International Journal of Scientific & Engineering Research Volume 12, Issue 1, January-2021
ISSN 2229-5518

Power Management Strategy Based on Fuzzy Inference System for AC Microgrid

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Abstract— These Microgrids (MGs) are being increasingly adopted as more efficient and resilient electrical networks. However, the output fluctuations of the integrated renewable energy sources (RESs) renders the system stability a challenging problem. A robust power management strategy (PMS) of the MG is needed to overcome this issue. This paper introduces a PMS based on fuzzy inference system (FIS) for AC MG consisting of a solar photovoltaic (PV) panel, a double fed induction generator (DFIG) driven by a wind turbine (WT) and a diesel generator (DG). The results were then compared after using the adaptive neuro fuzzy inference system (ANFIS) for system management to assess effectiveness. The proposed AC MG with the PMS is designed by the MATLAB/Simulink software, different climatic conditions and electrical faults were simulated. Both the used PMSs produced similar results.

Index Terms: Adaptive neuro fuzzy inference system (ANFIS, diesel generator (DG), fuzzy Inference system (FIS), Microgrid (MG), power management strategy (PMS), photovoltaics (PV), renewable energy resources (RERs), wind turbine (WT).

1 Introduction

The ongoing improvements of the power industry have always prioritized the enhancement of power system reliability and resiliency. Power distribution systems are increasingly transformed into active distribution networks with smaller and more manageable subsystems, known as microgrids (MGs). MGs are rising as a prominent approach because they can operate in both the grid-connected mode, where they offer an auxiliary source of power to the main grid, and/or islanded mode, where they can be isolated from the main grid in case of faults. Both modes can increase the overall power system reliability [1]. Moreover, the use of MGs as hybrid networks allows better coping with power system failures resulting from the high impact events, the abrupt changes in the climate and the expected future rise in the frequency of natural disasters such as cyclones, floods, tornados and hurricanes [2].

Traditional energy sources like diesel generators (DGs) depend on burning of fossil fuels, such as oil and natural gas, and the release of the emission gases, such as carbon dioxide and methane. The fossil fuels cannot be found constantly, and the end products cause pollution and climate changes. Yet, DGs still possess cheap capital cost and high efficiency and reliability. The renewable energy sources (RESs), such as solar, wind, hydropower, hydrogen, biomass and geothermal energy, though intermittent, can outweigh the traditional power sources being clean energy resources with much lower running costs. The solar and wind energy are the most popular clean power sources with global extracted power reaching 613 GW and 793GW, respectively by the end of the year 2020 [2]. The concept of "the hybrid power system" was proposed to merge the RESs with the traditional sources like DGs, trying to take the advantages of both types and minimize the disadvantages. The traditional source of power will be able to meet the energy need when one of the renewable systems drops or fails to produce energy [3].

For a proper and smooth operation of a MG, an efficient Power Management Strategy (PMS) is mandatory. This strategy enables the system to control the terminal power of each distributed generation unit, regulate the MG voltage and frequency, guarantee the optimum cost and power sharing and, most importantly, maintain the balance between the power generation and the power demand.

The power management of networks in remote areas is usually challenging as it should provide quick operation of a MG with multiple distributed generation units, particularly in autonomous mode, for a reliable and efficient power supply. The PMS assigns the real and reactive power references of all the distributed generation units to be effectively employed for optimum sharing of the load requirement [4]. The master controller of the smart MG is responsible for the maximum extraction of the clean power through the coordination of control between the RESs and fuel-based generators [2].

In our study, we propose a MG consisting of a double fed induction generator (DFIG) driven by a wind turbine (WT) and a solar photovoltaic (PV) panel as a hybrid renewable energy system in combination with a DG. The PMS is based on Fuzzy Inference system (FIS) with different objectives to improve the efficiency of MG operation. Different input variables and case studies are collected to the fuzzy and studied de-

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pending on the weather conditions and the state of the network. Also, the PV is used to drive the rotor of the DFIG with different scenarios depending on the density of the solar irradiation. Another PMS based on the adaptive neuro fuzzy inference system (ANFIS) was reconstructed. The system output was compared after using each of the two techniques.

Many previous works have integrated different RESs (i.e. solar, wind, geothermal, hydro) with different storage units (i.e. fuel cell, batteries, fly wheel) and loads in MGs to investigate the ability of different fuzzy logic based PMSs to satisfy the demand and balance the system elements. Authors in [5] designed a residential DC-MG with a Fuzzy Logic based PMS. It had small number of rules and was meant to fulfill the demand and keep the balance between the different sources, storage units and loads. The fuzzy logic controller in [6] exploited the nonlinear mapping between sources and improved the system bus voltage regulation under different operating conditions. In [7], an islanded AC MG consisting of a PV, battery, load and auxiliary supplementary unit was introduced. The proposed supervisory controller was based on fuzzy logic and meant to maintain a stable power flow regardless of variations in the load demand or the intermittent power of the RES. It also assured that the state of charge (SOC) and charging/discharging power of the battery are kept within their design limits. The droop control of a standalone DC MG in [8] was modified through a distributed control algorithm based on fuzzy logic to overcome the mismatch in power sharing between sources to maintain the stable power flow within the MG. In [9], the Fuzzy logic based controller of an autonomous MG was proposed when the system is operating only with conventional DGs and when integrated PVs are operated. The reactive power management along with the DPC technique have improved the performance of the MG operated with PV power plant and provided voltage stability when the MG is subjected to the fault. Also the authors in [10] chose to build a fuzzy logic supervisor for the smart MG power management along with developing a new approach of active damping technique based on mathematical model of voltage source convertor without any additional sensors.

