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Optimal Power Quality Enhancement through Fuzzy Control in Integrated Solar Photovoltaic and DFIG Wind Energy Systems for Grid Integration

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Abstract:

This paper explores the synergistic integration of solar photovoltaic (PV) and doubly fed induction generator (DFIG) wind energy systems, presenting a novel approach to enhance power quality. The proposed system employs a Fuzzy Logic Controller (FLC) to optimize the operation of the integrated hybrid system, addressing the inherent variability and intermittency associated with renewable sources. The FLC acts as an intelligent control mechanism, dynamically adjusting parameters to ensure seamless grid integration while prioritizing power quality improvements. The hybrid system's components, comprising solar PV and DFIG wind turbines, are strategically coordinated by the fuzzy controller to achieve optimal performance under diverse environmental conditions. Key focus areas include voltage regulation, frequency stability, and mitigation of harmonic distortions. The study aims to demonstrate the effectiveness of the fuzzy control strategy in achieving a harmonious balance between renewable energy generation and grid compatibility. The proposed system simulation results are evaluated with IEEE 1547 standard for showing the effectiveness of the system. The fuzzy controller has been developed for maximum power point tracking for 10 KW photovoltaic power systems and analyzed with various weather conditions.

Keywords: PV, DFIG, Grid, Fuzzy, Power Quality, Hybrid.

1 Introduction

In response to the escalating global demand for sustainable energy solutions, the integration of renewable energy sources into conventional power grids has gained paramount importance. Solar photovoltaic (PV) and wind energy systems, owing to their abundant availability and environmental benefits, stand out as key players in the pursuit of a cleaner and greener energy landscape. However, the inherent intermittency and variability associated with these sources pose challenges to their seamless integration into the power grid, necessitating advanced control strategies for optimal operation. Nowadays the researchers have developed advanced configurations of PV power conversion systems and MPPT controllers. The main advantage of solar photovoltaic power is its ability of generating electricity from sunlight without environmental collateral damage, less maintenance, no noise and 15 - 25 % efficiency. A common arrangement for large wind turbines is based on the DFIG with back-to-back converters between the AC grid and the rotor windings. The main advantage of the DFIG is its ability to change operational speed with only 20 - 30 % of the generated power passing through the power converters. The conventional controllers do not perform well in a DFIG system. Therefore, in this paper, fuzzy logic controller has been designed for DFIG control systems and is based on rotor current vector control with d-q decoupling. Primary energy resource is at a lower availability level while the subordinate one is usually at a higher availability level. For the occasion, in the winter seasons, the wind speed is generally highly available while the solar radiation is at its lowest intensity. The primary objective of this study is to improve power quality during the grid integration of the hybrid solar-wind energy system. Power quality encompasses parameters such as voltage stability, frequency regulation, and mitigation of harmonic distortions, all of which significantly impact the overall performance of the power grid. The FLC serves as an intelligent decision-making tool, dynamically adjusting system parameters to optimize the hybrid system's operation in real-time, thus ensuring a harmonious and stable interaction with the grid. During the night hours, sunlight cannot be used for power generation, whereas the wind energy can be successfully used. Hence, simultaneous utilization of multiple energy resources significantly improves to meet consumer load demands. In this study, the objective function is to improve the power quality of the hybrid system as a function of PV and Wind parameters. To achieve this

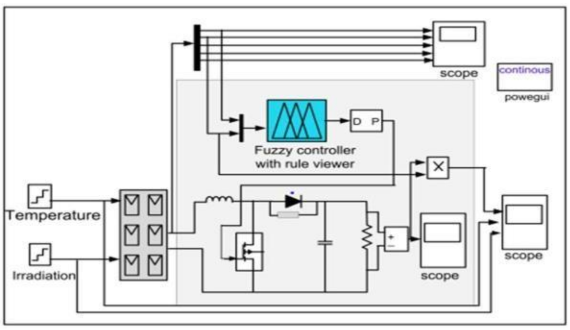


Fig. 1: Fuzzy based MPPT controller simulation model for 10KW PV system Design of Fuzzy Logic Controller.

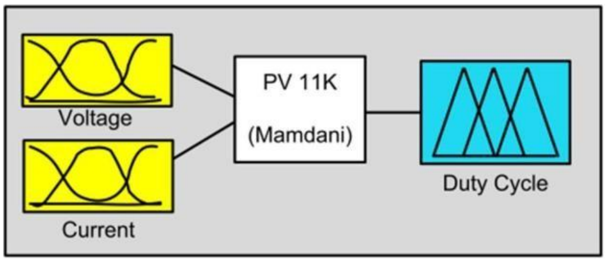


Fig. 2: Fuzzy controller structure for MPPT controller.

