, voltage regulation, control the stability of the power system, and control the frequency of the load. AI methods allow processing large amounts of data faster than numerical optimization methods and therefore can improve the performance of energy systems.

INTRODUCTION

During the Transition AI conference 2023 in Boston, USA, David Groarke, Director of Indigo Advisory Group, presented the results of an analysis of current energy sector trends that are transforming the industry. The report concluded that artificial intelligence in energy is not just a technology, but a harbinger of a new phase of progress in this field. https://www.latitudemedia.com/events/transition-ai-boston

Let's consider the presented results of the analysis as stages of energy sector development [1-11]:

1. Energy Restructuring (1970-1990): During this period, the energy sector underwent significant restructuring, coinciding with the emergence and growing popularity of renewable energy sources. The sector began to refocus on diversifying the energy mix and searching for cleaner alternatives.

2. Energy Digitalization (2000-2020): From the beginning of the new millennium until recently, the energy sector experienced a period of digitalization. Technological advances have facilitated the digital transformation of various processes and systems in this sector. Digitalization has served as the foundation for the energy transition, enabling improved efficiency, data management, and the integration of renewable energy sources into the grid.

3. Energy Automation (2020 onwards): The modern era is marked by the emergence of automation, enhanced by AI. AI-powered automation is set to play a key role in achieving net zero goals. It enables intelligent decision-making, optimization, and automation of energy systems, thereby facilitating the transition to a sustainable and low-carbon future, whether through improved operational efficiency, grid optimization, demand response, predictive maintenance, or the efficient integration of renewable energy sources. The current and future impact of AI on the global energy sector is shown in Figure 1.

The development of artificial intelligence (AI) in the energy sector is dynamic and noticeable. As energy companies strive to meet ever-increasing electricity demand while reducing carbon emissions, they are turning to AI as a game-changing solution. AI technologies are being integrated into all aspects of the energy sector – from exploration and production to distribution and consumption. Advanced algorithms will allow companies to analyze vast amounts of data collected from sensors, smart meters, and other sources, providing invaluable insights into energy consumption patterns, consumption habits, and infrastructure performance. With AI, energy companies can optimize their operations, identify anomalies, and make data-driven decisions that improve efficiency and promote sustainable development. Figure 2 illustrates the current and future impact of AI on the global economy and climate change [12-16].

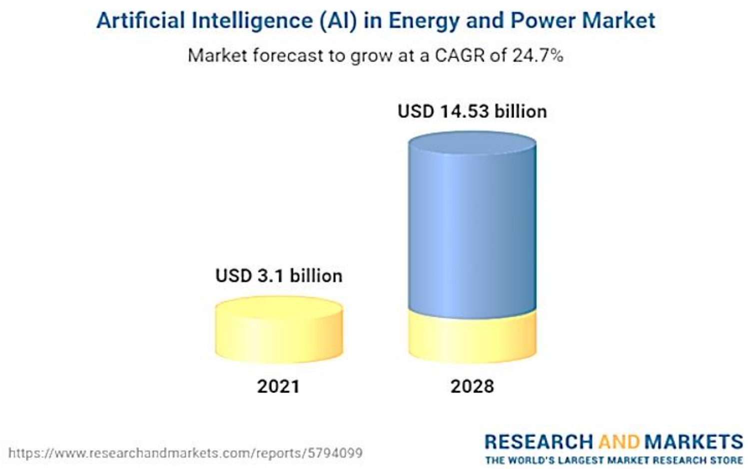

FIGURE 1. The Impact of Artificial Intelligence on Energy and the Energy Market

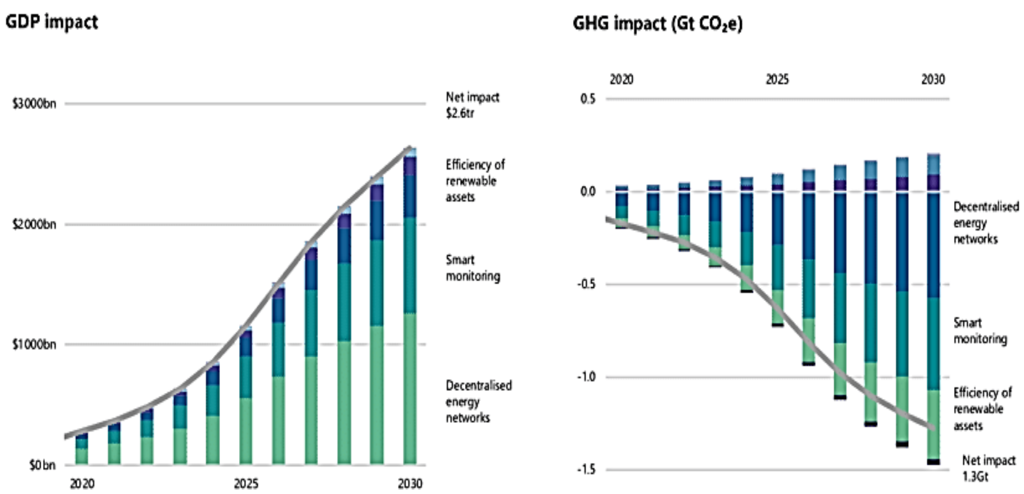

FIGURE 2. Global Impact of Artificial Intelligence in the Energy Sector on GDP and Greenhouse Gas Emissions