Accordingly, this paper is arranged as following: an over view for FIS and ANFIS techniques, then a system description for the proposed MG with detailed description of the proposed PMS and the used distributed energy resources. Finally, the conclusion after simulation and results will be displayed.

2 FUZZY INFERENCE SYSTEM (FIS)

The Fuzzy logic-based methods have been widely applied to the control of power electronic systems, e.g., speed control, MPPT and energy management, to name a few [11]. Fuzzy Logic is a rule-based method extending the Boolean logic into a multi-valued case. It is considered an ideal tool to tackle the system uncertainties or noisy measurements.

In this system, the precise input crisp values are not used directly. The first step is a "fuzzification" process performed on the input variables with several membership functions ranged 0 to 1 as the fuzzy sets. They include triangular, trapezoidal, Gaussian, bell-shaped, singleton, and other customized shapes. Then, the fuzzy input signals are aggregated with fuzzy rules in the inference module according to IF-THEN fuzzy rules in the knowledge base derived from the expert experience. "Defuzzification" is subsequently performed on the inference result by considering the degree of fulfillment and output a crisp value. The crisp value is manipulated in a fuzzy space that completes the nonlinear mapping between the input and output with carefully designed principles. One example of the fuzzy rule is: Antecedent: IF X is Medium AND Y is Zero, Consequent: Then Z is Positive, where the degree of fulfillment for both the antecedent and consequent is determined by the membership functions [11], [12]. Fig. 1 displays the FIS structure.

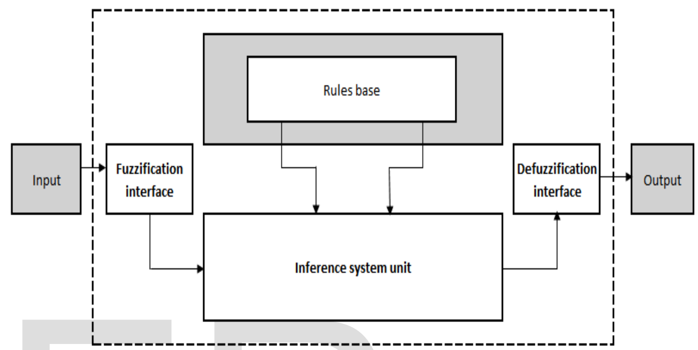


Fig-1 Fuzzy Inference System structure.

There are three distinct types of fuzzy inference systems: "the Mamdani-type", which uses fuzzy sets as rule consequence, "the Sugeno-type" that uses linear functions as rule consequence, and "the Tsukamoto-type" in which the consequent of each fuzzy rule uses a monotonically membership function [11].

The fuzzy system offers a lot of advantages: (1) It is similar to human reasoning, and (2) based on linguistic model. (3) It uses simple mathematics for nonlinear, integrated and complex systems. (4) It shapes the human knowledge into membership rules and functions. (5) Method of nonlinear control and ability to be used efficiently for HVAC systems. (6) High precision, and (7) rapid operation [13]. On the other hand, it is notable that the fuzzy logic controller lacks the internal updating mechanism and thus has a limited adaptability [11]. Also, the expert experience plays a critical role in the design of the membership function and the fuzzy rule, so in most cases, this method may not be practical and is only applicable to experts. Nevertheless, from this perspective, the expert experience can be coped with fuzzy logic and then incorporated with other artificial intelligence techniques as a hybrid method [11], [12].

3 ADAPTIVE NEURO FUZZY INFERENCE SYSTEM (ANFIS)

ANFIS is a multi-layered adaptive network that combines the learning ability of artificial neural networks and the inference principles of fuzzy logic. The addressed hybrid learning algorithm uses both back propagation and least square algorithms. In order to apply the ANFIS method, first of all, a data set containing inputs and outputs is required. Then, the number and type of membership functions are selected, and the established model is accordingly created using a learning algorithm. The method uses the created fuzzy set of if-then rules. ANFIS architecture is created by determining parameters to minimize the difference between output and target values [14].

Five layers are necessary to create the ANFIS inference system. Each of these layers consists of several nodes defined by the node functions. The ANFIS architecture is given in Fig. 2, while the adjustable parameters are denoted with square nodes, the nodes which parameters are fix are denoted in circles. [14]

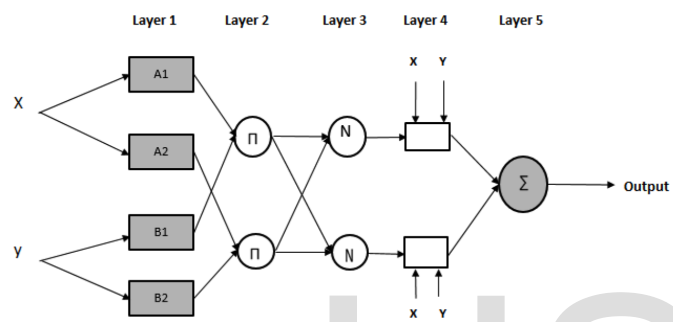


Fig-2 ANFIS architecture

4 Proposed MG System Description

Fig.3 shows a schematic diagram of the proposed MG. The MG is composed of two renewable power sources (DFIG driven by a WT and PV) and a traditional DG. The MG is required to continuously supply a two-megawatt residential load.

The DFIG stator is directly connected to the grid whereas the PV is directly connected to a DC bus through a maximum power point (MPP) boost circuit to feed the DFIG rotor through the rotor side converter (RSC) and also supply the grid occasionally through grid side converter (GSC) via a chock coil. The DG stator is coupled with the grid through a step up power transformer that raises the voltage from 400 V to 575 V as the main MG and load voltage.

