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Design of power management and control system with FLC based controller for Hybrid DG tied Microgrid System

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Abstract:

In this paper, a novel approach is proposed for controlling a micro-grid integrated with hybrid renewable energy sources, specifically wind and solar. The wind energy is harnessed using a Doubly Fed Induction Generator (DFIG), while solar energy is converted through a photovoltaic (PV) array. Both energy sources are connected to a common DC bus, which also interfaces with a battery energy storage system for enhanced energy management and reliability. The system is designed to ensure seamless operation even when wind power is unavailable, with the PV array and battery providing the necessary power support.

To regulate key electrical parameters such as voltage and frequency, an indirect vector control strategy is applied to the line-side converter. Additionally, Maximum Power Point Tracking (MPPT) techniques are employed to maximize the energy extracted from both wind and solar sources under variable environmental conditions.

A significant enhancement in the proposed system is the integration of a Fuzzy Logic Controller (FLC), which outperforms conventional controllers like PID in several aspects. The FLC offers greater adaptability, robust performance under system nonlinearities, faster dynamic response, and reduced steady-state error. Unlike conventional controllers that require precise mathematical models and often underperform during abrupt load or source fluctuations, the FLC adapts to real-time system changes based on expert-defined rules, making it ideal for renewable-based micro-grids.

The complete system is modeled and simulated in the MATLAB/Simulink environment. Simulation results under various loading scenarios demonstrate the effectiveness, flexibility, and enhanced performance of the proposed FLC-based hybrid energy management system, highlighting its potential for practical implementation in modern smart grid applications.

Keywords: Doubly fed induction generator, Photovoltaic array, Maximum power point tracking, Battery bank, DC bus.

1.Introduction:

Solar Photovoltaic (PV) has emerged as a major contender to serve as an alternative energy source and is currently playing a leading role in supporting the existing conventional power generation systems. Even though the grid connected PV systems are in extensive use today, solar PV as an energy source was first employed for off-grid (stand-alone) purposes ranging from low power electronic gadgets (e.g. calculators, watches, toys etc.) to high power, strategic applications like spacecrafts and satellites. Stand-alone PV systems remain an important entity today with their applications extending to remote power systems (where there is no power grid as in rural villages and remote islands) and agrarian irrigation.Fig. 1 shows a typical power conversion configuration for a stand-alone PV system [1-3]. The forward power path from solar PV source to the load typically consists of two stages, as shown. The battery back-up is interfaced with the DC link through a bi-directional dc-dc converter.

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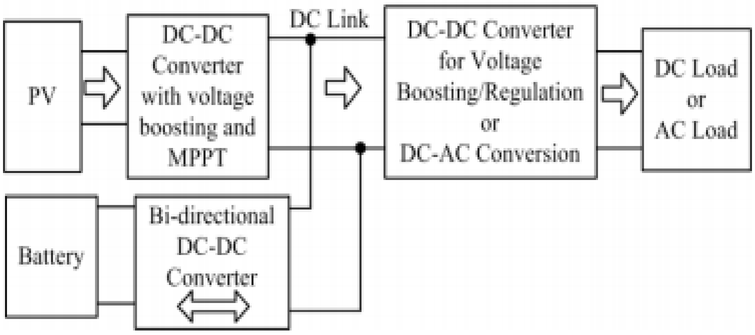

Fig.1 Schematic diagram of two stage stand-alone PV system.

A hybrid energy system consisting of two or more type of energy sources, has ability to reduce the BES requirement and increases reliability. Wind and solar energies are natural allies for hybridization. Both have been known to be complementary to each other in daily as well as yearly pattern of the behavior. Acknowledging advantages of this combination, many authors have presented autonomous wind solar hybrid systems [5-10]. The most favorite machine for small wind power application, is permanent magnet synchronous generator [4-5]. It is possible to achieve gearless configuration with PMSG, however, it requires 100% rated converter in addition to costlier machine [11]. Some authors have also used wind solar hybrid system with a squirrel cage induction generator (SCIG) [6], Though SCIG has commercial edge regarding machine cost, however, the scheme doesn’t have speed regulation required to achieve MPPT. Moreover, if the speed regulation is done, it requires full power rated converter. A doubly fed induction generator (DFIG) as a generator is commonly used for commercial wind power generation and its applications, have been presented by many authors in their publications for autonomous application along with solar PV array [7-10]. DFIG may operate variable speed operation with lower power rated converters. However, to work the system as a micro-grid, the generated voltage should be balanced and THD (Total Harmonics Distortion), must be within requirement of IEEE-519 standard at no-load, unbalanced load as well as nonlinear load. Moreover, both the wind and solar energies sources should operate at MPPT. None of the authors, has reported all these issues. They have not presented performance parameters e.g. power quality, system efficiency etc under the different operating conditions. Moreover, they also lack experimental verification.
In this paper, a novel approach is proposed for controlling the micro-grid in the presence of wind and solar based hybrid energy sources. In this, doubly fed induction generator (DFIG) would use to convert the energy and the battery bank is connected to a DC bus of the network. Moreover, the solar power converted by using a solar photovoltaic (PV) array. The electrical parameters such as voltage and frequency can regulate by an indirect vector control of the line side converter. It is able to operate when the power coming from wind is not available. Furthermore, maximum power point tracking (MPPT) is used to control the system. For battery charging, the system initially contributed the supplementary power support without any additional requirement.

2.Proposed system

A single line diagram of the proposed renewable energy generation system (REGS) fed micro-grid is shown in Fig. 1. The same has been designed for location having maximum power demand and average power demand of 15 kW and 5 kW, respectively. The rated capacity of both wind and solar energy block in REGS, is taken as 15 kW. The capacity utilization factor of 20% is considered for both energy blocks, which is enough to provide full day energy requirement of the hamlet. As shown in a schematic diagram, the wind energy source is isolated using a 3-pole breaker from the network in case of insufficient wind speed. The DC side of both RSC and LSC along with HV side of solar converter, is connected at the battery bank. RSC helps the wind energy system to run at the optimum rotation speed as required by W-MPPT algorithm. The LSC controls the network voltage and frequency. The energy flow diagram of the system is shown in Fig. 2. The design methodology of major components of REGS, is shown in following sub-sections.

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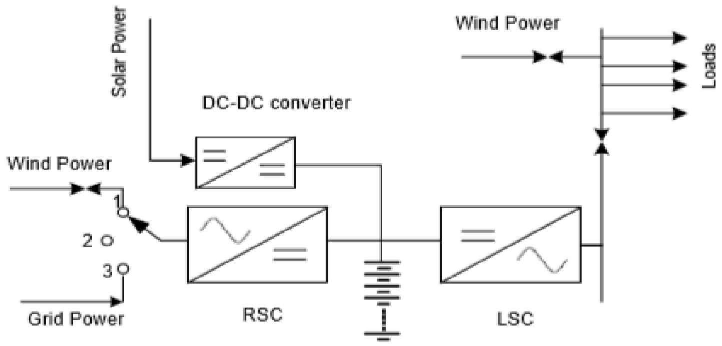


Fig.2 Energy Flow diagram with renewable energy sources with battery system.

