Fuzzy Logic and Artificial Neural Network Based Grid-Interactive Systems For Renewable Energy Sources: A Review

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***Abstract*—Smart grid is getting popular day by day since renewable and distributed energy sources are connected to the grid. Many researchers have been studying how to reduce the impacts of renewable energy connections to the grid. Especially, voltage and frequency fluctuations during the connections are creating big problems on the grid. So that, many smart grid technologies have been proposed to overcome these problems.**

In this study, different techniques applied in active-reactive control and voltage frequency control structures were investigated by examining the studies carried out with fuzzy logic and artificial neural network in order to ensure the smooth interaction of the renewable energy sources and the grid.

***Keywords*—grid-interactive systems, voltage instability, frequency fluctuation, grid failure, fuzzy, artificial neural network**

I. Introduction

In today's world, where energy consumption is increasing and fossil fuels are in danger of being depleted, the interest in renewable energy sources is increasing in parallel. Voltage and frequency fluctuations and active-reactive (PQ) power control are important issues in the operating conditions of the grids under variable load. These fluctuations and power flow become more difficult to control when integrating renewable resources such as solar, wind, battery storage units into the grid and operating them with grid interaction. Unbalanced load situations and sudden power changes of the sources make it difficult to control the systems during the grid connection of the renewable energy sources that work with the grid.

When the problems of grid-interactive systems working with renewable energy sources are examined, many different problems have been identified both on the source side and on the load side. If some of these problems are listed;

- Voltage and frequency fluctuations due to the power generation uncertainty of renewable energy sources,
- Voltage and frequency disturbances caused by load imbalance in grid-interactive systems,
- Imbalances in active and reactive power transmission depending on the variable load conditions of the sources,
- Reflection of production surplus to the grid as reactive power, which occurs as a result of incorrect planning in renewable energy systems,
- Connection problems experienced during the grid connection of renewable energy sources,

In the studies conducted to solve these problems, decision support methods such as fuzzy logic and artificial neural network (ANN) are more preferred instead of working with complex mathematical models of systems.

In Fuzzy and ANN applications, it is aimed to determine the inputs and outputs correctly, and the control method to be applied will provide efficiency-enhancing benefits to the system. It is important that photovoltaic (PV) systems and wind turbines (WT) follow the maximum power point (MPPT) during power transfer to the grid and that the voltage and frequency at the connection point are kept constant in systems that will operate in parallel with each other. In systems, where different sources are operated together, it is provided to operate with different power electronic structures and filters in order to provide active reactive power control or to control the power flow of the sources correctly.

In this study, the applications of all these defined problems and solution methods in grid-interactive systems are examined. A comparative analysis of different control methods has been carried out by examining the studies on reducing voltage and frequency fluctuations and PQ control methods of systems operating with grid interaction, in particular fuzzy logic and artificial intelligence.

In the second part of the study, the theory of the use of fuzzy logic and ANN structures in grid-interactive systems is given. In the third chapter, fuzzy logic applications and ANN applications in voltage and frequency fluctuations are examined. In the fourth chapter, fuzzy logic applications and ANN applications used in active-reactive power problems are examined. In the fifth and last part, a comparative analysis of the studies in the literature is done and suggestions for evaluation are presented.

II. Use of Fuzzy Logic and ANN Application in Grid-Interactive Systems

In computer-based software applications for smart systems, fuzzy logic and ANN are used in different areas from applications used every day in daily life to industrial control systems.

Fuzzy logic and ANN can deal with the uncertainties of systems in decision making stages by changing the parameters of control mechanisms. As a result, fuzzy controller can enable fast decision-making action in nonlinear power system.

Fuzzy logic and ANN applications evaluate the controller according to direct measurements, long-term experience and knowledge of users in the field, unlike traditional control theories, which are basically designed based on linearized mathematical equations.

The use of fuzzy logic structures in grid-interactive systems that can operate with renewable energy sources such as solar and wind is realized through switching signals applied to power electronics converters on the system [1]. In the control structures of these converters, voltage and frequency control can be done separately, or both variables can be controlled with structures such as droop control. In addition, the active-reactive power balance is controlled by ensuring the interaction of different sources to be connected to the system. If the number of renewable resources in the system increases, the number of variables that the fuzzy logic controller will decide simultaneously also increases. The block diagram for the implementation of the fuzzy logic structure over a converter is given in Figure 1[2].