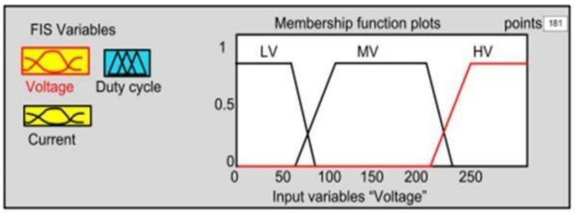


Fig. 3: Fuzzy input memberships function of PV voltage.

fuzzy logic controller has been developed for hybrid PV and DFIG wind energy system and synchronized with power grid for improving the power quality. This paper is organized as follows. The maximum power point tracking of PV system using Fuzzy logic controller is presented in Section II. Then, in Section III, the design of the DFIG wind energy system and rotor current control by using fuzzy controller is implemented. In Section IV, a discussion of implementation of fuzzy controller based grid integration of hybrid PV / DFIG and finally in Section V, the conclusion of research work is presented.

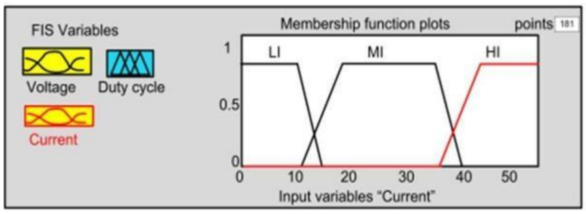


Fig. 4: Fuzzy input membership function of PV current

2 MPPT Controller for PV system

The Maximum power point tracking algorithmis playing a very essential role in renewable energy sources for generating maximum power at various weather conditions. The solarphotovoltaic system

generates electricity with respect to falling of sunlight on modules. The sunlight irradiance is nonlinear characteristics that intermittent availability cause solar PV modules unable to generate maximum power. In literate survey, different types of MPPT controllers based on Perturb and Observe (P&O) algorithm, Incremental Conductance algorithm, Feedback voltage and current,

feedback power algorithm etc. are designed and verified. In this paper, the fuzzy logic controller based on MPPT algorithm has been developed and simulated in MATLAB environment and compared with conventional controller. The boost converter based PV MPPT system has been developed in MATLAB as shown in fig 1. The fuzzy logic controller has been developed with two inputs and one output functions such as PV voltage, PV current and duty cycle of the PVboost converter as shown in fig 2. The fuzzy PV voltage input membership function is classifiedinto three ranges such as low voltage, medium voltage and high voltage as presented in fig 3. The fuzzy PV current input membership function is classified into three ranges namely low current, medium current and high current as presented in fig 4. The fuzzy duty cycle output membership function is classified into three ranges that are low duty cycle, medium duty cycle and high duty cycle as presented in fig 5. The fuzzy membership function are designed based on the trapezoidal method for Fuzzification process and used centroid methodfor de-fuzzification process.

The fuzzy rules are formed based on input data and analysis duty cycle various conditions such as low input, medium input and high input arepresented in fig 6 to fig 8. The fuzzy rules surface waveform presented in fig 9. The proposed fuzzy control based PV MPPT controller has been simulated at various climatic conditions such as various irradiance and various temperature ranges. To carry out the simulation the different irradiance values like 250 W/m2, 500 W/m2 , 750

Table 1: Fuzzy vs INC MPPT algorithm

Irradiance	Inc Conductance	Fuzzy Logic
1000 W/ M^2	9662 W	10039 W

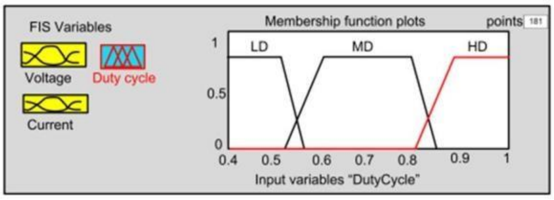
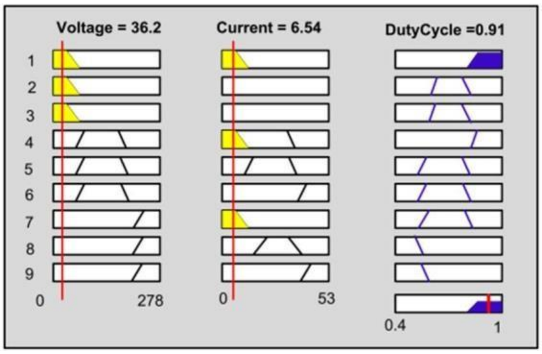


Fig. 5: Fuzzy output membership function for



duty cycle of boost converter

Fig. 6: Fuzzy rules based system for MPPT controller (lower membership function)