The proposed PMS for the mentioned MG is responsible for dealing with the uncertainty of different climatic conditions by consecutive detection of the PV and DFIG outputs and dispatching the required amount of mechanical power that enables the DG to complete the electrical power for the residential load. The FIS will save the use of an adaptive online controller and is quite simple to undergo any future upgrading.

The proposed fuzzy controller is fed by three inputs; the wind speed (as indication for WT output), the solar irradiation and the ambient temperature (as indication for PV generator output). The fuzzy output is the expected mechanical power that should be dispatched to DG to complete the power required to balance the residential load as previously illustrated. The number of membership functions for each input is three and their type is triangular. The number of used rules in rule base is 27 rules and the defuzzification technique used is the Sugeno-type. Fig. 4 shows the proposed fuzzy rules viewer.

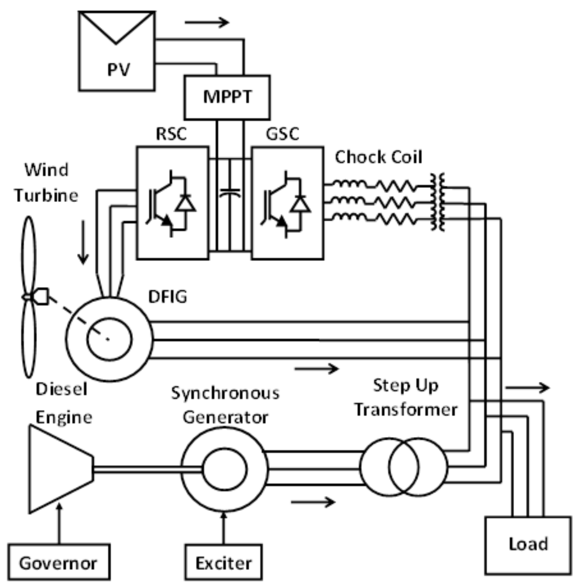


Fig-3 The proposed MG hybrid power system structures.

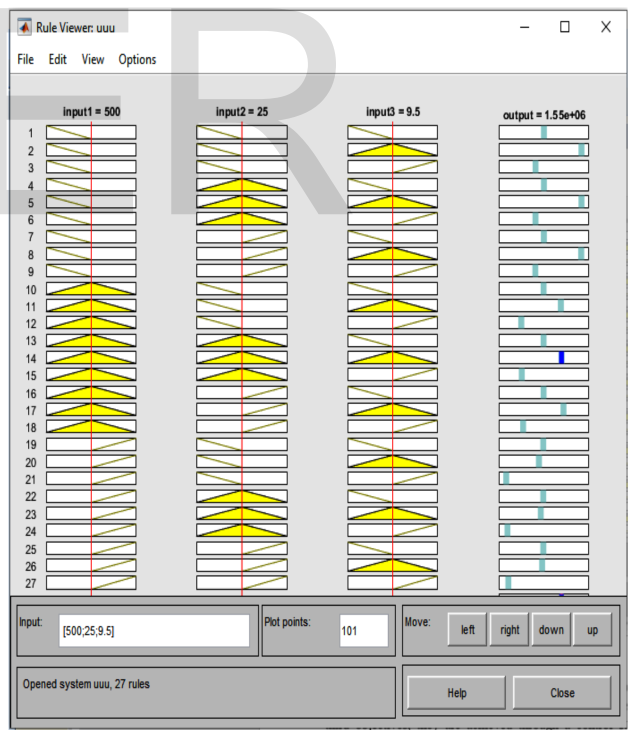


Fig- 4 Proposed fuzzy rules viewer.

The parameters of inputs' membership functions were determined after many trials and errors. To overcome the need of these multiple attempts, an ANFIS-based PMS was implemented. Unlike the FIS, ANFIS uses benefit of the learning capability of neural networks and automatically creates sufficient rules concerning input and output data. It does not need expert opinion for modelling and training the system. ANFIS is currently one of the effective tools used for pattern recognition, system identification and generation of precise models of systems [11].

For the ANFIS controller, the same inputs and output were used. The training with the various climatic conditions used a hybrid learning algorithm combining the least square and gradient descent methods with 200 epochs and 385 training samples. Table 1 presents ten random training samples. The same type and inputs' membership functions of the FIS were intentionally used with the ANFIS for better comparison between the FIS-based and ANFIS-based techniques.

TABLE 1.
Ten random samples from ANFIS training samples:

Input 1 Wind Speed (m/s)	Input 2 Solar Irradiation (W/m^2)	Input 3 Ambient Temp, (c°)	output DG Mech. Power (W)
9.6	1000	40	879600
12	600	30	611900
7.2	700	15	1801250
8.4	800	35	1206500
9.6	300	25	1343400
12	200	15	871800
8.4	400	20	1457300
7.2	100	30	1382400
8.4	0	35	1725000
12	900	25	404000

In the WT of the proposed system, the torque speed drives the DFIG to run always in sub-synchronous operation mode even in the case of any expected high or low wind speeds. This provides the advantage of exploiting all the mechanical power output of the WT and the electrical power of the rotor by the DFIG stator.

The hybrid power system is meant to overcome the uncertain nature of the renewable power components as the DG is always in service to supply the grid with the precise amount of its contribution determined according to the proposed controller as previously discussed.

Fig. 5 shows a summary for the main power flow segments of the proposed system all day long. When the solar irradiation is maximum, a part of the PV power output supplies the DFIG rotor and the rest feeds the grid through the GSC that acts as an inverter. The power rating of the used PV array at the maximum expected solar irradiation and minimum expected ambient temperature is chosen to be more than the highest DFIG rotor power consumption according to the following relation [15]:

$$P_r = sP_s \qquad (1)$$

Where P_r and P_s are the DFIG rotor and stator power, respectively and   is the slip.