A. DFIG

A Doubly Fed Induction generator as its name suggests is a 3-phase induction generator where both the rotor and stator windings are fed with 3 phase AC signal. It consists of multi-phase windings placed on both the rotor and stator bodies. It also consists of a multiphase slip ring assembly to transfer power to the rotor. It is typically used to generate electricity in wind turbine generators.Before going to further details about a Double Fed Induction Generator used in wind turbine generators, let us have a brief idea about power generation using wind energy.The DFIG consists of a 3-phase wound rotor and a 3-phase wound stator. The rotor is fed with a 3 phase AC signal which induces an ac current in the rotor windings. As the wind turbines rotate, they exert mechanical force on the rotor, causing it to rotate. As the rotor rotates the magnetic field produced due to the ac current also rotates at a speed proportional to the frequency of the ac signal applied to the rotor windings. As a result, a constantly rotating magnetic flux passes through the stator windings which cause induction of ac current in the stator winding. Thus, the speed of rotation of the stator magnetic field depends on the rotor speed as well as the frequency of the ac current fed to the rotor windings.The frequency of the rotor ac signal increases as the rotor speed decreases and is of positive polarity and vice versa. Thus, the frequency of rotor signal should be adjusted such the stator signal frequency is equal to the network line frequency. This is done by adjusting the phase sequence of the rotor windings such that the rotor magnetic field is in the same direction as the generator rotor (in case of decreasing rotor speed) or in opposite direction as the generator rotor (in case of increasing rotor speed).

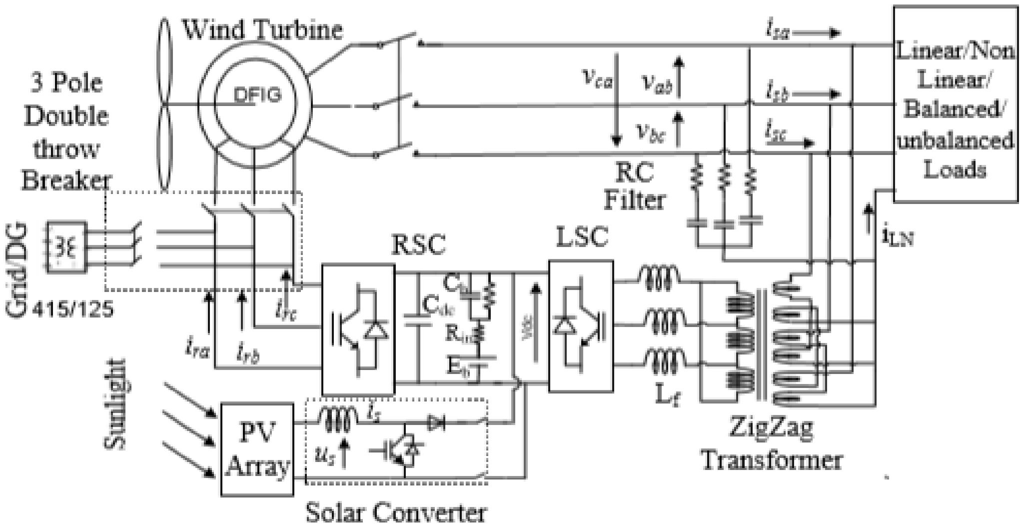


Fig.3 Energy Flow schematic structure with renewable energy sources.

B.Battery Sizing

The maximum operating slip of machine is 0.3. The DFIG speed corresponding to this slip is 110 rad/s. At this slip, the line voltage of rotor Vrmax become 125 V (415×0.3). The required DC bus voltage (Vdc) for PWM control is as,

V_L is the higher of the line voltage of low voltage (LV) side of the zig-zag transformer and the rotor voltage at highest slip. The maximum operating slip is 0.3 and accordingly the highest rotor voltage as well as LV side of zig-zag transformer is 125 V. The modulation index, mi is chosen to be unity. Based on these inputs, the DC bus voltage Vdc required for functioning of PWM control must not be less than 204 V. In the presented scheme, Vdc is taken 240 V. The proposed micro-grid is designed to provide load requirement of 5 kW without any generating source for an up to 12 hours. Taking additional 20% margin for energy losses during exchange of energy, the required battery storage capacity becomes 72 kWhr. At the DC bus voltage of 240 V, the Ampere-Hour (AH) rating of battery becomes 300 AH (72,000/240). This is achieved using 40 numbers of 12V, 150 AH lead acid batteries divided equally into two parallel circuits.

C. Solar system

The basic element of a solar PV system is the solar cell, which is based on the work of Rey-Boué et al [12]. The solar panels are configured such that the open circuit voltage of the solar string remains less than the lowest downstream voltage of solar converter or DC bus voltage, Vdc. The cell numbers (Nc) in a string, is a function of its DC voltage and cell open circuit voltage Vocc as,

$$N_c = V_{dcm}/V_{occ}$$

The value of Vocc based on a typical commercially available cell characteristics and its value, is taken as 0.64 V. As evaluated in sub-section (D), the minimum battery voltage can fall down upto 216 V. Solar array voltage (us) can vary up to 3%, which is due to manufacturing tolerance of electrical quantities of module.Standard configuration, 324 cells are taken, which are divided in 9 modules of 36 cells each. The ratio of Vocc to cell voltage at maximum power point (MPP), Vmpc for a typical module characteristic is 1.223. Accordingly, the module voltage at MPP becomes (Vmpc x 36) 18.83 V and us becomes 169.47 V. At 15 kW solar array capacity, the cumulative string current at MPP becomes {15000/(9*18.83)}88.5 A. The number of string in the solar array is chosen to be 11, accordingly module current at MPP, Imp becomes 8.04 A. The ratio of short circuit current Isc to Imp for a typical module is 1.081 and accordingly Isc is taken as 8.69 A.

D. Fuzzy logic controller

In recent years, the number and variety of applications of fuzzy logic have increased significantly. The applications range from consumer products such as cameras, camcorders, washing machines, and microwave ovens to industrial process control, medical instrumentation, decision-support systems, and portfolio selection. To understand why use of fuzzy logic has grown, you must first understand what is meant by fuzzy logic. Fuzzy logic has two different meanings. In a narrow sense, fuzzy logic is a logical system, which is an extension of multivalve logic. However, in a wider sense fuzzy logic (FL) is almost synonymous with the theory of fuzzy sets, a theory which relates to classes of objects with unsharp boundaries in which membership is a matter of degree. In this perspective, fuzzy logic in its narrow sense is a branch of fl. Even in its narrower definition, fuzzy logic differs both in concept and substance from traditional multivalve logical systems.

In fuzzy Logic Toolbox software, fuzzy logic should be interpreted as FL, that is, fuzzy logic in its wide sense. The basic ideas underlying FL are explained very clearly and insightfully in Foundations of Fuzzy Logic. What might be added is that the basic concept underlying FL is that of a linguistic variable, that is, a variable whose values are words rather than numbers. In effect, much of FL may be viewed as a methodology for computing with words rather than numbers. Although words are inherently less precise than numbers, their use is closer to human intuition. Furthermore, computing with words exploits the tolerance for imprecision and thereby lowers the cost of solution. Another basic concept in FL, which plays a central role in most of its applications, is that of a fuzzy if-then rule or, simply, fuzzy rule. Although rule-based systems have a long history of use in Artificial Intelligence (AI), what is missing in such systems is a mechanism for dealing with fuzzy consequents and fuzzy antecedents. In fuzzy logic, this mechanism is provided by the calculus of fuzzy rules. The calculus of fuzzy rules serves as a basis for what might be called the Fuzzy Dependency and Command Language (FDCL).