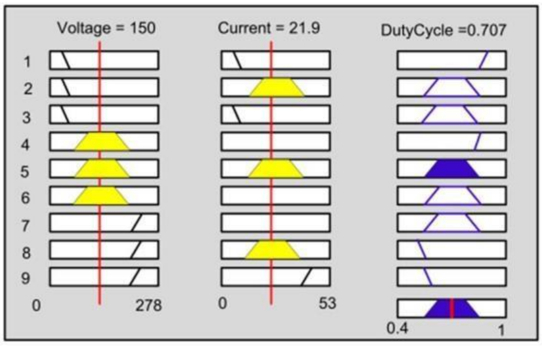


Fig. 7: Fuzzy rules based system for MPPT controller (medium membership function)

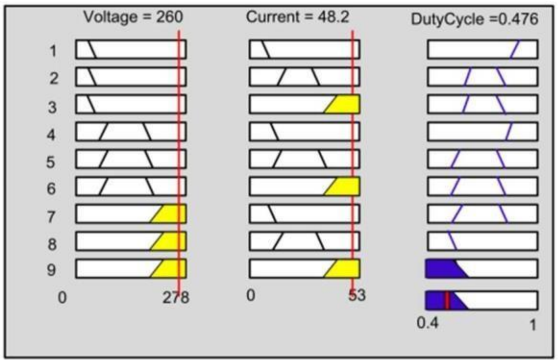


Fig. 8: Fuzzy rules based system for MPPT controller (high membership function)

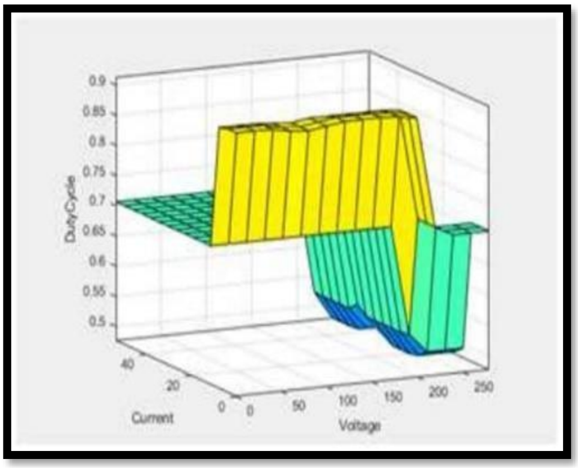


Fig. 9: Fuzzy rules surface system for MPPT controller

W/m2 and 1000 W/m2 are considered. The irradiance of 250 W/m2 is set during the period0 to 0.05 sec. This gives PV power of 1800 W. Similarly during interval 0.05 sec to 0.1 sec irradiance was increased to 500 W/m^2 , which will produce PV power of 3000 W. Later during 0.1 sec to 0.15 sec irradiance of 750 W/m2 was set to give PV power of 6000 W. Finally Irradiance of 1000 W/m2 was set to give PV power of 10 KW. The temperature values varied and set to 250C, 260C, 280C and290C during the intervals 0 to 0.05 sec, 0.05 to 0.1 sec, 0.1 sec to 0.15 sec and 0.15 to 0.2 secrespectively.

The above weather conditions are applied in proposed simulation model and analysis the PV output power waveform as shown in fig 10.The PV boost converter voltage and current waveform are presented in fig 11. The PV output power waveform has been presented infig 12. The Conventional MPPT controller (Incremental Conduction) PV outputwaveform has been presented in fig 13. The comparative analysis has been presented in table 1. Fig. 10: Fuzzy based MPPT controller PVoutput power waveform under various irradiance and temperature

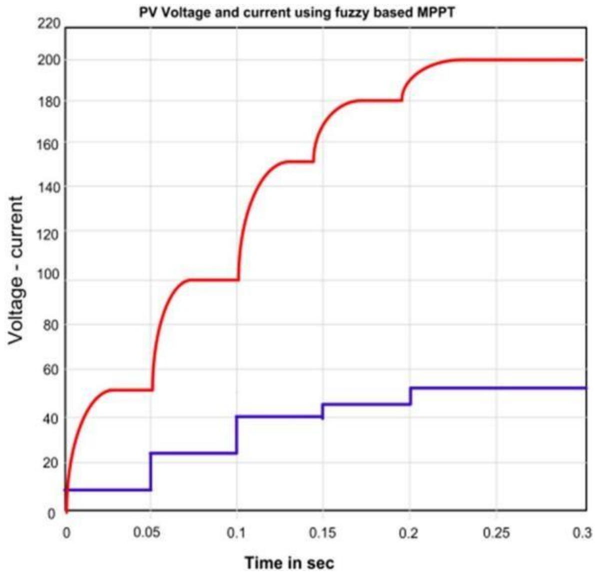


Fig. 11: Fuzzy based MPPT controller boost converter voltage and current waveform under various irradiance and temperature (Blue: Voltage) (Red: Current)

