

Optimization of Wind Energy Systems in Smart Grids Using ANFIS-Based Intelligent Control

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Abstract: Building on the smart grid design for wind-based renewable energy systems presented in Paper 1, this study introduces an ANFIS-based intelligent controller to further optimize system performance. The ANFIS controller effectively manages the complex dynamics of wind energy generation, reducing Total Harmonic Distortion (THD) and improving power quality. By minimizing harmonic losses, the proposed system enhances overall efficiency, ensuring better integration of renewable energy into the grid. The results demonstrate a significant reduction in THD and improved system stability, validating the potential of ANFIS for achieving optimized performance in renewable energy applications. **Keywords:** Wind Energy Systems, Smart Grids, Intelligent Control.

I. INTRODUCTION

In terms of long-term reliability and effectiveness, renewable power sources are inherently unstable. Take solar energy systems as an example. They are able to generate electrical energy while the sun is bright, but they are unable to do so when it is cloudy or nighttime. Because of this structure's instability and intermittent nature, significant challenges emerge. As time goes by, their performance also changes [1]. Thus, this matter is being researched with greater rigor. In addition to obtaining the energy, the studies' overarching goal is to regulate the current energy and eradicate any variations it may produce in the system, as well as to bring the energy to the right values.

A solar panel cannot supply a steady stream of electricity regardless of changes in temperature or sun irradiation. Unlike conventional energy sources, renewable energy cannot be delivered at predetermined times [2]. Renewable energy systems that incorporate storage units allow for the continuous provision of energy to consumers by storing the generated energy. To put this energy into reserve, energy storage applications might be utilized. Especially during peak hours, energy storage units have made it more feasible to use.

Energy management is necessary due to changes in loads, in the weather, and during the day and night. There is mutual assistance between the energy management systems, which can turn on and off, charge and discharge the batteries based on their charge levels, and reconnect to the grid when the batteries die. In order to address the issue of renewable energy sources' instability, energy storage is a crucial component [3]. With energy storage, it's possible to handle electricity more flexibly by exchanging it in a planned manner; this allows the storage unit to function as its own active and reactive power source.

Emerging nations use solar energy to meet social and individual energy needs, which helps them achieve balance and progress. The most environmentally friendly way to transmit power in the future will be through electric vehicles and renewable energy resources (RERs) [4]. Improving economy, safety, efficiency, and dependability requires updating the transmission and distribution networks. The traditional grid's distribution and transmission grids are made more efficient by implementing a communication and control system. Improved network administration and operation, smart meters, and faster problem diagnoses are causing a shift in the traditional grid [5]. The fast growth of renewable energy power has solidified renewable energy's position as a key player in the energy landscape of the future. Wind and solar photovoltaic (PV) are two examples of RES, and integrating them into the power system is no

joke. The electric market structure must coordinate the RESs management strategy in light of the recent modifications to the pricing components of energy marketing and designs [6]. In contrast, renewable energy sources like fuel cells, wind, and solar power will be around forever. There are many new uses for solar energy, and its popularity has skyrocketed thanks to the proliferation of solar-powered electric vehicles (EVs), lighting, and homes. There is a scarcity of resources for renewable energy since its technologies cannot compete financially with those of conventional fuels. There are RESs that can function independently of the grid, RESs that can link to the grid, and RESs that can do both. The communication issues associated with renewable energy technology are higher than those associated with non-renewable energy sources [7]. Energy storage solutions for smart grids have improved with the passage of time. There are a variety of electric vehicles that can be charged by plug-ins, including plug-in hybrids, energy storage systems, and other similar devices. This innovation supplanted the earlier method of transporting electric vehicles that relied on hydrocarbon power. To combat the ever-increasing emissions of greenhouse gases (GHGs), they are being included into the current network to enhance its intelligence. In contrast to conventional power plants, RESs have unique output variables [8].

II. LITERATURE REVIEW

A large number of wind turbines with variable speeds make use of DFIGs, or doubly-fed induction generators. In order to stabilize the power system faster, DFIGs are used in conjunction with bidirectional electronic power controllers to keep the rotor speed higher than the synchronous speed [9]. Further investigation is needed to determine the perspective of DFIGs doing even more to subsidize stability, especially as the share of DFIGs in smart power grid increases. Some types of voltage and frequency regulation capacity from DFIGs are presented in the literature on the standard DFIGs' control procedures, which include de-loaded control, inertia control, and coordinated rotor side and grid side control. The grid-integrated DFIG experiences loading torque fluctuations on the drive chain, as demonstrated by the research academics in [10].