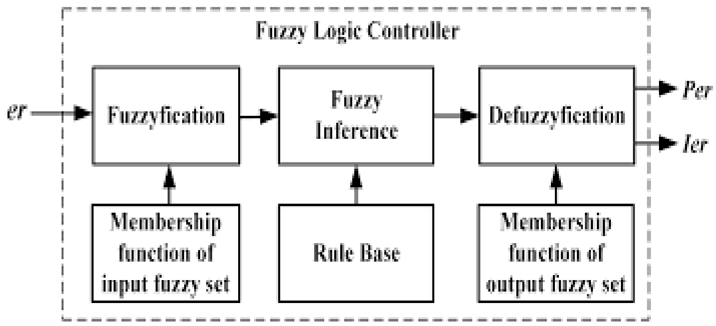


Fig.4 Fuzzy logic controller diagram.

3.Control algorithm

As shown in Fig.2, REGS consists of three converters, which control descriptions, are given as follows

A. Control of LSC

Since the onshore wind turbine generates power only for 60-70% of the time, the system should be designed to work when no wind power is available. As shown in the control diagram in Fig. 4, i*qs consists of two components. The first component, iqs1 corresponds to the power component of DFIG current, when wind turbine is in operation. The second components iqs2 corresponds to the power component drawn when stator of DFIG is not connected to the load terminal.

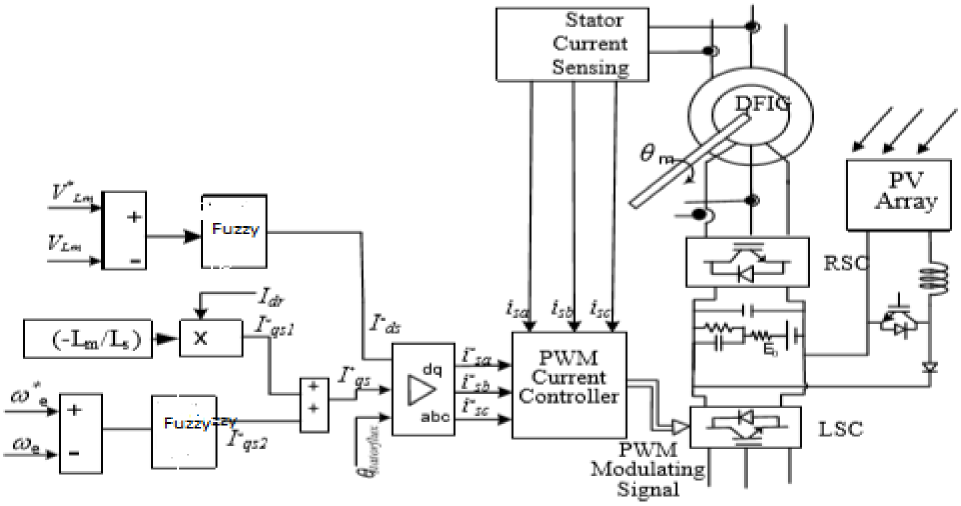


Fig.5 Control diagram of LSC for REGS energy fed micro-grid with fuzzy

B. Control of RSC

RSC regulates the speed of turbine so that the system operates at MPP irrespective of varying wind conditions. It also provides magnetizing power to the generator. The control philosophy as shown in Fig. 6, includes control algorithm for determination of quadrature and direct components of rotor currents, Iqr, Idr and transformation angle, θslip

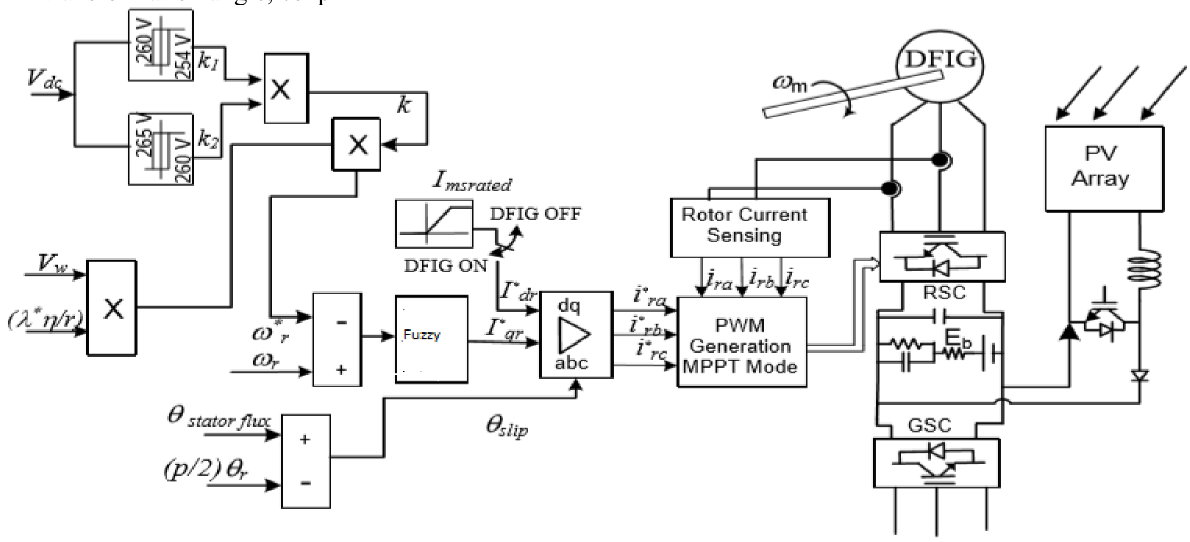
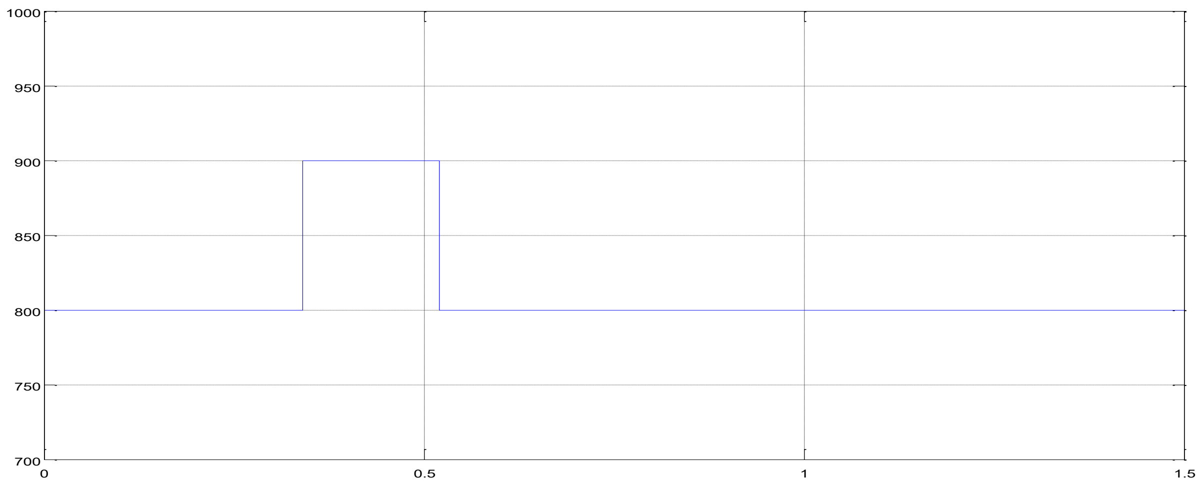
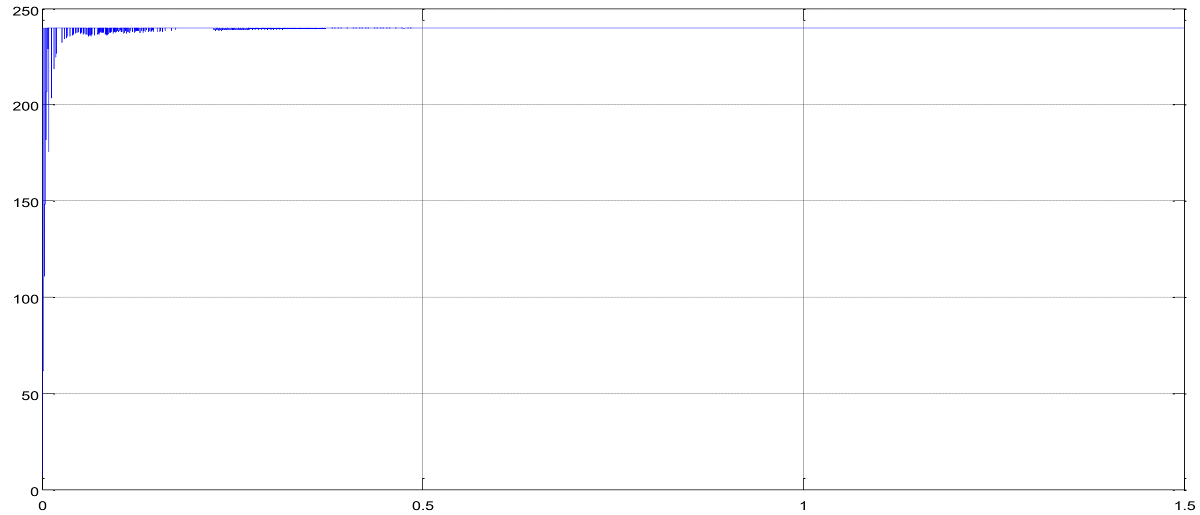