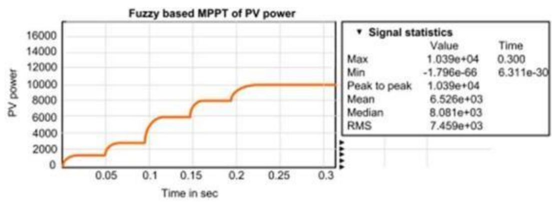


Fig. 12: Fuzzy based MPPT controller PV output power waveform under various weather conditions

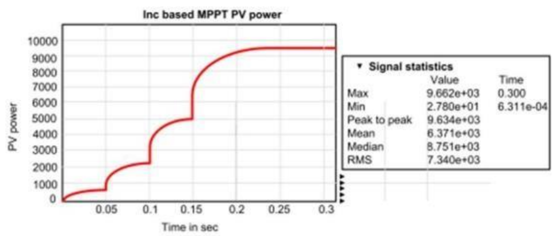


Fig. 13: INC based MPPT controller PV output power waveform under various weather conditions

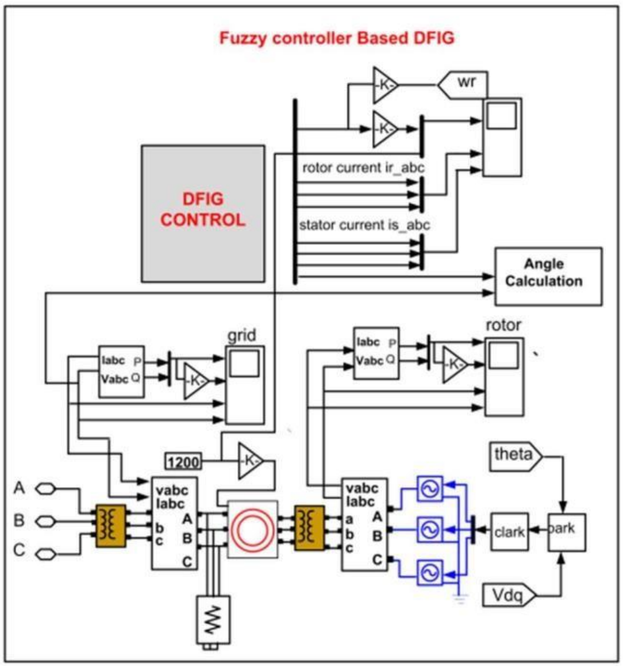


Fig. 14: A simulation model of fuzzy controller based DFIG based wind energyconversion system.

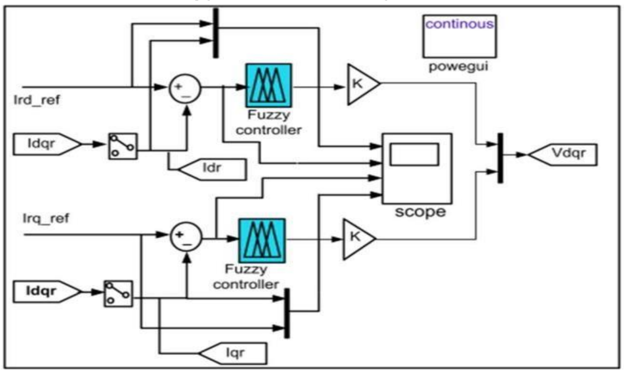


Fig. 15: Fuzzy based Rotor Current controller

3 Fuzzy Based Rotor Current Control for DFIG

The doubly-fed induction generator (DFIG) system is a widespread system in which the power electronic interface controls the rotor currents to achieve the variable speed necessary for maximum energy capture in variable winds. Because the power electronic only processes the rotor power, typically less than 25% of the overall output power, the DFIG offers the advantages of speed control with reduced cost and power losses. The fuzzy logic controller has been developed for DFIG rotor current controller for improving the systempower quality as shown in fig 14 and fig 15. The DFIG rotor currents are classified into two types such as direct axis current (Id) and quadrature axis current (Iq). Therefore fuzzy logic controller has been developed separately for controlling currents Id and Iq as shown in fig 16 and fig (17 a) respectively. The fuzzy

Input and output membership function is developed by using trapezoidal function, and then the centroid is used for defuzzification method. The fuzzy controller has been developed for direct axis current regulation and has direct axis current as an input membership function as shown in fig (17 b), regulated direct axis current as an output membership function as shown in fig (17 c). Also the fuzzy controller has been developed for quadrature axis current regulation and has one input and one output membership functions such as quadrature axis current as an input membership function as shown in fig (17 d), regulated quadrature axis current as an output membership function as shown in fig 18. The direct and quadrature axis fuzzy rules are formed based on input data and presented in fig 19 and fig 20.