As the solar irradiation declines, the PV power is decreased and feeds the rotor only. When the sunlight goes even weaker, the GSC, acting as a converter, contributes with the PV in the rotor supply with an amount of power from the MG through the DC bus. Finally, when the solar irradiation fades away, the rotor is totally fed by the MG.

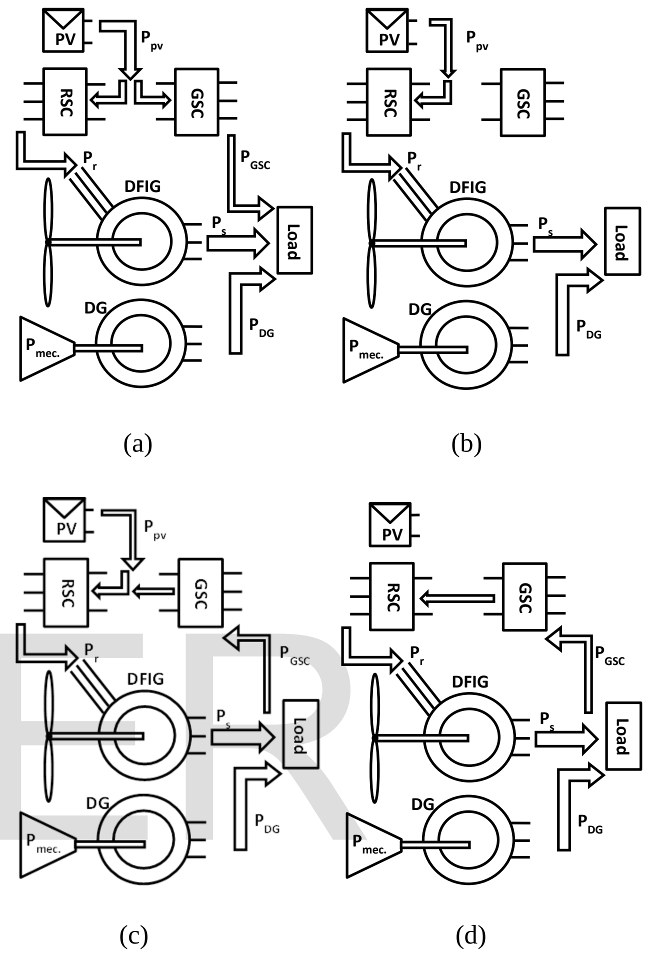


Fig-5 The main power flow segments of the proposed hybrid power system during most of the day:
(a) PV supplies both of the DFIG rotor power and the MG load directly during high solar irradiation.
(b) PV supplies the DFIG rotor power only when the sunlight is light.
(c) The DFIG rotor power is supplied by the PV and the MG when the solar irradiation becomes weaker.
(d) The DFIG rotor power supplied only by the MG during solar irradiation fading.

4.1 THE PV

The PV generator has a nonlinear voltage current characteristic based on solar irradiation and ambient temperature. It can be expressed from the following formula:

$$V_g = \frac{1}{A_g} \ln\left[\frac{GI_{phg} - I_g + I_{og}}{I_{og}}\right] - I_g R_{sg} \qquad (2)$$

Where V_g & I_g are the PV generator voltage and current, respectively; $A_g = \Lambda/Ns$ is the PV generator constant;

Λ=q/(ε×Z×U), is the solar cell constant; q=1.602×10^{-19} C. is the electron charge; Z=1.38×10^{-23} J/K is Boltzman constant; U= 298.15; K is the absolute temperature; ε =1.1 is the completion factor; $R_{sg}=R_s\times(N_s/N_p)$ is the PV generator series resistance; N_s is the series connected solar cells; N_p is the parallel paths; Rs is the series resistance per cell; $I_{phg}=I_{ph}\times N_p$ is the insolation-dependent photo current of the PV generator; I_{phg} = 4.8 A is the photo current per cell; $I_{og}=I_o\times N$ is the PV generator reverse saturation current; I_o=2.58e^{-5} A is the reverse saturation current per cell; G is the solar insolation in per unit, and 1.0 per unit of G=1000 w/m² [16].

The proposed PV array type is SunPower SPR 305E-WHT-D built from 440 parallel strings and each string consists of 5 series modules with attached MPP tracking boost circuit. The philosophy of PV power rating selection, as displayed in the proposed array technical specifications, Table 2, is to determine the sufficient power that should supply the DFIG for optimum running at 1000 w/m² solar irradiation and 25 c° ambient temperature during all expected wind speeds and in case of any excess power, it feeds the grid directly.

TABLE 2.
The main technical specifications of the used PV array at 1000w/m2 solar irradiation, 25 c° ambient temperature

Description	Specification
Array type	SPR 305E-WHT-D
Rated maximum power	671500 W
Voltage at maximum power	273.5 V
Current at maximum power	2455 A
Open circuit voltage	321 V
Short circuit current	2622 A

4.2 THE DFIG DRIVEN BY WT

The wind energy conversion system transforms the wind kinetic energy into mechanical energy by means of the aerodynamic forces that produce lift on the rotor shaft blades. It can be calculated as:

$$P_\omega = \frac{1}{2}\rho\pi R^2 v_\omega^3 C_P(\lambda,\beta) \qquad (3)$$

Where $P\omega$ is the extracted wind power, ρ is the air density (1.225 kg/m³), R is the rotor radius, v is the wind speed and C_P is the efficiency coefficient of the turbine which is the function of the tip-speed ratio λ and the blade pitch angle β. The tip-speed ratio λ is expressed as:

$$\lambda = \frac{\omega_t R}{v_\omega} \qquad (4)$$

Where ω_t is the turbine rotational speed [17].