Fig.6 Control diagram of RSC for REGS fed micro-grid with fuzzy.

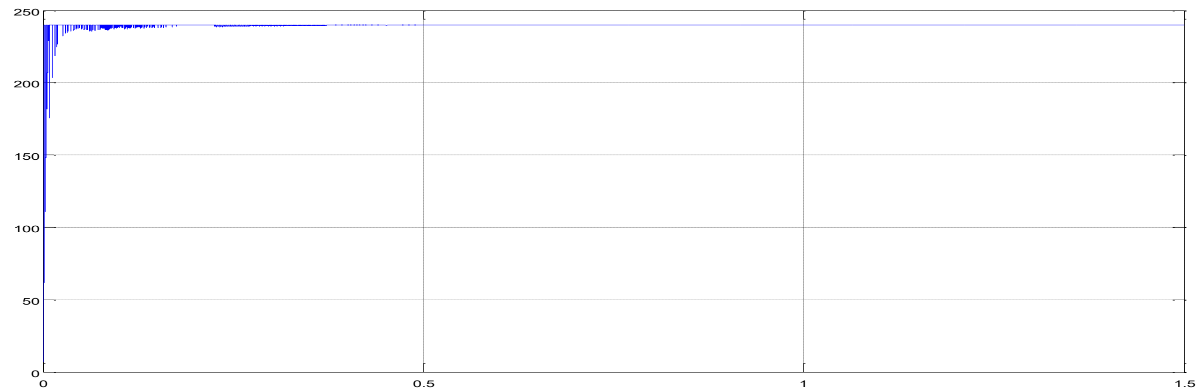
4. Simulation outcomes



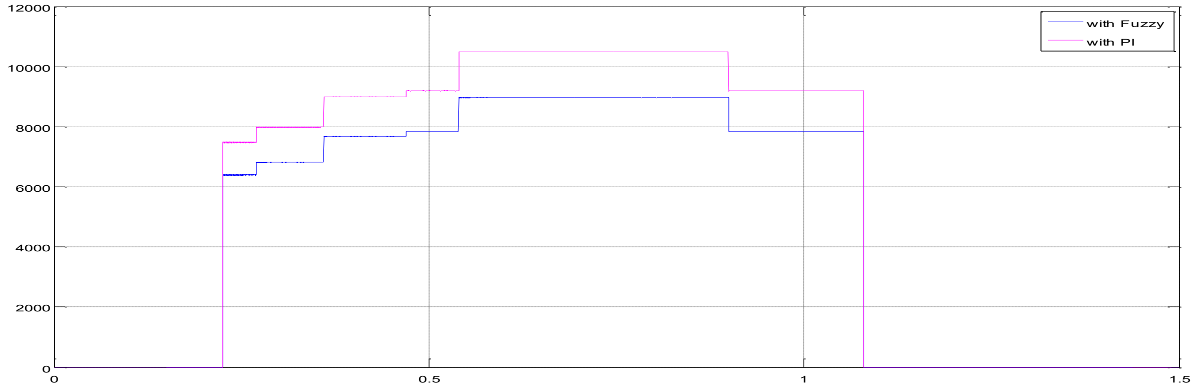
(a) Wind Speed



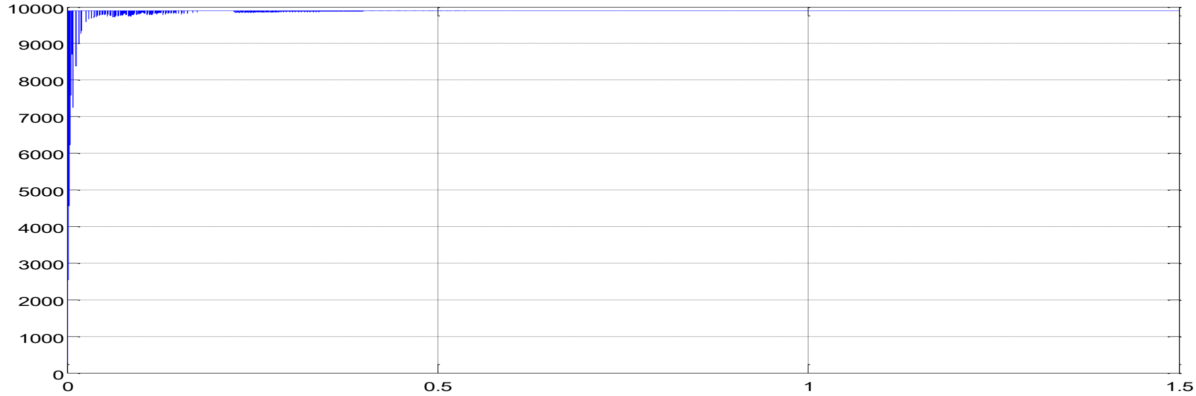
(b) Voltage at PV terminals



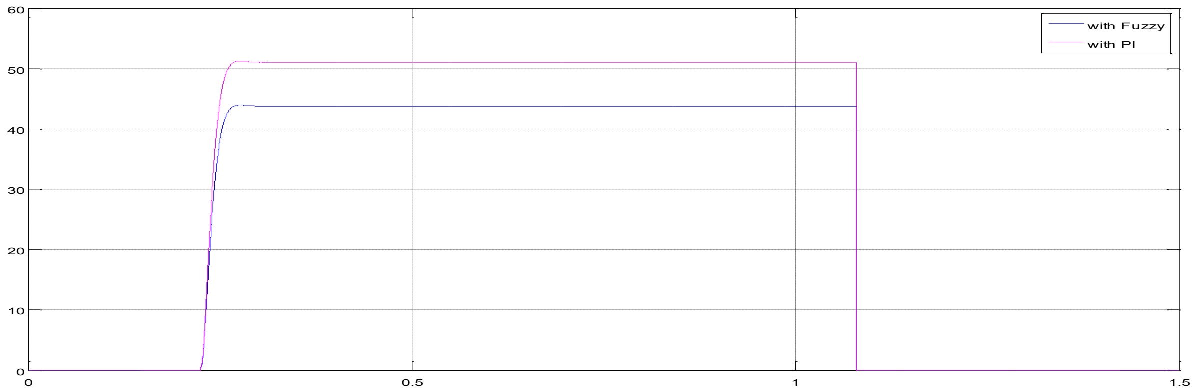
