IoT-Enabled Supervisory Control of Wind-Driven Induction Generators Using Interval Type-2 Fuzzy Logic for Dynamic Load Management in Off-Grid Systems

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Abstract: The integration of renewable sources such as wind energy into off-grid systems poses challenges in system stability and power quality due to natural fluctuations in wind and dynamic load conditions. In this paper, an Internet of Things (IoT)-based supervisory control strategy using Interval Type-2 Fuzzy Logic Control (IT2FLC) is introduced for a wind-powered Induction Generator (IG) system. The IT2FLC is designed to handle uncertainties and nonlinearities of wind speed fluctuation and load variations to guarantee robust performance. The IoT component enables real-time monitoring and adaptive control for enhancing system responsiveness. The suggested system is simulated and modeled in MATLAB/Simulink and validated with low-cost hardware implementation on microcontrollers. Simulation results and suitable experiments validate better voltage regulation, reduced total harmonic distortion (THD), and improved dynamic response over conventional control schemes.

Keywords: induction generator, Internet of Things (IoT), Interval Type-2 Fuzzy Logic Control (IT2FLC), wind energy

1. Introduction

The worldwide drift toward green energy resources has increased the use of wind energy equipment, particularly in remote and off-grid locations. Induction generators driven by wind turbines are popular due to their cost effectiveness and reliability [1]. Yet the variability of wind and load variation in off-grid applications present monumental challenges in voltage stability and power quality. For grid connected applications, three-phase induction generators or Doubly-Fed Induction Generators (DFIG) are often used for generation [2–4]. Mostly in wind energy systems, the three-phase Self-Excited Induction Generators (SEIG) are used in grid isolated applications [5–7]. Nowadays, for easy supply of single-phase grid-isolated loads, the single-phase induction generators are also used [8]. Of all the isolated generations, the common problem of voltage regulation is prevalent. Also, the problem worsens with the changing loads along with varying wind speeds [9, 10]. Traditional control methods, such as the Proportional-Integral (PI) controller, are observed to fail in controlling the nonlinearities and uncertainties of wind power systems. These uncertainties become more difficult to control with increasing system size and load variability.

Fuzzy Logic Controllers (FLCs) and their modifications have been employed to bypass this limitation, with the hope of greater adaptability [11]. Type-1 FLC, however, is limited in controlling the uncertainties with crisp membership functions. Sometimes, neuro-fuzzy adaptive control is also used for better control but with increased complexity [12]. Recently, sliding mode control [13] model based predictive control [14] are also popular. However, the sliding mode control has problem of discontinuous nature of law of control and model predictive control suffers from modelling uncertainty. In [15], the IG is used with dynamic voltage loop-based control and the load is controlled using Internet-of-Things (IoT).

Type-2 Interval Fuzzy Logic Controllers (IT2FLCs) are more advanced than Type-1 FLCs with the addition of a Footprint of Uncertainty (FOU) and the ability to handle greater system uncertainty. IT2FLCs were shown through experiments to offer better performance in most applications, including wind power systems [16]. However, the system becomes somewhat sluggish with the control. Internet-of-things is used in the proposed system which also makes the system faster with better reliability.

The advent of the Internet of Things (IoT) has introduced new possibilities for real-time monitoring and control of the energy system. IoT sensors detect and transmit data, providing adaptive control strategies that respond to changing system conditions [17–19]. Renewable related IT2FLC controllers are also slowly gaining popularity [20–21]. Despite these advancements, research is essential in the integration of IoT and IT2FLCs for the supervisory control of wind-driven IGs in off-grid applications.

The current study attempts to fill the gap by designing and simulating an IoT-based supervisory control system using IT2FLC for dynamic load management in off-grid wind power systems. The chief advantages of the proposed scheme are:

- Decent voltage regulation under varying wind speed and load uncertainty using IT2FLC with footprint of uncertainty.
- Real-time load optimization through IoT-based control, enabling dynamic arrangement of critical loads.
- Minimal hardware requirement using low-cost ESP32 microcontroller, suitable for remote and grid-isolated energy disposition.
- Improved response time and reduced deviation compared to conventional PI and Type-1 fuzzy controllers.

The paper is organized as: Section 2 of the paper describes the control methodology with system modelling, IT2FLC controller details and IoT based supervisory control. Section 3 describes the simulation and experimental systems and shows the obtained simulation results validated by suitable experiments. Finally, conclusion and future scope is presented in Section 4.