[1] identified five factors that determine the benefits of implementing AI in the energy sector [17-23]:

1. **Preventive Maintenance**: AI-based preventive maintenance is a game-changer for energy companies. By analyzing sensor data and equipment characteristics, AI algorithms can detect potential faults before they occur. This proactive approach to maintenance can reduce downtime by up to 50% and reduce maintenance costs by 10-40% (according to Accenture).

2. **Energy Trading**: Artificial intelligence is transforming the energy trading industry. With its ability to analyze massive amounts of data and market trends in real time, AI algorithms can optimize energy trading strategies and increase profitability. According to a McKinsey report, AI-powered energy trading algorithms have shown an average increase in trading profits of 2-4%.

3. **Load Forecasting**: AI-powered demand response programs are proving effective in balancing energy supply and demand. By encouraging consumers to adjust their energy consumption during periods of peak demand, energy companies can avoid costly infrastructure upgrades and reduce their reliance on fossil fuel-fired power plants. Research by the International Energy Agency (IEA) has shown that AI-powered demand response programs can reduce peak electricity demand by 10-20%.

3. **Renewable Energy Production**: Artificial intelligence plays a critical role in optimizing the production and integration of renewable energy sources. By analyzing data from renewable sources, AI algorithms can forecast energy production, optimize power generation, and improve grid integration. AI-powered solar forecasting models have reduced forecast errors by 30% compared to traditional methods.

4. **Data Generation and Anomaly Detection**: Generative AI models have proven their value in creating synthetic data that closely resembles real-world energy data. This synthetic data plays a crucial role in scenarios where obtaining real-world data is limited or difficult. By comparing real-time data and generated synthetic data, any deviations or anomalies can be quickly identified, enabling the early detection of equipment malfunctions, grid outages, or cyber security threats.

5. **Digital Disruption**: The integration of AI into the energy sector is fueling innovation and stimulating the development of transformative technologies. Machine learning algorithms are dramatically improving renewable energy forecasting, leading to more accurate solar and wind power generation forecasts. According to a study published in the journal Applied Energy, using machine learning algorithms to forecast solar energy yields a 25% reduction in forecasting errors compared to traditional methods. A World Economic Forum report emphasizes that smart home energy management systems powered by AI algorithms can reduce household energy consumption by up to 10%. By providing real-time data and insights, these systems enable consumers to make smart energy choices, identify areas where waste is generated, and implement energy-saving measures. This not only helps reduce carbon emissions but also leads to significant cost savings. To support this assertion, we present some real-world achievements of energy companies [1] that have been achieved by implementing AI technologies in various aspects of their operations: https://www.datadynamicsinc.com/blog-ai-in-energy-your-data-is-the-game-changer-7-reasons-why/

6. **Next Era Energy**: One of the world's largest renewable energy companies, used AI to optimize the operation of its wind turbines. Using AI algorithms to analyze real-time wind data and turbine performance, they achieved a 20% increase in energy production at their wind farms.

7. **Duke Energy**, a leading electric utility holding company in the US, has implemented AI-powered demand response programs. These programs help customers reduce energy consumption during periods of peak demand. Through these AI-powered initiatives, the company has reduced peak electricity demand by 10%. This allows it to better balance energy supply and demand, optimize infrastructure, and provide reliable service to its customers.

8. **Enel:** The Italian multinational energy company uses AI for predictive maintenance. By analyzing sensor data and equipment performance, they can anticipate and prevent potential failures at their power plants. This proactive approach to maintenance has reduced downtime by up to 30% and maintenance costs by 20%.

9. **Tesla:** The company has entered the energy sector with AI-powered energy management solutions. While advances in artificial intelligence are recognized in the modern world, the importance of high-quality and rich data cannot be overstated when it comes to maximizing AI performance. The key to unlocking the power of AI lies in data. To fully utilize AI capabilities, data quality and availability are paramount, as data powers algorithms, enabling them to learn, make predictions, and generate insights. Therefore, it is essential to improve the methods for processing and using data. Unified Data Management (UDM) is the key to unlocking the untapped potential of enterprises, allowing them to extract value from their data and harness the full power of AI.