(c) DC Voltage



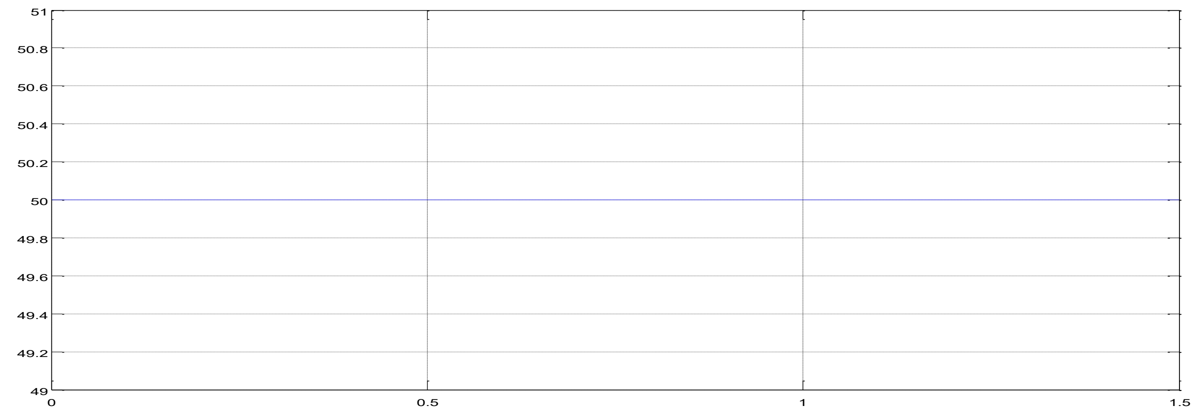
(d) Generated Power (Pg)



(e) Load Power (Pl)



(f) Source Current



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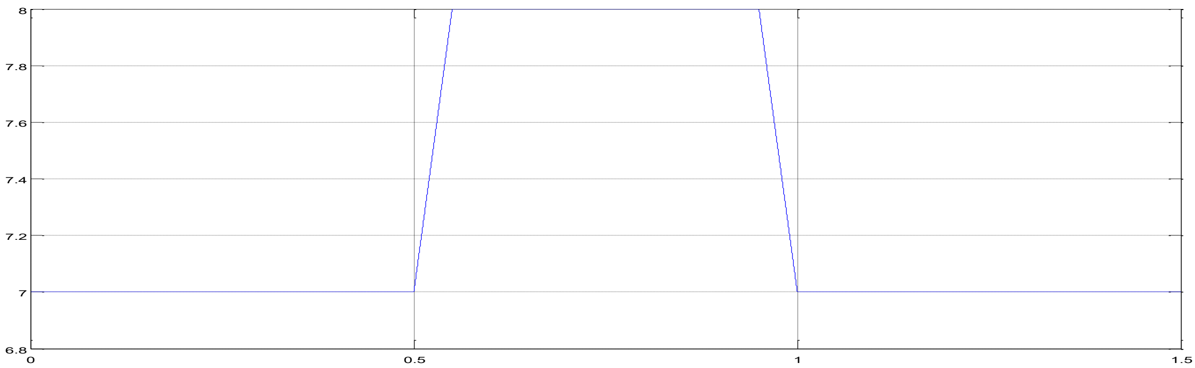
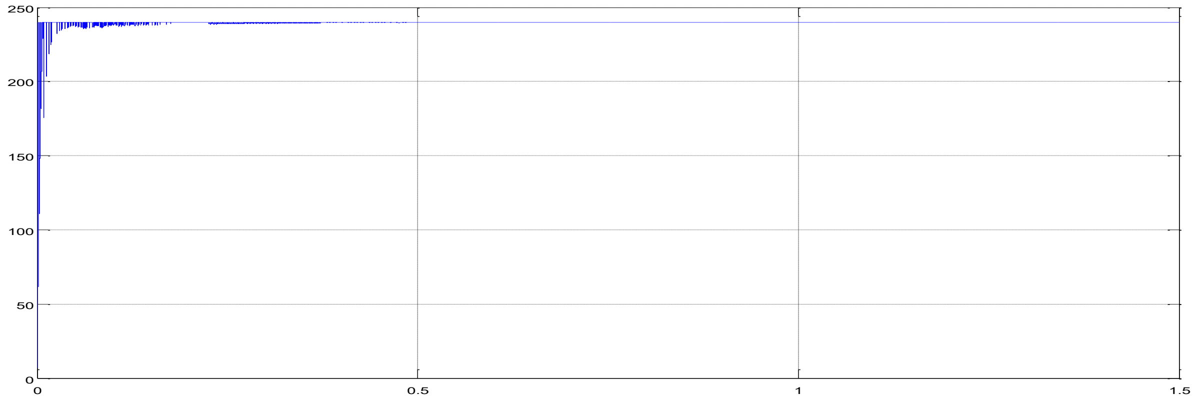
(g) Frequency