2. Control Methodology

2.1. System Modelling

The wind energy conversion system comprises a variable-speed wind turbine driving a squirrel-cage IG. The generator's output is connected to a power electronic interface which is bidirectional converter. The converter regulates voltage and frequency to match load requirements. The system is modeled in MATLAB/Simulink, incorporating wind speed profiles and load variations.

The suggested system comprises a variable speed wind turbine driving a Squirrel Cage Induction Generator (SCIG) whose power is conditioned by a bidirectional power converter in the form of controlled converter-inverter. The converter offers voltage and frequency control to supply stable power to dynamic loads in an off-grid system. The inverter connected to load side operates at a fixed frequency to facilitate stable frequency supply. The SCIG system model comprises electrical and mechanical subsystems to react to wind speed variation and generator dynamics. A supervisory control layer is employed in the form of an Interval Type-2 Fuzzy Logic Controller (IT2FLC) to control voltage stability and power flow. A remote monitoring and control of loads is enabled by an IoT-based interface for adaptive response to demand variation. The proposed system model is shown in Fig. 1.

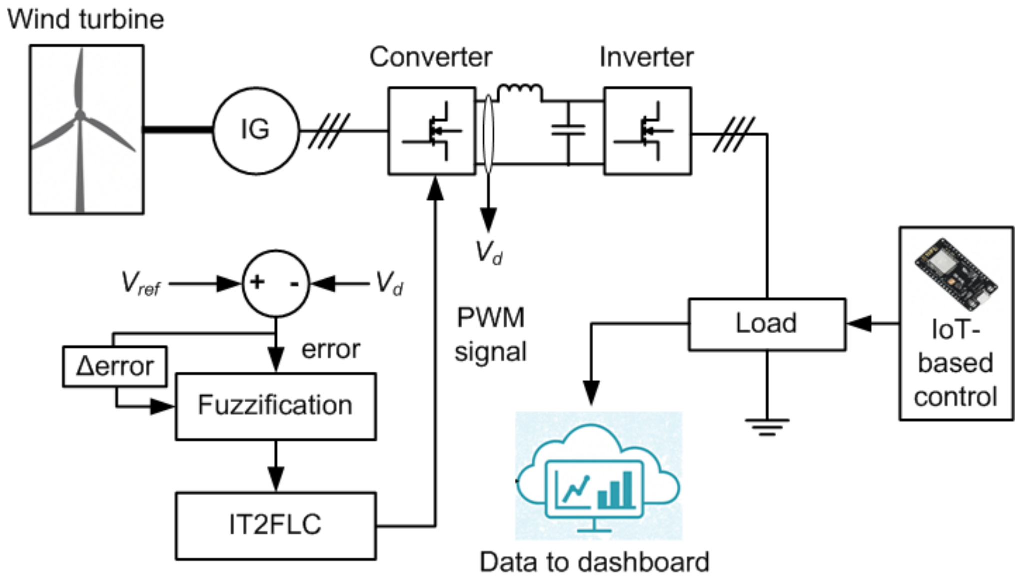

Fig. 1. Block diagram of the proposed system with control.

2.2. Interval Type-2 Fuzzy Logic Controller Design

Interval Type-2 Fuzzy Logic Controller (IT2FLC) is designed to control the uncertainty in the load demand and wind speed affecting the output of the induction generator. IT2FLC possesses a Footprint of Uncertainty (FOU) in membership functions, in contrast to Type-1 fuzzy controllers, which makes it more responsive to varying and fuzzy input conditions.

For wind-driven off-grid systems utilizing a Squirrel Cage Induction Generator (SCIG), a stable output voltage is challenging to obtain since SCIGs lack the natural voltage control feature along with the wind speed and load demand fluctuations. The IT2FLC is utilized to regulate the output voltage by modulating the bidirectional converter that is connected to the generator. The IT2FLC aims to minimize the voltage error, and its rate of change as,

$$e(t) = V_{ref} - V_{IG}(t) \tag{1}$$

$$\Delta e(t) = e(t) - e(t-1) \tag{2}$$

These two signals form the inputs to the fuzzy inference system. The output $u(t)$ controls the modulation index of the inverter section of the bidirectional converter, which in turn adjusts the voltage at the generator terminal. Interval Type-2 fuzzy sets with FOU are defined for every input to enable the controller to manage uncertainty in the measured voltage and its fluctuations. Mamdani-type rules are employed in the fuzzy rule base to translate input conditions to control actions. Fuzzy inference involves type-reduction based on the Karnik-Mendel iterative algorithm to compute the centroid of the output set and defuzzification to generate a crisp control signal. This output adaptively regulates converter switching to hold SCIG terminal voltage constant against wind and load variation to provide reliable power in isolated operations.