The DFIG is the commonly used WT-driven generator especially when high power ratings are needed as implemented in the proposed system. It has three modes of operation categorized according to the operating rotational speed and the rotor power direction. In the "super-synchronous" mode, the operating speed is always above the synchronous speed and the rotor supplies a part of the generated power. The second mode is called "synchronous" mode, where the operating speed is the synchronous speed and the rotor does not supply or receive any AC power but receives a DC power to act as an exciter. The third is the "sub-synchronous" mode, where the operating speed is always below the synchronous speed and the rotor receives a part of the generated power.

The power characteristic curve between the rotational speed and the output power for any WT has a MPP that changes according to the wind speed. Therefore, the MPP tracking curve specifies the reference power for the control system of the driven electrical generator according to the actual speed of the WT [18], Fig. 6. The figure also shows that the proposed turbine is designed to produce always the maximum power at speeds less than the DFIG synchronous speed even with different wind speeds. The sub-synchronous operation mode of the DFIG is the part assigned to our study where the wind speed is chosen to be ranged from 13.2 to 6 m/s. Table 3 summarizes the main technical specifications of the proposed wind energy system.

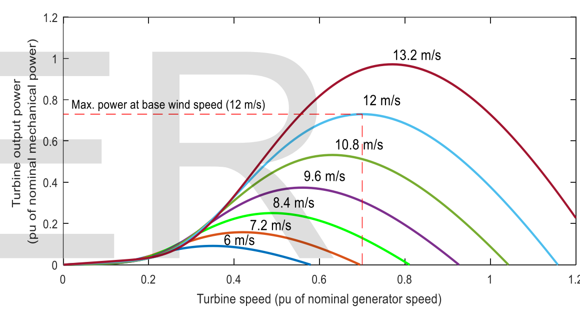


Fig- 6 The power characteristic of the used WT

TABLE 3.
The main technical specifications of WT and DFIG

Description	Specification
Turbine nominal mechanical power	1.5 MW
Base wind speed	12 m/s
Maximum power at base wind speed	0.73 pu of nominal mechanical power
Base rotational speed	0.7 pu of base generator speed
DFIG rated capacity	1.67 MVA
Nominal stator voltage	575 V
Nominal frequency	50 Hz
Poles pairs number	3
DC bus voltage	1200 V
Stator resistance & inductance	0.023 & 0.18 pu
Rotor resistance & inductance	0.016 & 0.016 pu
Mutual inductance	2.9 pu
Inertia constant	0.095 s
Friction factor	0.054 pu

In this work, the stator voltage oriented control (SVOC) is used to control and get the maximum DFIG stator active power and also regulate the DFIG voltage terminals to rated voltage.

4.3 THE DG

The stochastic and intermittent characteristics of wind and solar powers necessitate the use of another power source that acts as a backup power source to cover the anticipated imbalance in load demand and guarantee the stability and reliability of the grid. DG system is considered one of the best selections to be integrated in a MG. Although it is criticized for the expensive running cost of fossil fuel and the great environmental damage caused by generating green gases such as carbon dioxide, it is still marked by its large capacity, continuous power supply, strong environmental adaptability and flexible operating characteristics [19]. The DG system consists of two main parts. These are; a mechanical part comprising a diesel engine and a governor system that controls the output frequency and active power. The second part is electrical, consisting of a synchronous generator and an automatic voltage regulator (AVR) responsible for the terminal voltage regulation and the output reactive power [20].

Table 4 displays the main technical specifications of the brushless synchronous generator used in this work. The selected rated output is asymptotic to the residential load so that the DG is able to supply the entire load in emergency situations.

TABLE 4.
The main technical specifications of used brushless synchronous generators

Description	Specification
Rated apparent power	2 MVA
Rated speed	1500 rpm
Rated field current	2.25 A
Rated line-line voltage	400 V
Number of poles	4
Exciter apparent power	8.1 kVA
Rated frequency	50 Hz

5 RESULTS AND ANALYSIS

The simulation of the proposed system was implemented by the MATLAB Simulink Software Package. The different power generation elements as well as the separate controller for each of WT and PV were modeled. The system performance under the proposed PMS was evaluated after using both FIS and ANFIS controllers.

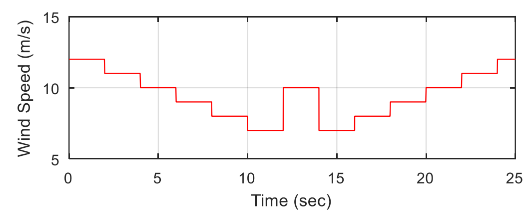
Evaluation of system performance is carried out under different climatic conditions that simulate the natural weather fluctuations throughout the day concerning solar irradiation, ambient temperature and wind speed. Both the solar irradiation and the ambient temperature reach their maximum value in the morning and gradually fades away till night. Paradoxically, the wind speed is relatively low during daytime with a gradual increase as the night falls. Abrupt weather changes were simulated from period t=12 to 14 s, as the wind speed may sometimes rise, decreasing the irradiation and temperature in turn while the sky becomes gloomy.

The step function is deliberately used in the weather conditions' changes for more ensured system robustness. As displayed in Fig. 10(a), the wind speed is set at 12 m/s o t=0 s. A constant gradual decrease towards 7 m/s is witnessed every two seconds from t=2 s until t=12 s. A sudden increase to 10 m/s for two seconds then decreases back to 7 m/s at t=14 s. Then, a constant gradual increase to reach 12 m/s again at t=24 s.