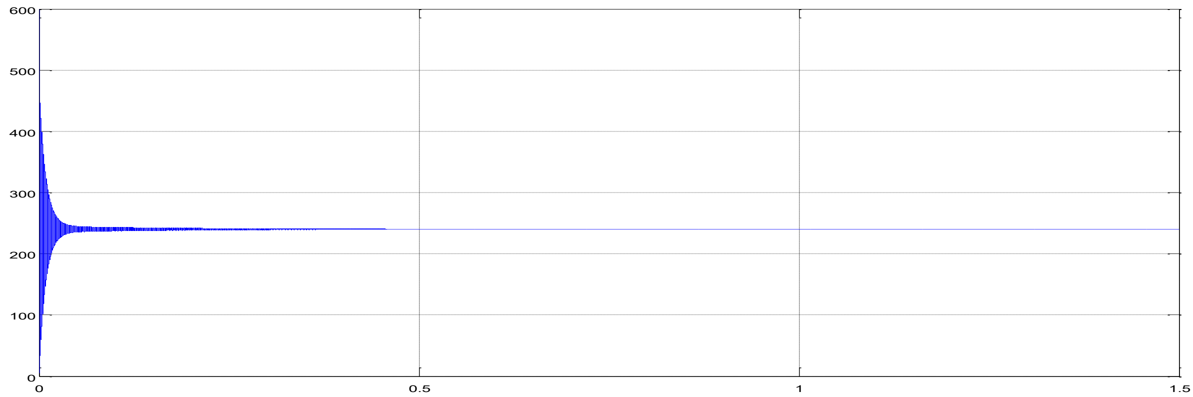
Fig. 7 Performance of the system without generating source and solar system is taken in the service with fuzzy.



(a) Wind Speed



(b) Voltage at PV terminals



(c) DC Voltage

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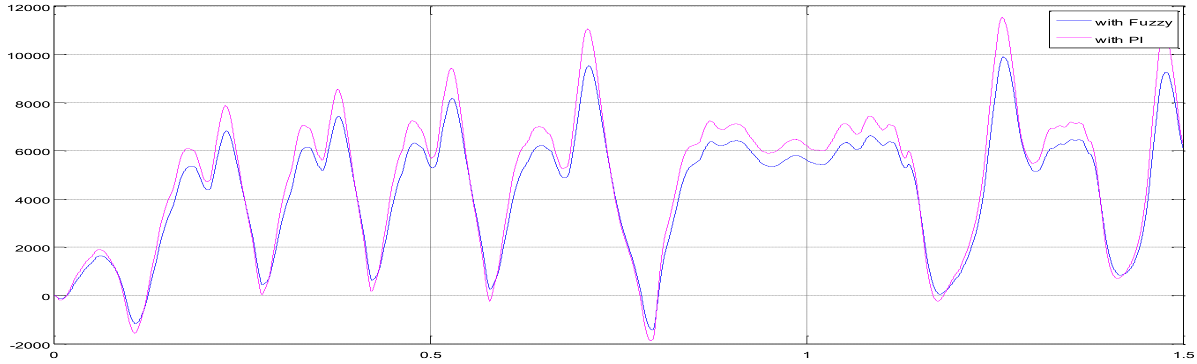
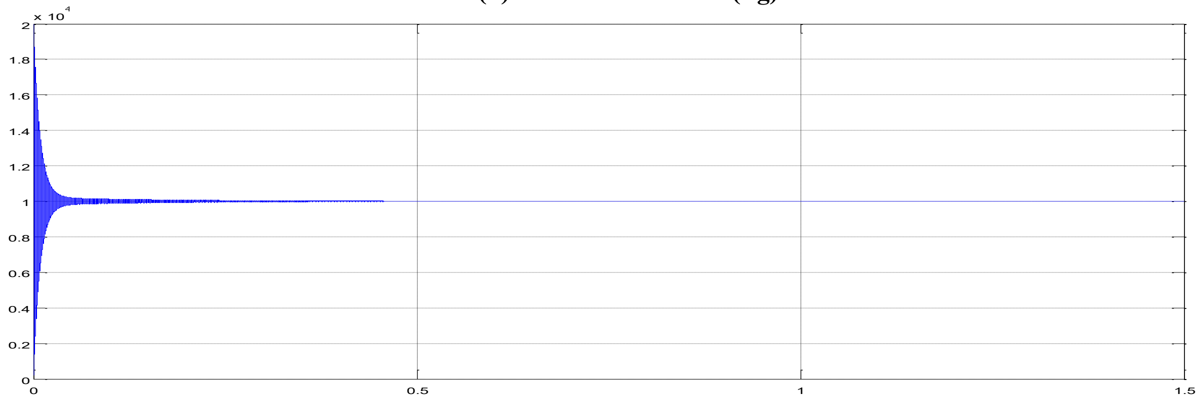
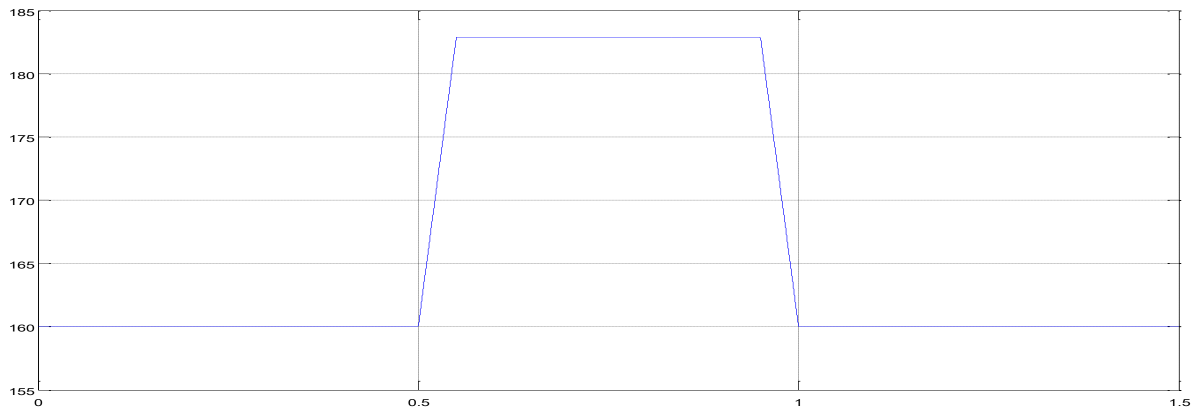


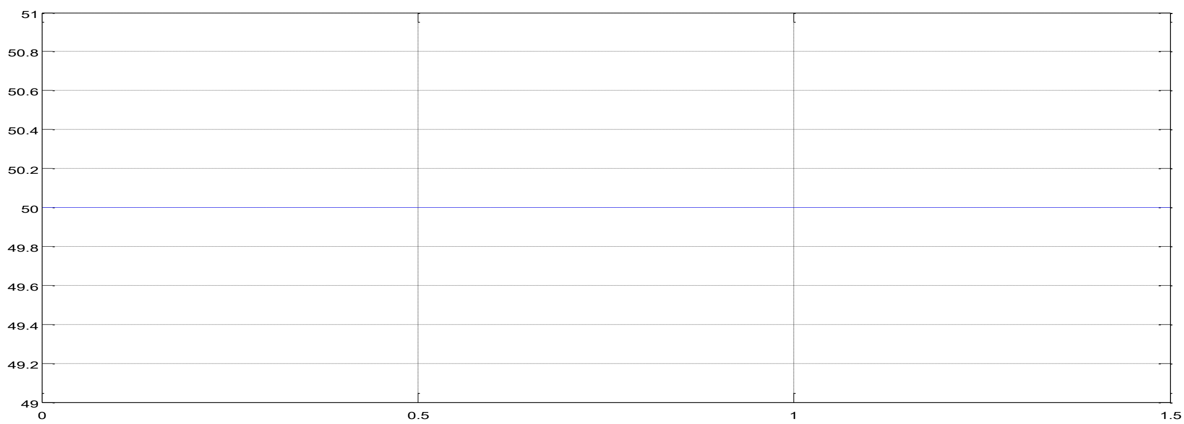
(d) Generated Power (Pg)