Oscillations in the induced driving torque can be caused by mechanical factors, changes in the DFIG magnetizing level, incompatibilities between control units and machine operating parameters, and random variations in wind direction and speed. The smart grid-integrated DFIG was unable to provide contributions to frequency regulations, as stated by the authors in [11]. The DFIG's rotor's connection to the electrical power system through AC/DC/AC power electronic converters leads to subpar frequency response. Due to complicated computations, uncertain machine parameters, and model nonlinearity, which produces an imbalanced output at variable generation, the power controllers use PI, PD, or PID controllers, which in turn require additional controlling units. The grid frequency expedition cannot be mitigated by absorbing or releasing the kinetic energy due to the decoupling properties of actual output power and grid frequency [12]. Furthermore, there is no reserved capacity to raise the output power of the DFIGs in the MPPT control techniques that use the tip speed ratio, hill-climb search algorithm, back-stepping control rule, and sliding mode.

Improving the stability of smart grid-integrated wind power systems is possible with the use of machine learning and deep learning techniques [13]. Using these approaches, we can create diagnostic tools that are accessible, inexpensive, and incredibly precise; these tools will be able to handle complex optimization problems including variable wind speed, non-linear load changes, power dispatch, and load control at the coupling point [14]. The goal of machine learning and deep learning is to create data-driven intelligent systems capable of doing tasks normally associated with human intelligence. Implementing ML techniques like ANN in wind-driven turbines as a low-computing procedure presents important conflicts and technical breaches, as outlined by the research academics in [15]. One advantage of the AI method is how accurate it is. But machine learning's biggest obstacle is its lack of interpretability. The paradigms of power system operation were transformed by the high penetration of

renewables. Energy management solutions are now essential for the majority of applications to keep up with these changes. This is why there is a wealth of literature on such systems in the scientific community. Classical methods [16], meta-heuristic approaches, AI methods, and model predictive control are only a few examples of the numerous methods used in energy management systems.

Energy management in residential micro-grids can benefit from a model predictive control technique that takes weather predictions into account in order to lower energy consumption and maximize the usage of renewable energy sources [17]. An optimal control problem with a finite time horizon is the basis of the MPC control technique that has been created. The conventional rule-based control logic was contrasted with this suggested solution. On average, primary fossil energy use drops by 14.5 percent while residential comfort levels rise.

The low-voltage distribution system experiences voltage fluctuations due to the PV power oversupply. In [18], the authors suggest a novel PID control method for PV interface inverters based on ANFIS and a controlled energy storage management system for PV system connections that use ANFIS to eradicate this issue. In order to regulate the DC bus voltage, it is recommended to use a fuzzy logic-based battery energy storage system (BESS) control method, as shown in [19]. In order to control the energy storage system, a fuzzy inference system (FIS) is suggested for use with renewable energy sources and storage units in a system [20]. The suggested FIS successfully reduced volatility and extended the life cycle of the energy storage system (ESS) when compared to a rule-based control technique.

III. WIND POWER GENERING SYSTEM

3.1 Introduction

The active energy of flowing air is essentially what wind energy is all about. Winds blowing over Earth as a result of the sun's intense, uneven heating of the planet's surface. Wind power is utilized to precisely track generators for electricity generated by wind turbines. In contrast to using non-renewable energy sources, wind power is abundant, sustainable, widely utilized, clean, and doesn't require much land, absorbs no water, or produce ozone-depleting compounds while operating. Compared to other, less sustainable electricity sources, the overall impact on the environment is clearly safer. Everyone knows that different kinds of land make up Earth's surface, and that there's a lot of water too, with about 71% of the surface under water.

The soil on different types of terrain is also different. Because the sun warms different parts of the Earth at different speeds, its heat isn't uniformly distributed over the planet's surface. The movement of air is caused by the difference in temperature across different parts of the planet. This means that convection flows occur in the air as a result of the uneven distribution of heat on Earth's surface. The point where land and enormous water meet is the sea bank, and it is there that wind forms.

Planetary air moves at a faster rate than oceanic air throughout the day. Because it has dissipated over the ground, the warm air is now thinner and lighter. Because heat rises more slowly in the air over water than in land, the density and weight of air over water remain higher than that of land. Because it is less dense, the hot air over the ground rises. A breeze occurs when this air rises because cooler air over the ocean rushes in to fill the void. Here we can see the wind energy buildings installed on the seashore during the day. At night, terrestrial surfaces radiate heat at a faster rate than water. From now on, land parcels chill down faster than water. That is why air over land becomes cooler than air over water. Consequently, as the sun sets, the thinner air rises over the lake, making it hotter. Cooler and heavier air will be drawn into this vacant gap from the land divide. After then, a wind will blow again, but in the opposite direction as throughout the day.