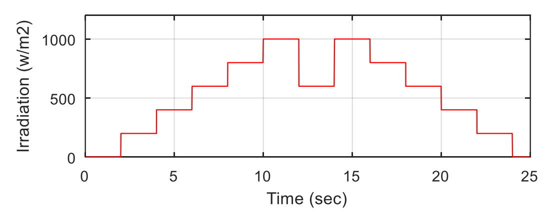
Fig. 7 (b) displays the changes in the solar irradiation. It is set at 0 W/m² at t=0 s. It undergoes a constant increase till 1000 w/m². At t=12 s, it suddenly decreases to 600 w/m² for two seconds. It re-increases to 1000 w/m² at t=14 s. Then, a constant gradual decrease to reach 0 w/m² again at t=24 s.

Fig. 7 (c) displays the changes in the ambient temperature. It is set at 15 c° at t=0 s. It undergoes a constant increase till 40 c°. At t=12 s, it suddenly decreases to 30 c° for two seconds. It re- increases to 40 c° at t=14 s. Then, a constant gradual decrease to reach 15 c°, again at t=24 s.

Fig. 7 (d) shows that, in case of FIS-based PMS, the deviation of MG voltage may reach 8% PU. While the ANFIS-based PMS succeeded to limit the error within only 5% PU, except for the overshooting of the system startup. On the other hand, the trends of the DC link bus voltage, the rotational speed and torque of the DFIG were quite similar between FIS and ANFIS controllers as shown in Fig. 7 (e, f and g). The error in the DC link voltage stability remained within 2%. Also the DFIG speed and torque kept the smooth performance without unaccepted overshootings even with the different wind speed changes.



(a)



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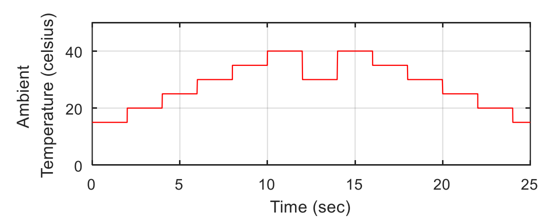


(c)

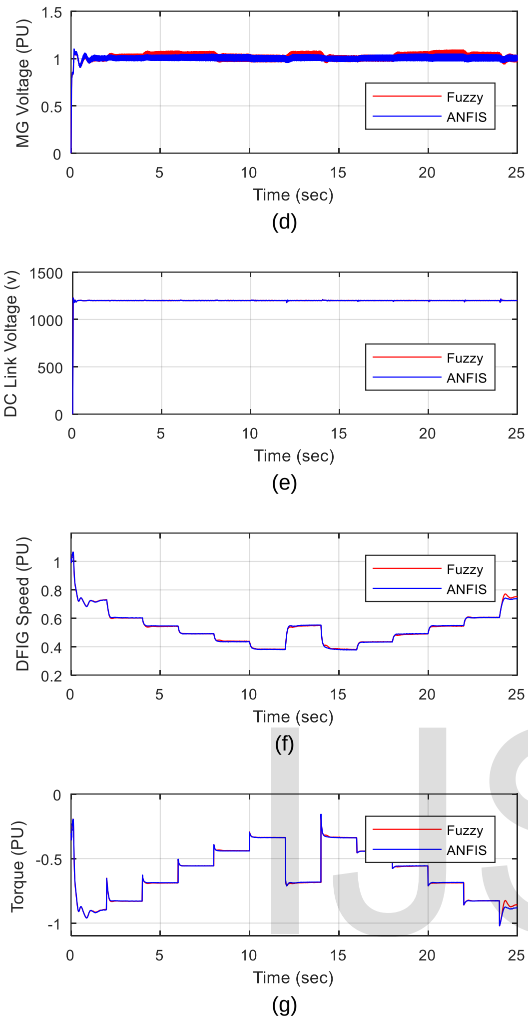
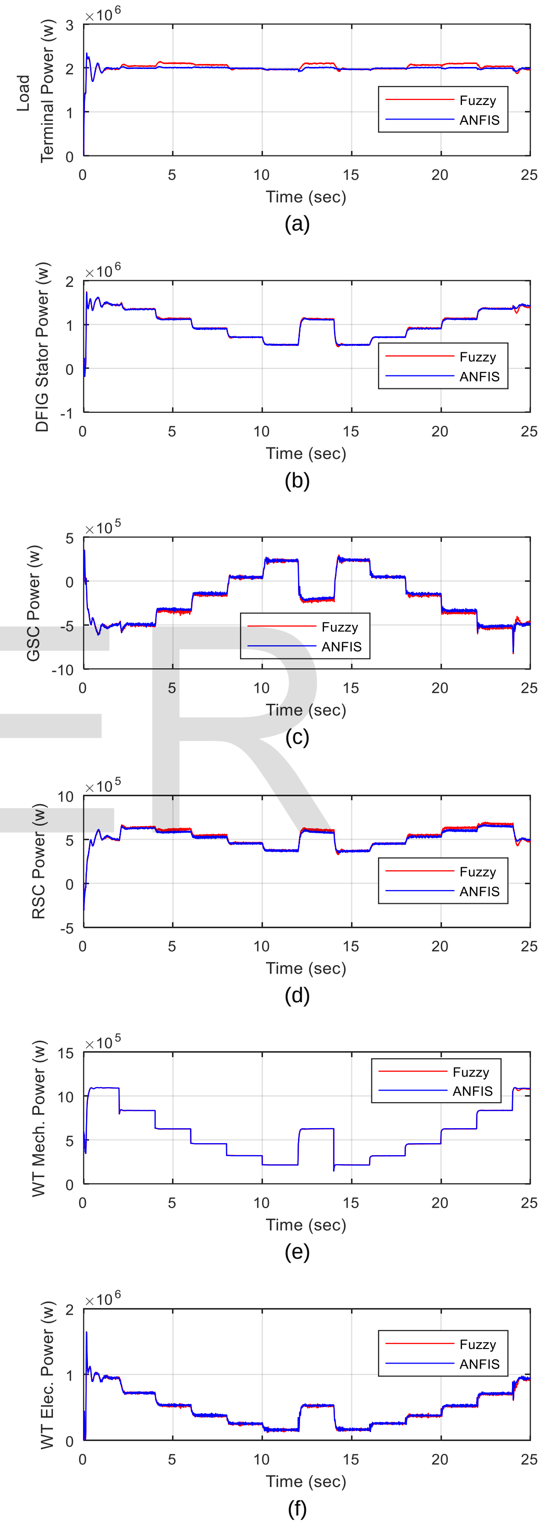