Recognizing the urgency of implementing AI in Uzbekistan's energy system, in this review, which, to our knowledge, is the first in this area, we present the most popular AI algorithms for energy applications, focusing on key energy areas where AI is already being applied: power system operation and control.

MATERIAL AND METHODS

Therefore, the demand for advanced research and technologies in the power grid sector is steadily growing [1]. Traditional research methods are rapidly becoming insufficient to address the global challenges that artificial intelligence can help solve and unlock important insights from the billions of data fragments scattered across power systems [2]. Assessing the use of AI technologies in power grids requires a comprehensive analysis of existing AI research [2].

TABLE 1. Application of AI in power system management

Application	Reference	Date	Purpose	Methods
Voltage regulation	Zidani et al. [24]	2018	The voltage and frequency of the automatic induction generator are controlled using new technology	Artificial neural network
	Sumathi et al. [25]	2015	Backpropagation feeder for ANN estimation of UPFC output variables for different load conditions in 24-bus Indian EHV power system.	Artificial neural network with backpropagation and feedforward
	Kanata et al. [26]	2018	Improving the quality of the power system by measuring the exact value of the control variable.	Particle Swarm Optimization and Hybrid Artificial Neural Network
	Abdalla et al. [27]	2016	Prevention of voltage disturbances in emergency situations through coordinated adjustment of PID controller parameters.	Genetic algorithm
	Chung et al. [28]	2008	Control systems for coordinating multiple microgrid generators for grid-connected and stand-alone operation using inverter-type interfaces are presented.	Particle Swarm Optimization
Power system stability control	Yousuf et al. [29]	2021	Power system automation provides restoration, error diagnosis, management and network security.	Fuzzy logic, genetic algorithm
	Aakula et al. [30]	2020	Optimization that allows to obtain enough reactive energy to improve the bus voltage.	Particle Swarm Optimization
	Karthikeyan et al. [31]	2017	STATCOM based on fuzzy PID controller to improve the stability of power system under fault conditions	Fuzzy logic,
	Torkzadeh et al. [32]	2014	The GA-FLC genetic algorithm is used to suppress low-frequency oscillations.	Fuzzy logic, genetic algorithm
	Dutta et al. [33]	2017	General solution needed for a power stabilizer to compress low frequency oscillations (PSS).	Ant Colony Optimization
Load frequency regulation	Safari et al. [34]	2021	MG microgrid is proposed for load frequency control (LFC).	Artificial neural network based on particle swarm optimization
	Joshi et al. [35]	2020	A new LFC control plan of hydropower system based on the combined efforts of fuzzy logic control and PID design based on PSO algorithm.	Fuzzy logic with particle swarm optimization
	Balamurugan [36]	2018	Balance of generation and demand of the power system	Fuzzy logic
	Kuma et al. [37]	2020	Scheduled solar and wind power is used to analyze load frequency, mitigate frequency variations, ensure GM grid stability, respond to unexpected surges in demand for charging power, and PI controllers from non-renewable sources.	Recurrent neural network
	Arora et al. [38]	2020	The designed method has shown excellent results for intelligent control of frequency problems	Genetic algorithm, particle swarm optimization

There are various energy systems-solar energy systems, wind energy systems, thermal power plants, nuclear power plants, geothermal power plants, etc. [4]. Each energy system has different designs and equipment for generating electricity [5], but the basic structure of a power system includes the following components: (i) Generating station; (ii) Transmission substation; (iii) Transmission substation; (iv) Distribution substation.

DISCUSSION

Of the three fundamental areas of energy where AI has already been applied, we will discuss the first two-operation and control of power systems-providing a brief statement of the problem and its solutions [39-42].

Optimal Power Flow [43-47].

Optimal power flow (OPF) is a very important method for determining optimal control parameter settings that improve or reduce a given objective function, but it also has a number of limitations. An important tool in power system design and operation is determining the optimal power flow rate to determine the best parameter settings that can maximize or minimize a given objective function within defined constraints. Voltage and reactive power regulation, known as OPD, is a subproblem of OPF that aims to reduce overall transmission losses by restoring reactive power. Optimal reactive power distribution is a nonlinear solution to the integer mixing problem, since some control variables, such as transformer tap ratios and the outputs of shunt capacitors and reactors, are different.

An alternative strategy for solving the problem is offline training of artificial neural networks (ANNs). A popular clustering method, k-means, is used to select suitable ANN inputs. With proper function training, neural networks can easily and accurately estimate the corresponding outputs.