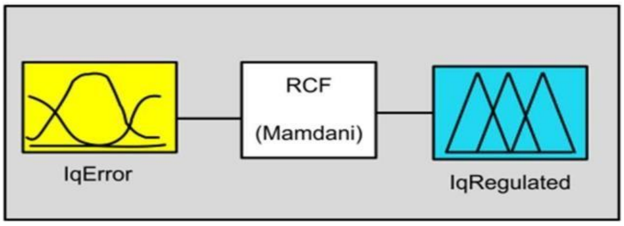


Fig. 16: Fuzzy based Rotor Current controller

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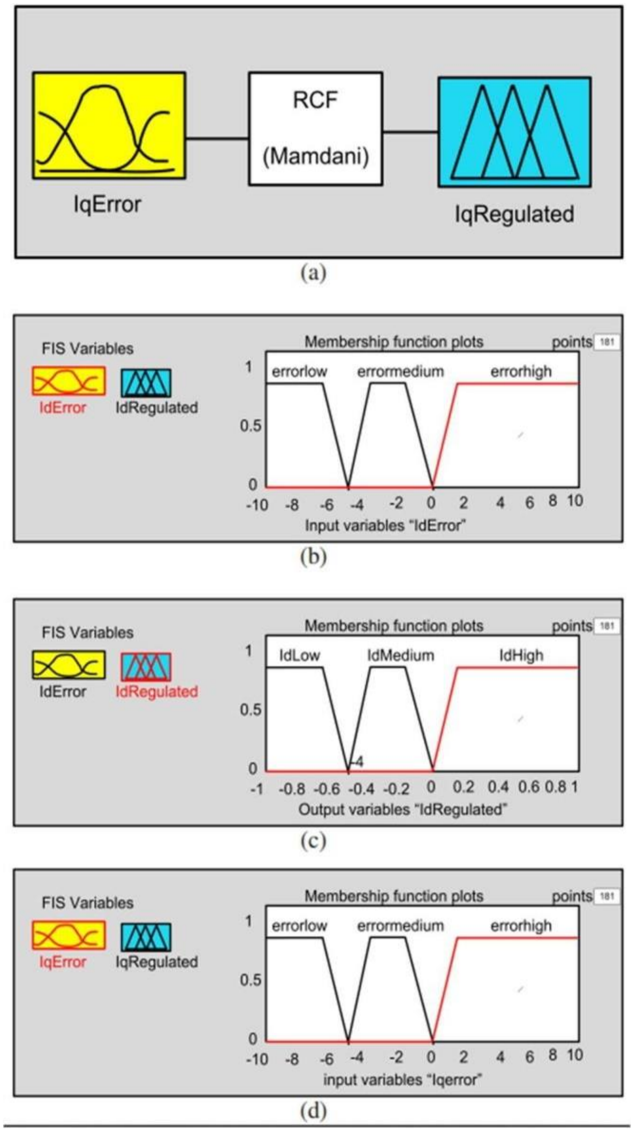

Fig. 17: (a) Design of Fuzzy Controller for I_q regulator (b) Input Membership function for Id regulator (c) Output Membership functionfor Id regulator (d) Input Membership function for Iq regulator