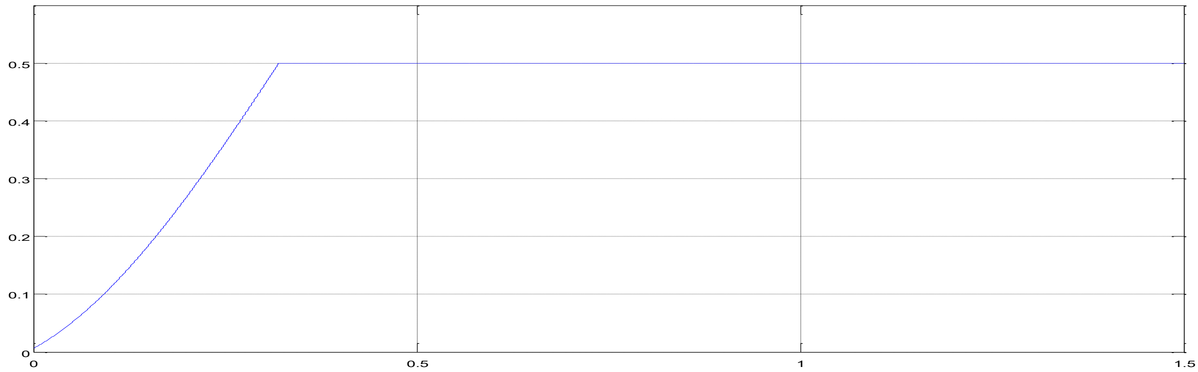
(e) Load Power (Pl)



(f) Generator Speed

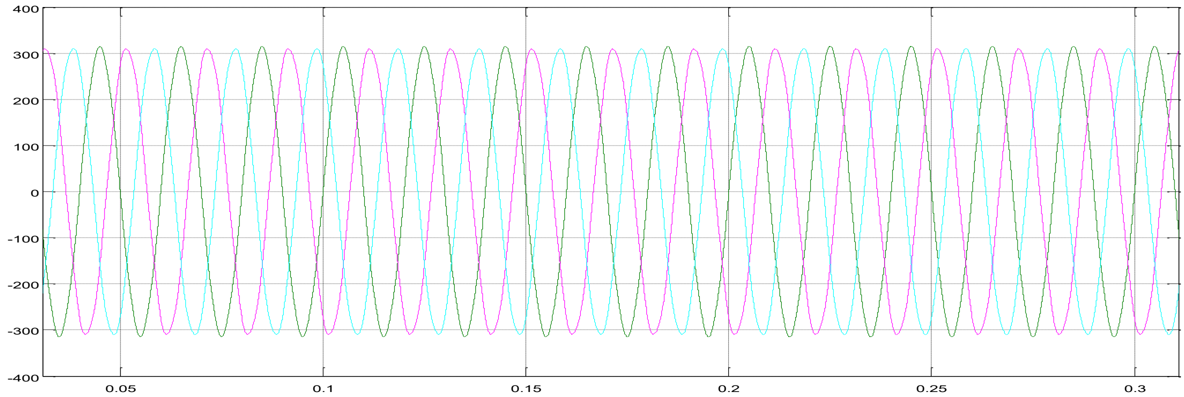


(g) Frequency

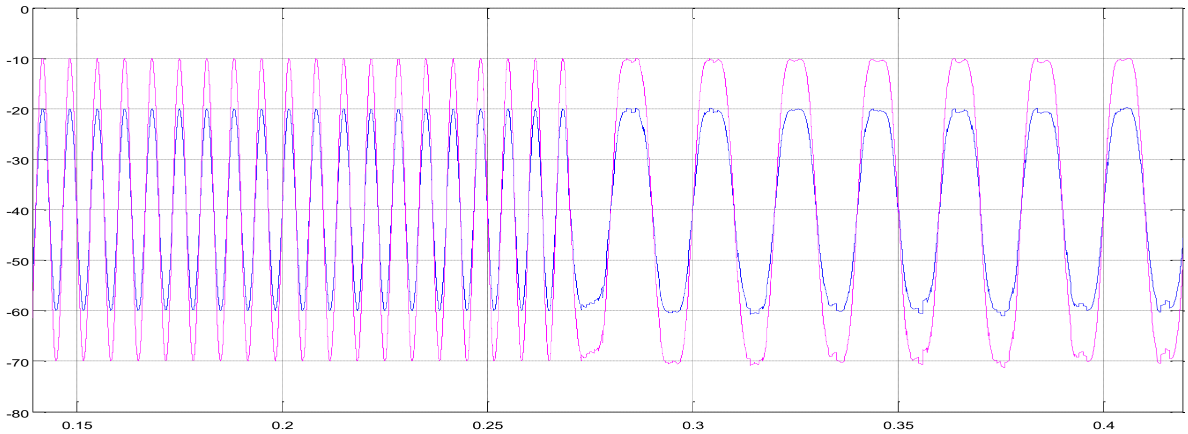


(h) Power Coefficient

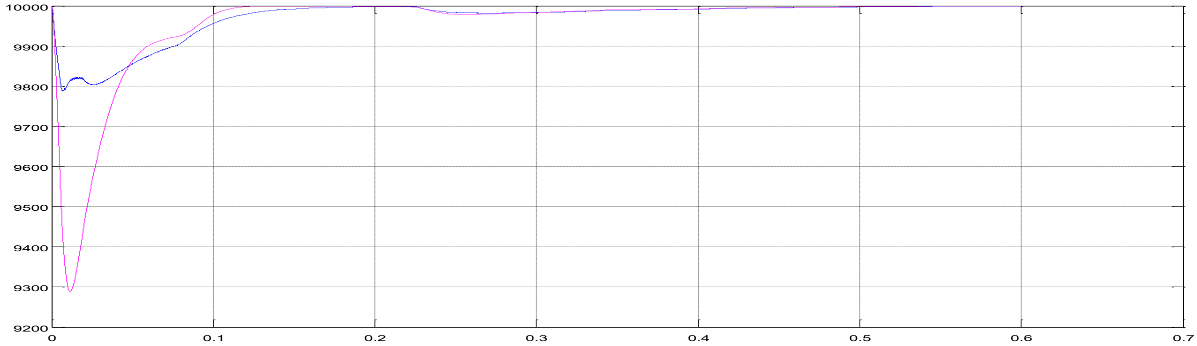
Fig. 8 Performance of REGS fed micro-grid with wind energy source with fuzzy.