The air closer to the north and south poles gets cooler than the atmosphere close to the equator, as was previously noted. Therefore, near the equator there are always twists. We are able to make effective use of the active energy that is available as a result of the stream, which is referred to as wind energy. A pure source of energy, wind is. The nursery has no effect on the

natural world. Charcoal, oil, gas, petroleum, and other non-renewable energy sources are replaced by this. Despite their importance as a fuel source for delivering electricity, such non-renewable energy resources are not easily accessible. To combat our reliance on petroleum derivatives, we are putting our focus on wind and other renewable energy sources to produce electricity. Currently, 67% of the world's energy comes from petroleum derivatives, 13% from thermal power, and 20% from environmental power sources like hydro, sunlight, wind, etc. Because of this, we are worried about this. The operational cost of supplying wind power is incredibly low. It is not necessary to insert the turbines and provide support for an extended period of time. The foundation for the wind energy age requires a small plot of land for construction, but most of their property can be utilized for farming or raising animals. Consequently, land poses little to no threat to wind turbine construction. Many situations involve the installation of wind turbines at great heights in order to generate a great deal of electricity quickly.

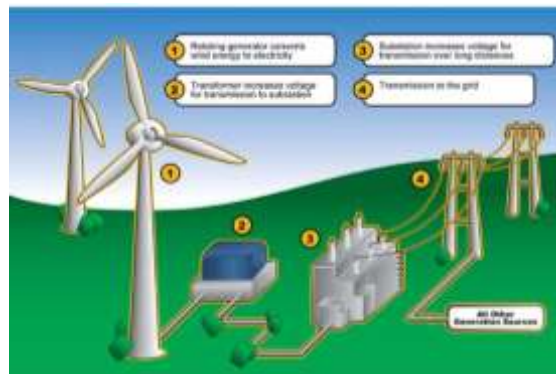


Figure 1. Wind power generation system.

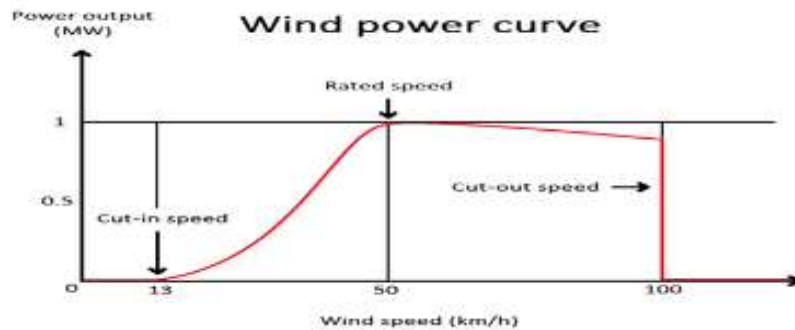


Figure 2. Wind power curve.



Figure 3. Wind power stations in Xinjiang, China

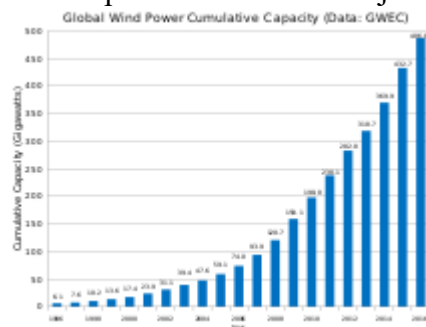


Figure 4. Increase in worldwide installed capacity

3.2 Wind power generation

Wind turbines employ wind power to precisely control wind power generators. When compared to using petroleum derivatives, wind power is a safe option because it is abundant, never runs out, dispersed, and uses very little land. It also doesn't include any active substances that deplete the ozone layer, doesn't burn any water, and uses very little water. In the end, using energy sources that aren't renewable is safer for the planet. Wind farms include a number of breeze generators linked to the power grid. Wind turbines provide for the exact regulation of wind power generators, while inland wind is a small power source. When compared to using petroleum derivatives, wind power is a safe option because it is abundant, never runs out, dispersed, and uses very little land. It also doesn't include any active substances that deplete the ozone layer, doesn't burn any water, and uses very little water. In the end, using energy sources that aren't renewable is safer for the planet.