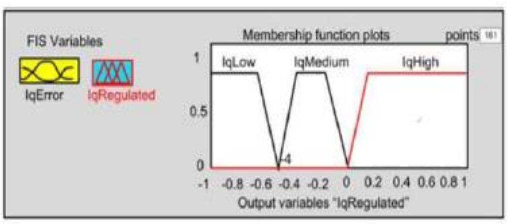

Fig. 18: Output Membership function for Iqregulator

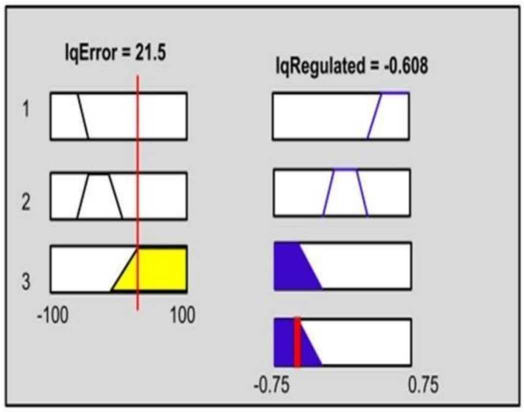

Fig. 19: Fuzzy rules for Id current regulator

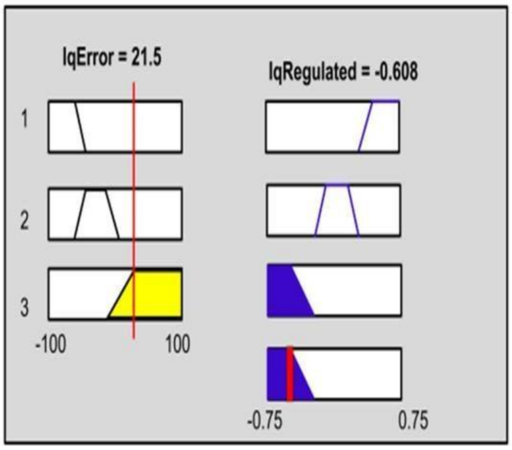

Fig. 20: Fuzzy rules for Iq current regulator

Fuzzy membership function

The membership functions are formed using straight lines. There are various membership functions namely Triangular Membership Function, Trapezoidal Membership Function, Gaussian Membership Function, Generalized bell Membership Function, pi- Shaped Membership Function, S- Shaped Membership Function.

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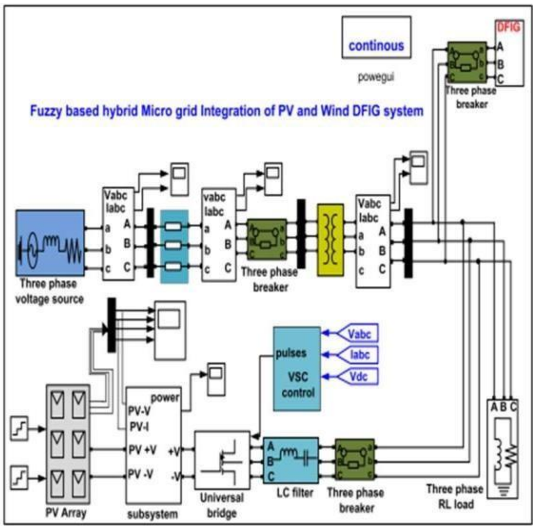


Fig. 21: A simulation model of hybrid PV / DFIG based grid integration system using fuzzy controller

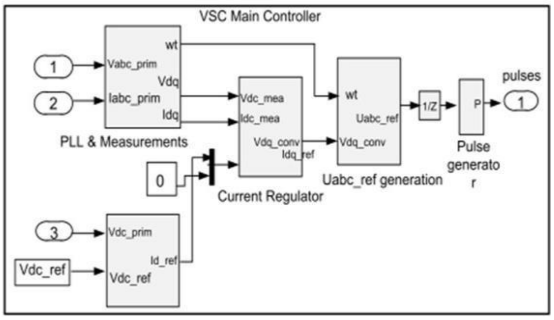


Fig. 22: Design of voltage source converters controller

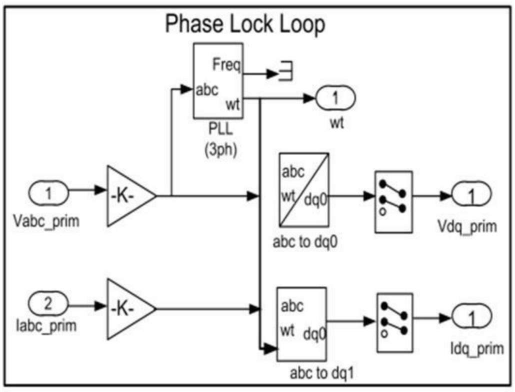


Fig. 23: Design of Phase lock loop

In this work triangular membership function and Trapezoidal membership functions are used for the controller design. The various fuzzy controllermembership functions are presented in fig 16 to fig 20. Fuzzy Based Voltage Source Converter Controller

The complete simulation model of hybrid PV and DFIG based wind energy system for the grid integration using