Fig-7 The system response under variable weather conditions for the proposed Fuzzy and ANFIS PMS: (a) wind speed, (b) solar irradiation, (c) ambient temperature, (d) grid Voltage P.U, (e) DC link voltage PU, (F) DFIG rotational speed, and (g) DFIG torque

Concerning the power sharing of all system generation elements, it was somehow similar between the different controllers, except for the DG mechanical and electrical power.

Then we assessed the system's capability to constantly provide the targeted 2 Mega-Watt residential load. It is clear in Fig. 8 (a) that, compared to FIS, the ANFIS-based PMS was more able to provide the target load without increase or decrease. This can be justified knowing that the generated output powers of the three system generation sources (PV, DFIG stator and DG) were reviewed all the time.

The output power trends of DFIG stator, GSC and RSC as well as the mechanical and electrical power produced from the WT were similar between the two controllers as displayed in Fig. 8 (b, c, d, and e). Also the PV generator produced similar outputs as shown in Fig. 8 (f). Whereas the DG power outputs were mismatched between the fuzzy and ANFIS based PMSs as Fig. 8 (g) shows. Clearly, the mechanical power inputs dispatched to DG from the two controllers were different. Fig. 8 (i) proves beyond any doubt that the ANFIS based controller was more efficient than the FIS based controller.



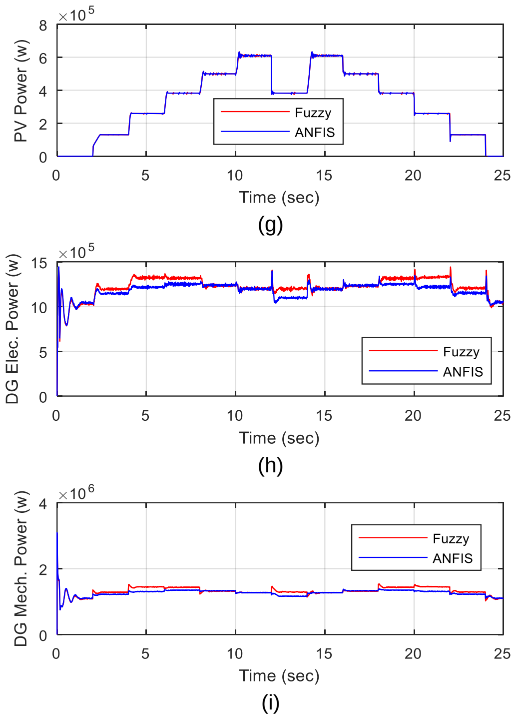


Fig-8 Power sharing of the different power sources in the proposed system: (a) load power (b), DFIG stator power, (c) GSC power, (d) RSC power (e), WT mechanical power, (f) WT electrical power, (g) PV power, (h) DG electrical power, and (i) DG mechanical power.

Tracking of the MPP from the different system elements is obviously one amongst the most important criteria that assess the overall quality of the proposed system, especially that it will decrease the fuel consumption by the DG. Fig. 9 (a) and (b) show that the system succeeded to track the MPP with no notable difference between the two tested controllers.

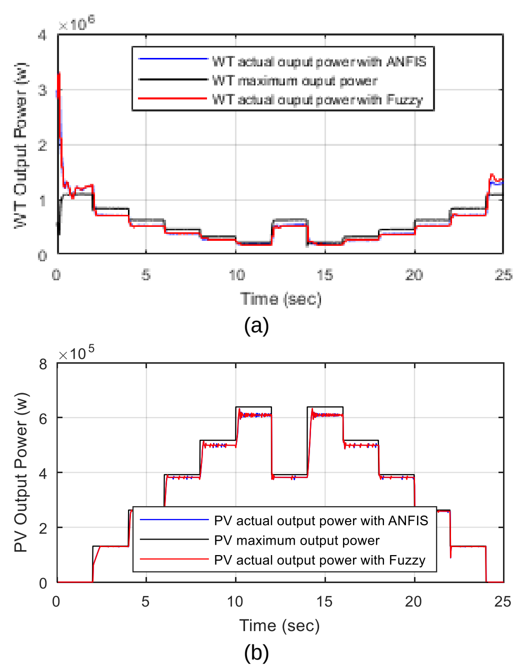


Fig- 9 MPP tracking capability for: (a) for the DFIG, and (b) for the PV

6 CONCLUSION

A smart PMS based on FIS has been proposed for a hybrid MG composed of DFIG driven by WT and PV, as RESs, together with a traditional DG. The ANFIS was also implemented to compare the results, as it provides greater independence from the human factor. With the different climatic and fault conditions tested, the results demonstrate the success of the FIS to achieve acceptable voltage stability, and balance of the generated power with the required loads. The ANFIS is proved superior to the FIS in voltage error percentages and mechanical power dispatched to the DG. Otherwise, the two controllers gave comparable performances allowing the system to achieve the required goals.