The ANFIS=Adaptive Neuro Fuzzy Inference System package develops a fuzzy inference system (FIS=Fuzzy Inference System) for a set of input/output data that maps correction parameters to a backpropagation process (https://github.com/topics/anfis-network).This update enables training on fuzzy data used in IEEE39 bus implementations and the ANFIS modeling software. Results show that ANFIS produces solutions that are as accurate as traditional ones, but are faster and very fast.

Voltage Regulation [47-51].

The primary objective of a power system with a voltage regulator is to maintain the voltage profile within a specified limit to minimize transmission losses and avoid voltage instability [19]. The VC system consists of three hierarchical control levels: AVR (automatic voltage regulator), tertiary voltage regulator (TerVC), and secondary voltage regulator (SecVC). The AVR is designed to control the voltage of buses equipped with reactive power sources (e.g., synchronous, static var compensators, and static synchronous compensators (STATCOMs)). Actions are performed locally at this control level. SecVC is used to monitor the voltage on a specific bus, which controls a load bus.

In situations where nearby hardware changes the AVR reference point, the control level typically operates slower than the AVR control level. SecVC is responsible for defining VC regions and correlating them with individual load buses. To adapt to changing conditions in the power system, SecVC must demonstrate flexibility in configuring control regions taking into account all network conditions. TerVC, on the other hand, determines the optimal reference value for networks with voltage at each load bus. The goal is to minimize power losses, optimize reactive power, and maintain minimal load shedding or redundancy. The service is typically updated every 30 minutes to 1 hour.

Inverse Algorithm Error propagation trains multi-layer feedforward perception. The minimum singular value method analyzes static voltage drop. The procedure uses the minimum time to estimate voltage stability after network training is complete. Complementary neural network and expert system methodologies can be combined to monitor voltage drop in the application [20].

An iterative optimization approach is used to train a particle swarm optimization (PSO) model. These objectives are achieved by using the optimal PSO value. The final results are initializations within the time-varying nonlinear particle swarm optimization (TVNLPSO) framework.

Power System Stability Control [52-58]

Power system stability is the property that allows it to remain in equilibrium under normal operating conditions and to restore an acceptable balance after changes. It can be seen that stability limits are declining worldwide [21]. Three of the many reasons for this are highlighted:

Hindering further transmission or construction due to economic and environmental constraints. Therefore, power systems must operate with smaller safety margins.

Power industry restructuring. The restructuring process reduces stability margins because power systems do not interact effectively [22].

Large nonlinear oscillations; frequency differences between weakly coupled regions of the power system; Interaction with complex devices.

Fuzzy logic attempts to address these issues by mimicking human reasoning and enabling optimal decision making based on available information. It can also be used to regulate the stability of non-modeled systems. To achieve improved performance, a fuzzy logic controller (FL) is combined with a proportional-integral-derivative (PID) controller.

A fuzzy logic controller consists of four main parts: fuzzification, a fuzzy rule base, fuzzy inference, and recovery. FACTS has proven to be an extremely promising tool for improving performance under stable conditions. The most promising FACTS device is the unified power flow controller (UPFC). Three control factors can be adjusted: bus voltage, line response, and the phase angle between two buses. While maintaining a stable state, power must be redistributed between the lines. This can also be used to increase damping during a temporary reduction in low frequencies.

Load Frequency Regulation [59-65].

Load frequency regulation, defined by controlling the generator output power in a given region, allows for adjustment of system frequency variations, dual-line loads, or interactions to maintain communication with other regions within a set limit or the scheduled system frequency [23]. The traditional proportional-integral (PI) controller is the most widely used among the various types of load frequency regulators. The PI controller is easy to implement and provides faster response, but its performance degrades when unwanted disturbances, such as load dynamics, increase system complexity. In this paper, a non-linear autoregressive moving average (L2 NARMA-L2) control architecture requires less computation. The plant output, reference, and control signals are included. Thus, the controller is trained to monitor the output of a reference model. The model network, which updates the controller settings, predicts the impact of plant performance changes.

CONCLUSION

Evaluating energy costs and implementing improvements can lead to significant energy savings. Smart technologies can reduce electricity demand and environmental impacts. Future research could expand sample sizes and examine smart meter readings. Future research should emphasize the importance of addressing technical, security, and privacy concerns, and encourage collaboration among stakeholders to expand the smart market. Although the developed approach has several advantages, the issue of calculating the condition index for equipment consisting of multiple functional units remains unresolved. Existing methods rely on assigning weights to each element based on expert judgment to determine its importance. Additional research could focus on improving condition index calculation methods for various types of power equipment and developing predictive models to predict equipment failures in the event of functional unit failures. Future research should prioritize the development of more accurate and reliable predictive models for power systems, taking into account challenges related to data availability and interpretability.

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