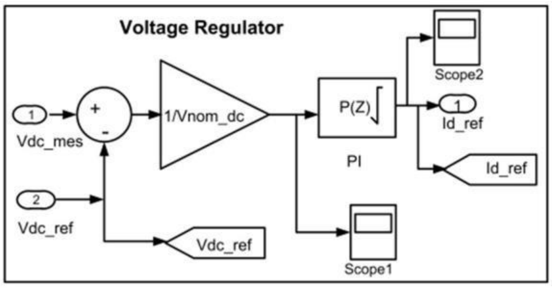
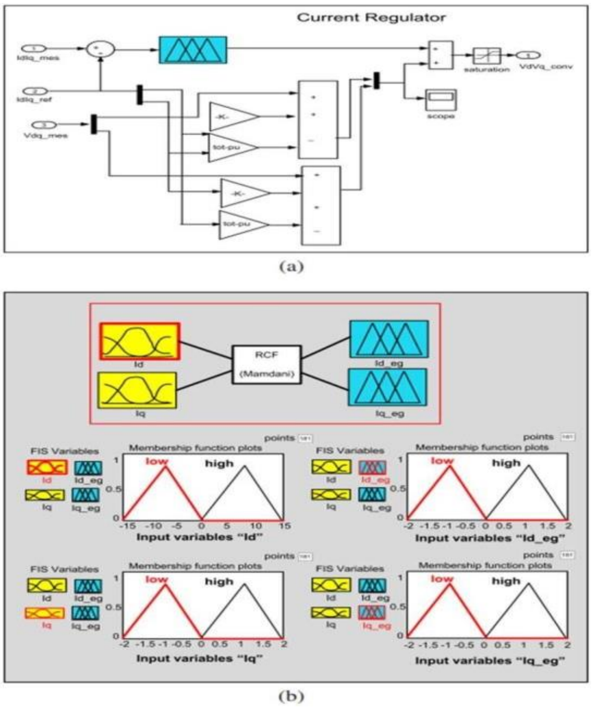
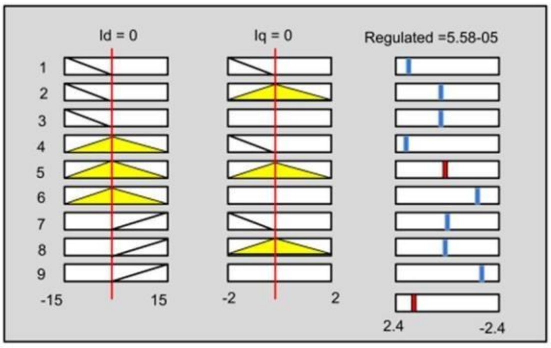
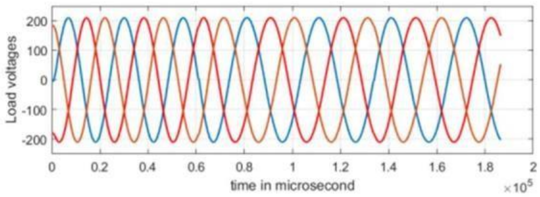


Fig. 24: Design of voltage regulator for gridintegration of PV system



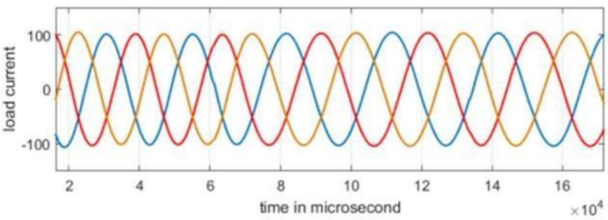


(c)

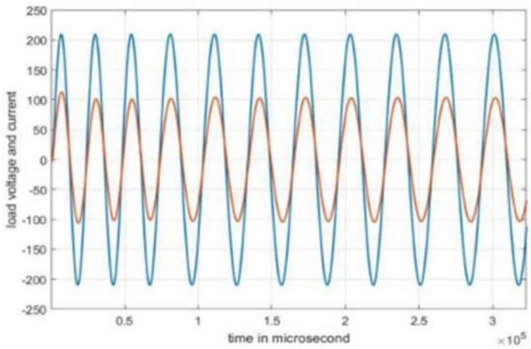


(d)

Fig. 25: (a) Design of current regulator for grid integration of PV system. (b) Fuzzy controller membership function and its rules for current regulator of VSC.; (c) Fuzzy rulesfor current regulator.; (d) Voltage waveform of grid integrated hybrid PV / DFIG power system.



(a)



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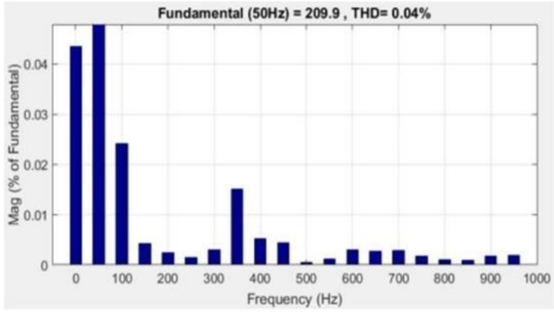