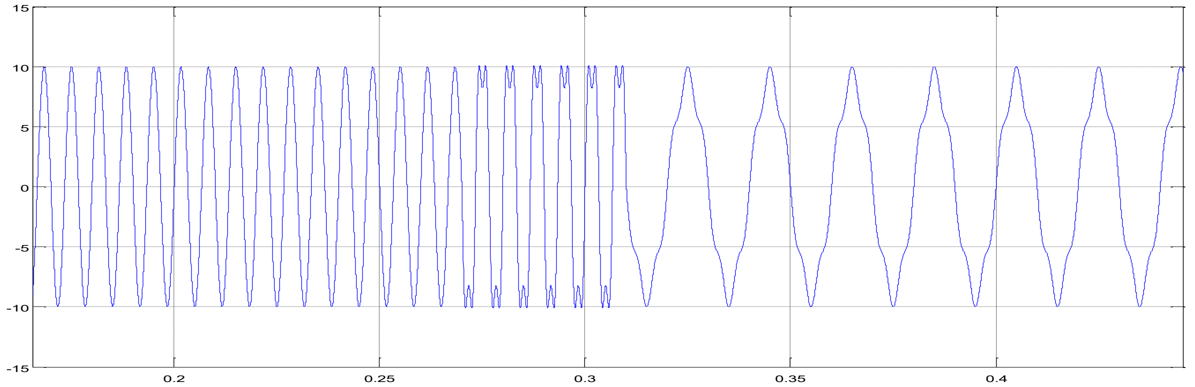
(a) Load voltage



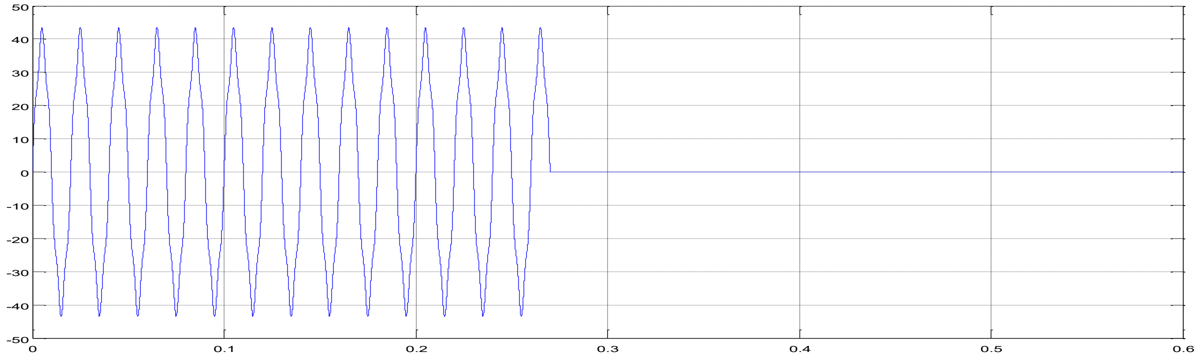
(b) Ib



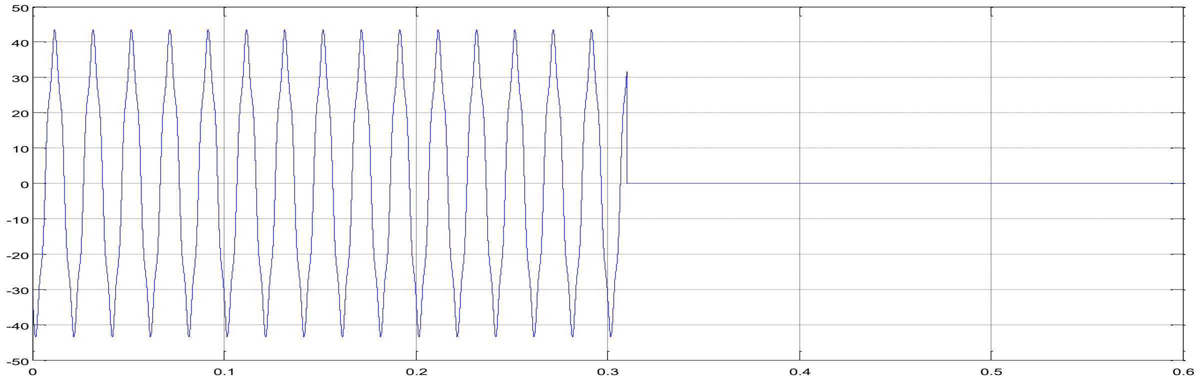
(c) Load Power



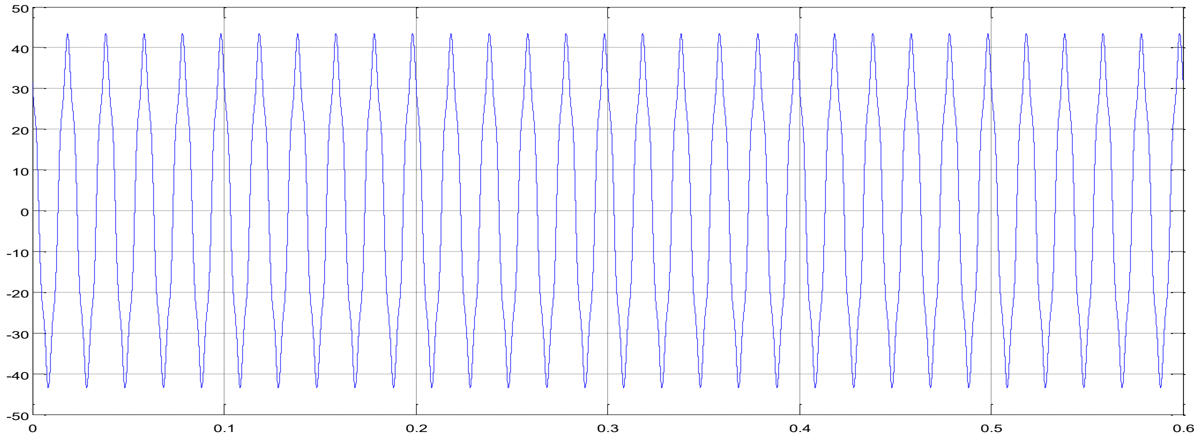
(d) Ina



(e) Ila



(f) Ilb



(g) Ilc

Fig. 9 Performance of the system at unbalanced and nonlinear load fuzzy.

5. Conclusion:

The proposed micro-grid system, incorporating wind and solar energy sources, has proven to be effective in meeting the power demands of isolated households. By utilizing renewable energy generation systems (REGS), the setup not only ensures maximum power extraction from both wind and solar sources but also significantly contributes to improving power quality delivered to the end-users. The system performance remains consistent and reliable under varying environmental and load conditions, demonstrating strong adaptability to dynamic input scenarios.

Simulation results validate that the system maintains stable voltage and frequency profiles across a wide range of load conditions, highlighting its capability to support decentralized energy needs efficiently. The system also supports external battery charging, facilitated through the rotor side converter operating at unity power factor, further enhancing its operational flexibility.

A key contribution of this work is the integration of a Fuzzy Logic Controller (FLC), which outperforms conventional controllers by delivering higher efficiency, faster response time, and improved dynamic behavior in the presence of uncertainties and nonlinearities inherent in renewable energy systems. The FLC effectively manages real-time fluctuations in generation and load, ensuring better energy management, smoother transitions, and enhanced system stability.

Overall, the proposed FLC-based hybrid control strategy demonstrates superior performance and offers a reliable and intelligent solution for micro-grid energy management in renewable-integrated systems.

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