A wind farm is a collection of interconnected wind turbines that produce electricity. Since inland wind power produces only a small amount of electricity, upgrading the network and reducing capacity are required to replace a conventional system when the amount of wind power in a given location increases.

In many cases, such as when dealing with an abundance limit, geologically suitable turbines, dispatchable backing tools, enough hydropower, trading and capabilities in nearby regions, or diminished interest in low wind turbines, the management approaches are forced to overcome these challenges. The electrical organization can also benefit from the climate-determining method by being able to prepare ahead of time for the planned variety. At least eighty-three nations throughout the globe rely on wind power to power their electrical grids; Denmark has been using wind power to produce forty percent of its electricity since 2015. The maximum allowed breeze capacity on Earth rose to 369,553 MW in 2014, a 16% rise from the previous year. Furthermore, wind power is becoming increasingly important, with a growing share of 4.4% overall and 11.4% in the European Union.

IV. METHODOLOGY

ADAPTIVE NEURO FUZZY INFERENCE SYSTEM

An ANFIS, or adaptable network-based fuzzy inference system, is a type of artificial neural network that derives from the Takagi-Sugeno fuzzy inference system. It was in the early 1990s that the technique was first proposed. It improves its chances of success by integrating the greatest parts of neural networks and fuzzy logic. A set of fuzzy IF-THEN rules that can be learned to approximate nonlinear functions form the basis of its inference approach. This is why ANFIS is considered a general estimator.

Applying the most effective parameters derived from a genetic algorithm allows for more efficient and optimal utilization of the ANFIS. An intelligent energy management system that is aware of its surroundings can make use of it.

ANFIS architecture

The network structure can be broken down into two distinct components: the premise and the consequence. More specifically, there are five levels that make up the architecture. Membership functions in the first layer are determined by the input values. Fuzzification is the common name for this layer. To determine the membership degrees for every function, the $\{a,b,c\}$ foundation parameter set is utilized. It is the second layer that generates the firing strengths of the rules. The "rule layer" is the moniker given to the second layer based on its role. The computed firing strengths are normalized in the third layer by dividing each value by the overall firing strength. In the fourth layer, the resultant parameters $\{p,q,r\}$ and the normalized values are fed. With the defuzzified values returned by this layer, the final output is generated by passing them on to the last layer.

Fuzzification layer

An ANFIS network's initial layer contrasts it with a standard neural network. Feature conversion into normalized values between 0 and 1 is a common data pre-processing step for neural networks. In order to perform the preprocessing phase of transforming numerical values into fuzzy values, an ANFIS neural network does not require a sigmoid function. One example is this: Pretend for a second that the network is fed the two-dimensional spatial distance between two nodes. The distance can take on values between zero and five hundred pixels. Membership functions, which include semantic descriptions like "near," "middle," and "far," transform numerical values into fuzzy numbers. A single neuron is responsible for assigning every conceivable language value. A number between zero and one is fired by the "near" neuron if the distance falls into the "near" category. If the distance falls within that category, the neuron in the "middle" will fire. An input value of "distance in pixels" is divided into three neurons: one for the near, one for the center, and one for the far as well.

Design of the proposed controller

Combining Neural Networks (NN) with Fuzzy Inference System (FIS), the Adaptive Neuro-Fuzzy Inference System (ANFIS) can resolve a number of optimization problems. The ANFIS controller, seen in figure.34, optimizes the torque in this article.

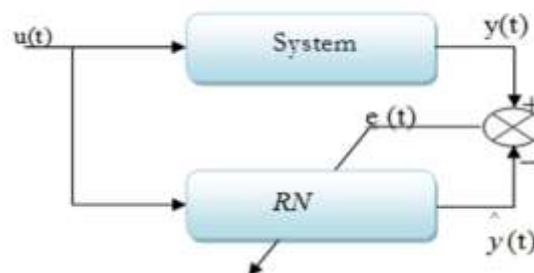


Figure 5. ANFIS controller proposed

In our example, the fuzzy controller uses 25 rules to connect the inputs with the outputs. Formembership function adaptation and fuzzy rule determination, artificial neural networks(ANN) are utilized. An ANFIS configuration is what you're looking at here. For the purposeof adapting neural-fuzzy systems, a hybrid technique is employed, which combines optimization through back propagation of the error with optimization through the least squares method (as illustrated in figure 6).