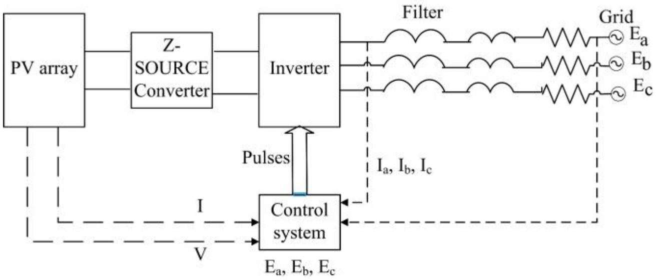

Fig. 1. Application of fuzzy logic structure to renewable systems

In these systems, in the first stage, the current and voltage reference information from the sources are applied as separate error signals as input information to the fuzzy controller. Then, these signals are processed in the fuzzy logic rule base, resulting in a control signal. At this stage, the controller uses the previously defined logic rules and the database created with the experiences during the fuzzification and defuzzification processes. The working structure of the controller for an input signal is given in Figure 2 [3].

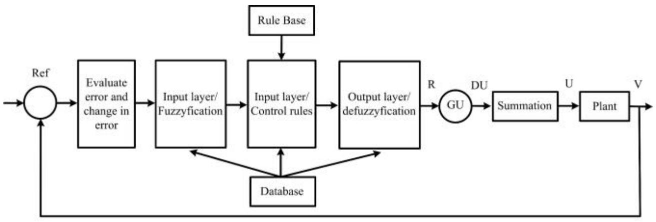

Fig. 2. Working structure of fuzzy logic controller

In fuzzy logic, the system makes precise decisions based on unclear or uncertain data, while artificial neural networks try to involve the human thought process to solve problems without being modeled mathematically. In addition, ANN includes a learning process that includes learning algorithms and requires training data.

ANN is a computational model developed based on neural networks in the human brain. ANN adapts its structure according to the input of the system. While developing an ANN structure, a series of processing steps called learning rules are followed. In this learning process, training data is needed for the algorithm to discover the good working point. ANN can be used to learn an approximation function for some observed data. However, the model to be used in ANN application should be carefully selected depending on the data defined as input. Using unnecessarily complex models in the created ANN structure will complicate the learning process of the system. It is also important to choose the right learning algorithm when looking for solutions to problems, some learning algorithms perform better with certain data types.

The use of ANN algorithms in grid interactive systems focuses on areas such as improving power quality, regulation of voltage and frequency waves (drop/swell), and estimation of MPPT point in variable conditions in solar and wind energy systems. As in fuzzy logic applications, in ANN studies carried out over control signals to be applied to power electronics converters, more than one input data is processed on a decision support system and an output is produced as a result. The block diagram of an ANN structure for active-reactive power control is given in Figure 3[4].

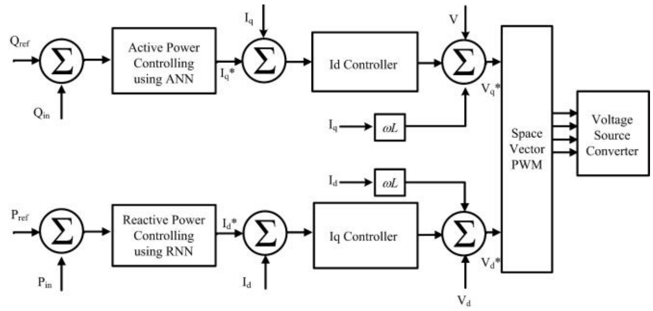

Fig. 3. ANN structure used in active-reactive power control

III. FUZZY AND ANN APPLICATIONS IN VOLTAGE AND FREQUENCY FLUCTUATIONS

Fuzzy logic and ANN algorithms have been applied by using different methods to reduce voltage and frequency fluctuations of grid interactive systems working in parallel with renewable energy sources. Some studies in the literature in recent years, especially fuzzy and ANN, are given below.