REFERENCES

[1] M. Z. El-Sharafy, S. Saxena and H. E. Farag, "Optimal Design of Islanded Microgrids Considering Distributed Dynamic State Estimation," in *IEEE Transactions on Industrial Informatics*, vol. 17, no. 3, pp. 1592-1603, March 2021.

[2] M. Yadav, N. Pal and D. K. Saini, "Microgrid Control, Storage, and Communication Strategies to Enhance Resiliency for Survival of Critical Load," in IEEE Access, vol. 8, pp. 169047-169069, 2020.

[3] E. Kabalci, H. Irgan and Y. Kabalci, "Hybrid Microgrid System Design with Renewable Energy Sources," 2018 IEEE 18th International Power Electronics and Motion Control Conference (PEMC), Budapest, 2018, pp. 387-392.

[4] Chitra Natesan, SenthilKumar Ajithan, Swathi Chozhavendhan, and Anitha Devendhiran " Power management strategies in microgrid: A survey". International Journal of Renewable Energy Research, vol. 5, pp. 334-340, 2015.

[5] J. C. Peña-Aguirre, A. Barranco-Gutiérrez, J. A. Padilla-Medina, A. Espinosa-Calderon and F. J. Pérez-Pinal, "Fuzzy Logic Power Management Strategy for a Residential DC-Microgrid," in IEEE Access, vol. 8, pp. 116733-116743, 2020.

[6] R. R. Deshmukh, M. S. Ballal and H. M. Suryawanshi, "A Fuzzy Logic Based Supervisory Control for Power Management in Multibus DC Microgrid," in IEEE Transactions on Industry Applications, vol. 56, no. 6, pp. 6174-6185, Nov.-Dec. 2020.

[7] R. Al Badwawi, W. R. Issa, T. K. Mallick and M. Abusara, "Supervisory Control for Power Management of an Islanded AC Microgrid Using a Frequency Signalling-Based Fuzzy Logic Controller," in IEEE Transactions on Sustainable Energy, vol. 10, no. 1, pp. 94-104, Jan. 2019.

[8] R. R. Deshmukh, M. S. Ballal, G. G. Talapur and H. M. Suryawanshi, "Distributed Control for Power Management Based on Fuzzy Logic in DC Microgrid," 2018 2nd IEEE International Conference on Power Electronics, Intelligent Control and Energy Systems (ICPEICES), Delhi, India, 2018, pp. 1-6.

[9] M. A. Djema, M. Boudour, K. Agbossou, A. Cardenas and M. L. Doumbia, "Fuzzy Logic Based Reactive Power Management for Autonomous MicroGrid," 2018 IEEE 27th International Symposium on Industrial Electronics (ISIE), Cairns, QLD, 2018, pp. 1249-1254.

[10] F. S. Tidjani, A. Hamadi, A. Chandra, P. Pillay and A. Ndtoungou, "Optimization of Standalone Microgrid Considering Active Damping Technique and Smart Power Management Using Fuzzy Logic Supervisor," in IEEE Transactions on Smart Grid, vol. 8, no. 1, pp. 475-484, Jan. 2017.

[11] Aengchuan, P., Phruksaphanrat, B. Comparison of fuzzy inference system (FIS), FIS with artificial neural networks (FIS + ANN) and FIS with adaptive neuro-fuzzy inference system (FIS + ANFIS) for inventory control. *Journal of Intelligent Manufacturing*, vol. 29, pp.905–923, 2018.

[12] S. Zhao, F. Blaabjerg and H. Wang, "An Overview of Artificial Intelligence Applications for Power Electronics," in IEEE Transactions on Power Electronics, vol. 36, no. 4, pp. 4633-4658, April 2021.

[13] F. Behrooz, N. Mariun, M. Marhaban, M. Mohd Radzi, and A. Ramli,

"Review of Control Techniques for HVAC Systems—Nonlinearity Approaches Based on Fuzzy Cognitive Maps," Energies, vol. 11, no. 3, p. 495, Feb. 2018.

[14] H. Acar, M. S. Özerdem and E. Acar, "Soil Moisture Inversion Via Semiempirical and Machine Learning Methods with Full-Polarization Radarsat-2 and Polarimetric Target Decomposition Data: A Comparative Study," in IEEE Access, vol. 8, pp. 197896-197907, 2020.

[15] Hesham M. Fekry, A. A. Eldesouky, A. M. Kassem and A. Y. Abdelaziz, "Power Management Strategy Based on Adaptive Neuro Fuzzy Inference System for AC Microgrid," in IEEE Access, vol. 8, pp. 192087-192100, 2020.

[16] A. M. Kassem, ''Modeling, analysis and neural MPPT control design of a PV generator powered DC motor-pump system,'' WSEAS Trans. Syst., vol. 10, no. 12, pp. 399–412, Dec. 2011.

[17] R. Nair and G. Narayanan,'' Emulation of wind turbine system using vector controlled induction motor drive,'' IEEE Trans. Ind. Appl., vol. 56, no. 4, pp. 4124–4133, Aug. 2020.

[18] B. Subudhi and P. S. Ogeti, ''Optimal preview stator voltage-oriented control of DFIG WECS,'' IET Gener., Transmiss. Distrib., vol. 12, no. 4, pp. 1004–1013, Feb. 2018.

[19] B. Zhu, H. Tazvinga, and X. Xia, ''Switched model predictive control for energy dispatching of a photovoltaic-diesel-battery hybrid power system,'' IEEE Trans. Control Syst. Technol., vol. 23, no. 3, pp. 1229–1236, May 2015.

[20] M. Salah, K. Bacha, A.Chaari, and M.E.H.Benbouzid "Brushlessthreephase synchronous generator under rotating diode failure conditions," IEEE Trans. Energy Convers., vol. 29, no. 3, pp. 594–601, Sep. 2014.