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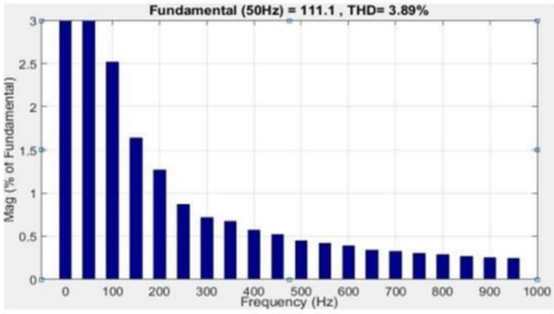
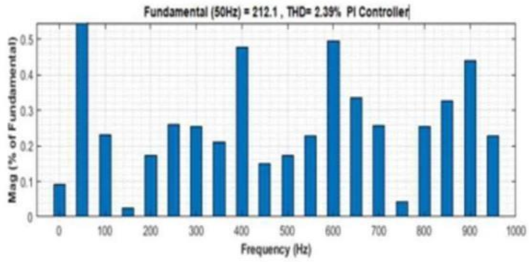
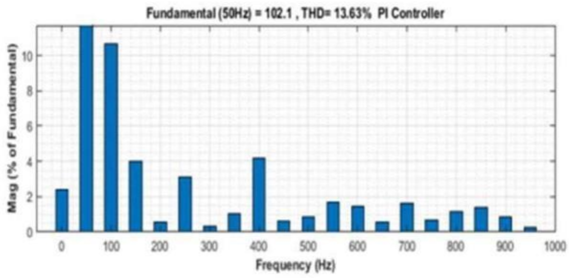


(d)



(e)



(f)

Fig. 26: (a) Current waveform of grid integrated hybrid PV / DFIG power system (b) Current in phase with voltage waveform (c) Voltage THD of hybrid system with fuzzy controller (d) Current THD of hybrid system with fuzzy controller (e) Current THD of hybrid system with fuzzy controller (f) Voltage THD of hybrid system with PI controller

Fuzzy controller is presented in the figure 21. The synchronizing of renewable energy source into the power grid has many challenges such as to match two AC source voltage profile, frequency profile and phase angle. The voltage source converter controller performs a major role in solving the above said problems and is presented as shown in fig 22. The voltage source converter controller has three major parts such as a Phase lock loop, Voltage regulator and current regulator. A phase lock loop (PLL) is a control system that generates an output signal whose phase is related to the phase of an input signal as shown in fig 23. Voltage regulation is to provide real-time control of voltage fluctuation, sag, and surge and also to control other power quality issues such as spikes and EMI/RFI electrical noises. It uses a MOSFET regulator generating pulse width modulated (PWM) AC voltage at high switching frequency as shown fig 24.

The current regulator will control the inverter operation of power flow. When the Ids current is positive the inverter generates the active power and when Iq positive the inverter absorb the reactive power. In this paper the fuzzy controller has been developed for current regulator as shown in fig (25 a). The fuzzy logic controller has been designed for a current regulator for VSC. The fuzzy controller has two input signals and two output signals such as input (direct axis and quadrature axis current) output (regulated direct axis and quadrature axis current) shown in fig (25 b). The fuzzy membership function are designed based on the triangle method for fuzzification process and used centroid method for defuzzification process

The fuzzy rules are represented in fig (25 c). The direct axis current value is positive converter delivers the active power to Micro grid and quadrature axis current value is positive converter that absorbs the reactive power from Micro grid. The proposed fuzzy control has been applied hybrid PV /Wind with Micro grid and its voltage source converter. The fuzzy output

Signal is fed into the feed forward current regulator of converter based on the input signal of PWM controller generates triggering pulses of inverter for synchronize into micro grid. Figure (25 d) and figure (26 a) presents Voltage and Current Waveform of fuzzy controller-based grid integration of Hybrid PV- DFIG Power system respectively. The resultant load current is in phase with load voltage as presented in figure (26 b). Finally, the total harmonic distortion values are measured and presented in figures (26 c) and (26 d) respectively. The THD values for the proposed system for load voltage are 0.04% andthe load current is 3.89%.

Also the performance of the hybrid system is also analyzed using conventional PI controller. The total harmonic distortion values in this case are measured and presented as shown in figures(26 e) and (26 f) respectively. The THD values for the load voltage are 2.39% and the load current is 13.63% using PI controller.

The above observed THD values are compared with IEEE 1547 standard. Based on the standard value of grid integration of renewable energy source THD values less than 5% is acceptable. The proposed system THD values are very less than IEEE 1547 standard.

Parameter Value	**THD of PI controller in percentage**	**THD of fuzzy controller in percentage**
Voltage	2.39	0.04
Current	13.63	3.89

Table 2: Comparison between PI Controller and Fuzzy Controller for hybrid solar wind system

4 Perspectives

This paper, discussed the modeling of hybrid solar PV system and DFIG based wind energy system. The fuzzy controller has been developed for maximum power point tracking for 10 KW photovoltaic power systems and analyzed its performance under various weather conditions. The DFIG wind energy system has been developed in MATLAB environment and the designed fuzzy logic controller for rotor current controller. Theproposed grid integration of hybrid PV and DFIG system has been simulated in MATLAB environment and hence developed a fuzzy controller for grid synchronizing of hybrid system into the power grid. The obtained results are compared with conventional controller and tabulated as shown in table 2. Also the proposed model simulation results are analyzed with different operating conditions and evaluated with IEEE 1547 standard for proving the effectiveness on the system.

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