Rajesh et al. propose a fuzzy logic controller to control the rotor frequency of the wind turbine connected to the system in hybrid renewable energy systems. The performance evaluation of the proposed model has been made on different controllers, according to switching time, settling time, rise time and percent overshoots, and it has been proven to work efficiently [3].

Fathy et al. propose an Adaptive Neuro Fuzzy Inference System (ANFIS) algorithm trained through the antlion optimizer (ALO) in order to achieve optimal load frequency control (LFC) in a system consisting of renewable energy sources. The error signal and PI output obtained from the designed fuzzy logic system are fed to ANFIS for the training process. The results obtained with the proposed ALO-ANFIS controller are compared with other approaches. Data such as performance characteristics, settling time, frequency and over- and under-draw of power line deviations were calculated and compared with other reference algorithms. [5].

Aziz et al. proposed an algorithm based on a dynamic deadband and moving average frequency filter to provide power-frequency response with a variable speed wind turbine generator model operating in grid interaction. The proposed load frequency controller implements a two-level control architecture that combines the advantageous aspects of fuzzy logic and traditional PID control. The fuzzy LFC controller provides adequate compensation for nonlinear conditions induced in the control area of the turbine generator due to predictable wind power variations. The resulting simulations claim that FGS-PID LFC controllers provide superior performance in a low inertia control area. [6].

Angalaeswari et al. proposed an Iterative Learning Controller (ILC) that can operate in variable conditions in an autonomous grid to maintain voltage and frequency stability in microgrids. The proposed ILC performed better in voltage and frequency stabilization compared to other controllers under varying conditions in both autonomous and grid connected modes. With the proposed technique, voltage unbalance is minimized and operating time is reduced. Maximum 79% error reduction is achieved with the recommended ILC controller [7].

Thao et al. propose a two-level coordinated structure with fuzzy logic to adjust the total active power supplied to a grid by the photovoltaic (PV) plant in order to regulate the grid frequency. Ultimately, simulations show that the proposed strategy can regulate frequency deviation within acceptable ranges of ± 0.2 Hz in transient mode and ± 0.05 Hz in steady state mode [8].

Tripathi et al. propose the fictitious reference iterative tuning (FRIT) method to optimize the efficiency of the DC side voltage controller in grid-connected PV systems. In the study, 2-DOF PI controller structure is used and optimal control of DC voltage is realized with improved distortion response. As a result, it was determined that better results were obtained in DC voltage regulation [9].

Peng et al. propose a fuzzy logic-based coordinated algorithm using the DFIG-energy storage couple to improve the short-term frequency response of DFIG generators in wind energy conversion systems. With the proposed design, the frequency response of the system is improved in the short term and at different wind speeds [10]. In another study, Peng et al. performed optimal control strategy and sizing with a fuzzy logic-based algorithm using DFIG-energy storage pair in wind energy conversion systems. It is stated that the proposed system has a valid performance in frequency control and power generation in wind turbine and battery storage systems [11].

Roselyn et al. propose an intelligent coordinated control strategy based on Adaptive Neuro-Fuzzy Inference System by combining control techniques such as reverse fall control, virtual impedance control and current control in order to minimize the imbalance between production and demand during the operation of the microgrid. As a result of simulation-based experimental studies, it is claimed that the proposed design performs better in different system conditions with fast switching response compared to other control algorithms [12].

Yu et al. propose an adaptive Multiple Input and Single Output (MISO) fuzzy logic algorithm to control frequency oscillation in power systems and to minimize the power generation cost of the system. PSO algorithm is used for efficient operation of the system in the controller design. As a result, it was stated that the MISO structure works more efficiently than the other structures compared [13].

Rahmann et al. propose a new artificial neural network-based control strategy to reduce the negative effects of partial shading on the frequency control of the grid in large power PV systems. The results obtained in the study show that the designed strategy significantly improves the frequency performance of the network [14].

Kaushal et al. proposed a new artificial neural network (ANN) based control system that can control power quality according to IEEE/IEC standards in order to minimize voltage and frequency fluctuations in systems where distributed resources are connected. The proposed controller structure has been implemented in a microgrid structure in the simulation environment [15].