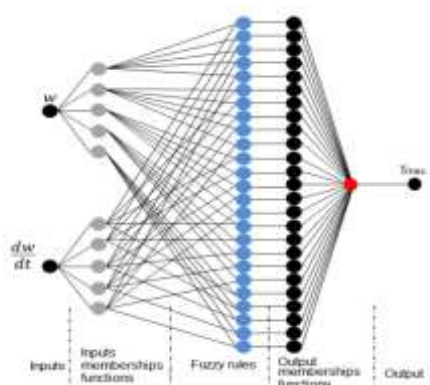


Figure 6. Proposed ANFIS controller

APPLICATION

The non-linear system is commonly controlled by this ANFIS controller. For the simple reason that it outperforms all other controllers, including the standard PID controller. The temperature water bath controller makes use of this controller. There are a number of uses for this controller, including controlling aircraft. Currently, there is study on developing intelligent planes that can learn to take off and land on their own.

V. EXTENSION WITH ANFIS CONTROLLER RESULTS: SIMULATION RESULTS

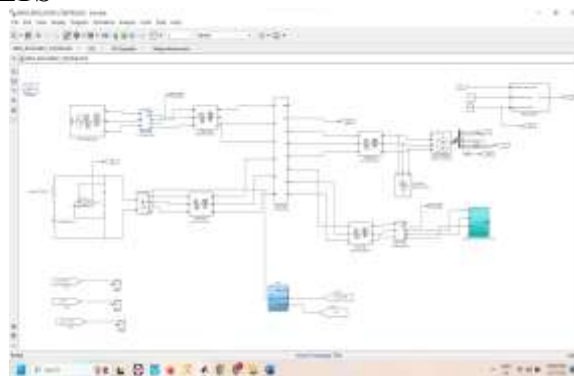


Figure 7. ANFIS controller based simulation block diagram.

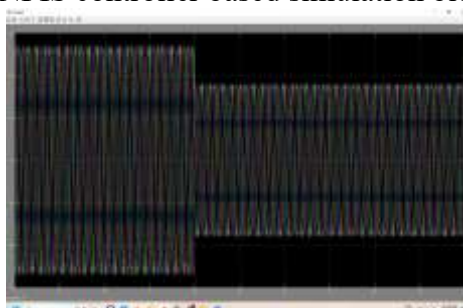


Figure 8. Source current

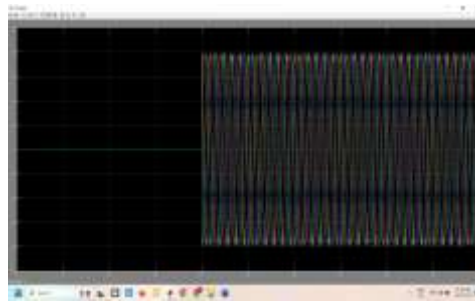


Figure 9. Inverter current



Figure 10. Load current

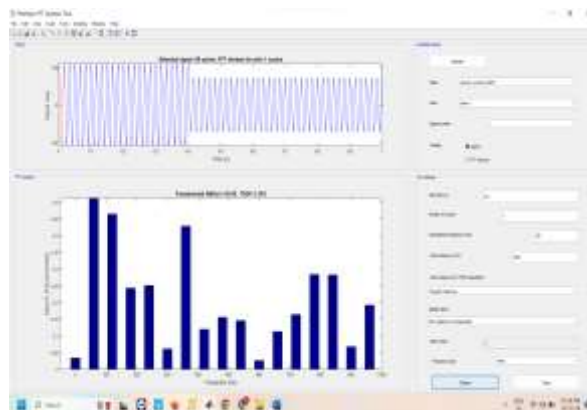


Figure 11. THD for source current.



Figure 12. THD for Load current.

When the ANFIS controller is turned on, as shown in Figure 8, the source current becomes sinusoidal and harmonic-free. Figure 9 displays the injected current that is delivered by the inverter. The system's load current is depicted in Figure 10. The load current, which is the sum of the source current and the inverter current, will be calculated during this interval. Figures 11 and 12 display the THDs.

CONCLUSION

The implementation of an ANFIS-based intelligent controller significantly enhances the performance of wind-based renewable energy systems by effectively managing complex generation dynamics. This approach minimizes Total Harmonic Distortion (THD), improves power quality, and reduces harmonic losses, ultimately leading to increased system efficiency and stability. These findings underscore the potential of integrating advanced intelligent controllers like ANFIS to optimize renewable energy systems, facilitating better grid integration and supporting the transition to more sustainable energy solutions.

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