Chettibi et al. proposed a method based on ANN and Deep Recurrent Neural Networks (DRNN) for very short-term grid voltage and frequency estimation in renewable energy systems. The validation data used during the tests of the system was obtained from the grid connected battery storage system installed at the University of Manchester. As a result, it has been determined that the designed algorithm predicts the variables with a satisfactory accuracy [16].

The above-mentioned literature survey puts forward that Fuzzy and ANN applications are very significant methods to reduce the voltage and the frequency fluctuations in the grid.

IV. FUZZY AND ANN APPLICATIONS USED IN ACTIVE-REACTIVE POWER CONTROL

Fuzzy logic and ANN algorithms have been applied using different methods for PQ control and power quality improvement of grid-interactive systems working in parallel with renewable energy sources. Some studies in the literature are given below in particular fuzzy and ANN.

Das et al. carried out a design using a shunt hybrid filter to improve power quality and improve PQ in microgrids. In the proposed design, fuzzy neural network was used and the results were compared with other control methods [17].

Ouai et al. developed a model for guaranteeing the possibility of exploiting the Photovoltaic System and the full capacity of the Power Conditioning, power quality of a SECS, reactive power compensation, and management of active power generation. Consequently, results of study show performance and the effectiveness of this control strategy and confirm that the SECS can complete at its maximum power although the power quality can be enhanced by active filtering and reactive power compensation [18].

Fuzzy proportional complex integral control method proposed by Hou et al. to optimize the control effect of the quasi-Z source grid-connected photovoltaic inverter. The exclusive of zero steady-state error improvement is included in this method for the AC disturbance signal of a specific frequency and exclude the steady-state error [19].

Carvalho et al. proposed fuzzy based model to power smoothing of a full-converter wind power fluctuations using a supercapacitor energy storage. Model operates the state of charge (SOC) of the supercapacitor during failings and augments wind power smoothing and in the simulated microgrid. According to the baseline case and conventional smoothing technique, proposing model presents better performance of the fuzzy based approach in all cases [20].

Faroug et al. developed Proportional-Integral (PI) controlled Static Synchronous Compensator (STATCOM) controllers and compared with Fuzzy Logic Controlled (FLC) STATCOM controllers. These controllers repair from the fault by injecting reactive power in the grid and, they used to stabilize the voltage in wind power plants by blocking tripping of Wind Generators (WG) [21].

Roselyn et al. developed an intelligent fuzzy based reactive and real power control of inverter to effective Low Voltage Ride Through (LVRT) capability. To classify the overshoot in dc link voltage during grid faults, dynamic braking resistor and a braking chopper are entered in the recommended LVRT scheme [22].

A fuzzy logic based optimal tip speed ratio maximum power point tracking controller to grid connected wind energy conversion system was proposed by Babu et al. The general system includes fuzzy logic controller (FLC), PWM inverter, DC boost chopper, three phase uncontrolled rectifier, permanent magnet synchronous generator (PMSG) and a three bladed fixed pitch turbine. The maximum power point tracking (generator side) controller completed its objective of extracting maximum power from the wind at any speed [23].

Yang et al. tuned Fuzzy Empirical Mode Decomposition in order to smooth the fluctuations of wind power with the use of battery energy storage system. With this reason, the wind power signal filtered into two sections as the low frequency part and the high-frequency part. Proposing filter is advanced restriction of the state of charge of the battery energy storage system and the power fluctuation rate. According to results, proposing model can accomplish tolerable smoothing achievement of wind power fluctuation [24].

Efrain et al. facilitated Fuzzy-based reactive control in order to smart PV inverters. In this study researchers used a real-time digital simulator to smart distribution power grids. According to results, proposing model reduces the power losses, synchronously minimizes the voltage rise magnitude and the PV reactive power injection [25].

Naidu et al. developed distributed power flow controller-based integrated hybrid system model. In this hybrid model, FOPID and PQ theory controller are used. Proposing system are validated by comparing ANFIS, FUZZY, PI controllers. As a consequence, FOPID controller shows better voltage performance with regard to harmonic reduction, transition fall voltage, transition rise voltage, compensation of voltage [26].

Rezaie et al. used Fuzzy-based static var compensator (svc) for low voltage ride-through capability of a wind-integrated power system. Proposing controller provided the maximum voltage drop under fault situations is declined and steady state voltage is enlarged and also the maximum voltage drop after the fault occurrence at the generator (wind farm) bus and the steady state voltage error at the load bus are declined by 25.16% and 74.44% on average, respectively [27].

Kaushal et al. developed power quality control based on power factor, total harmonic distortion, frequency, unbalancing, voltage sag/swell using artificial neural network in PV integrated AC microgrid. This system is proved with the development of line communication and impedance delay for the assessment of power quality parameters. Consequently, controller can work suitably even if the nature of distributed energy resources is changed [28].

Kumar et al. used shunt active power filter in a PV-wind-fuel cell-based hybrid renewable energy system to address the power quality problems. In this study, the dynamic performance of shunt active power filter is optimized using adaptive neuro-fuzzy inference system, neural network, and fuzzy logic-based control algorithms. These controllers minimize the total harmonic distortion (THD) produced and provide the smooth DC-link voltage using the balanced/unbalanced and nonlinear loads [29].

Douiri et al. facilitated an Artificial Neural Network based Direct Power Control strategy to synchronizing Double Fed Induction Generator and controlling power flow with Voltage Oriented Control and grid. The proposing model scheme obtain much shorter execution times and then, the errors lead to by control time delays are minimized [30].

Abdalrahman et al. developed intelligent blade pitch control for small-scale Darrieus vertical axis wind turbine with respect to power output. To determine the ideal pitch angles, ANSYS Fluent Computational Fluid Dynamics (CFD) software was used and the power coefficient (Cp) was calculate and the result depicts that MLP-ANN results in better power according to a conventional proportional integral derivative (PID) controller [31].

Kow et al. proposed memory self-organizing incremental neural network, which uses clustering technique in order to detect the occurrence of power fluctuation events and output power. This method catch power fluctuation events with a high detection rate of 92.69 % and show better performance according to nonlinear autoregressive with exogenous input (NARX) networks, focused time delay neural network (FTDNN), k nearest neighbor (KNN) and conventional self-organizing map (SOM) [32].

Mordjaoui et al. used dynamic neural network in order to forecasting of daily power consumption. The performance and suitability of this method confirmed and showed on load data collected from French Transmission System Operator (RTE) website. According to results of prediction method, mean absolute percent error is 4.223% for historical loads and for the forecasted load of one day ahead is 3.266% [33].

Monteiro et al. analyzed seven different training algorithms in artificial neural networks to prediction of generate active power. In this study, the hours per day, temperature of the solar panel, air temperature and irradiation are used dataset and researchers compared best results with Kalman filter and Support Vector Machine. Consequently, mape result of ANN, SVM and KF are 0.02%, 0.33% and 3.41%, respectively [34].

Saviozzi et al applied load prediction and modeling with Artificial Neural Networks ensembles. In this study researchers used historical load time series and data identify with network customers as a data set. According to results, researchers encourage to people to use both proposing methods to take good result on real distribution network [35].

The above-mentioned literature survey highlights that Fuzzy and ANN applications are very important techniques in order to achieve successful active-reactive power control in the grid.

V. Conclusion

In today's electricity generation systems, where smart grids are gaining importance, grid interactive systems are an important topic. Supporting the grids with renewable resources and integrating different resources into the systems are important in terms of reducing the cost of energy and ensuring continuity. Grid-interactive systems working with renewable resources face problems in connection and load distribution.

In the solution of these problems, control algorithms such as Fuzzy and ANN are increasingly used instead of classical systems. Many uses of these intelligent control structures such as active-reactive power balancing, voltage and frequency fluctuations, grid smooth switchover, the effects of shadowing in PV systems, and the use of batteries on PQ control in power transmission systems are found in the literature When the studies in the literature are examined, Fuzzy applications are used in the production of control signals to power electronics converters in the decision-making phase, while ANN applications are mostly used in prediction and optimization applications. The use of ANN applications with other metaheuristic algorithms increases the efficiency and reliability of the controllers. In this study, a literature review was conducted regarding the different uses of these algorithms in recent years. It is expected that this study will guide the researchers who will work on the subject in the future.

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