Thus, the IT2FLC is designed with two inputs: the error between the reference and actual voltage, and the change in error, and the output serves as the control signal to the power electronic interface. The membership functions are defined with an FOU to capture uncertainties. A rule base is established based on expert knowledge and system behavior. The fuzzy inference mechanism involves three main steps:

- Fuzzification of inputs using interval Type-2 membership functions, characteristically modeled as Gaussian shapes with upper and lower bounds.

- Rule evaluation based on a Mamdani-type rule base, where, if $e(t) = \widetilde{A}_i$ and $\Delta e(t) = \widetilde{B}_j$, then $u(t) = \widetilde{C_{ij}}$ where, $\widetilde{A}_i$, $\widetilde{B}_j$, and $\widetilde{C_{ij}}$ are interval type-2 fuzzy sets.
- Type-reduction and defuzzification using the Karnik-Mendel algorithm to obtain a crisp output control signal. The pseudocode for the IT2FLC is provided in Appendix A.1.

This control output dynamically adjusts converter operation, ensuring system voltage remains within bounds even under abrupt changes in wind or load. Fig. 2 shows the membership functions of input error, change in error and membership function of output. The shaded portions are the FOU as described previously.

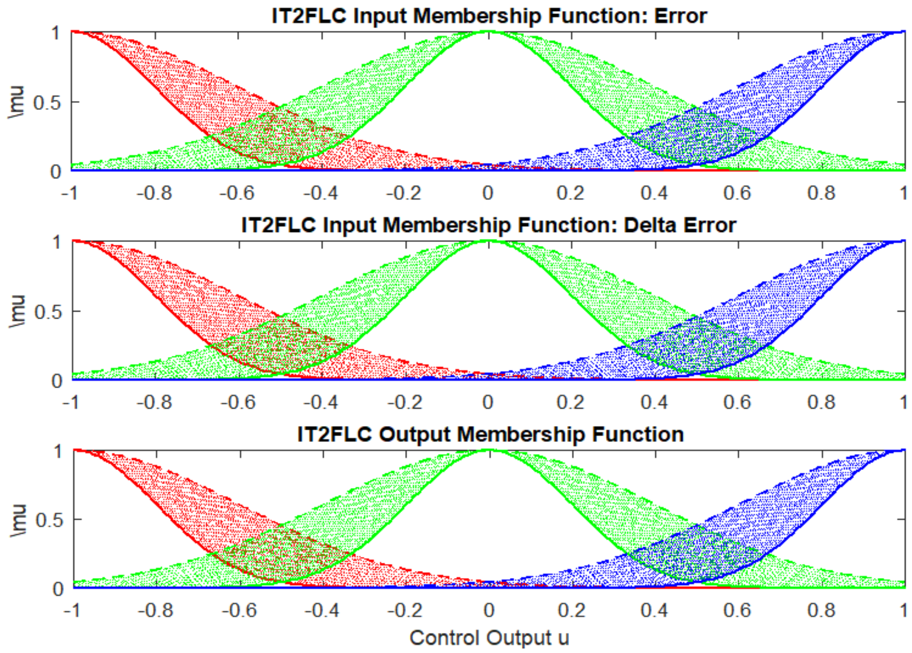

Fig. 2. Membership functions of input error, change in error and membership function of output.

2.3. IoT-Based Supervisory Control

For off-grid wind power systems driven by induction generators, regulation of dynamic and load profile is essential to ensure voltage stability and continuous power delivery. Unlike grid-based systems, off-grid systems need to address these fluctuations on their own. To overcome this difficulty, an IoT-based supervisory control is incorporated into the system to track and react to load changes in real time.

The IoT infrastructure includes low-cost microcontrollers like ESP32 devices integrated with voltage, current, and load-switching sensors. These units continuously monitor system parameters and send data wirelessly to the central controller or cloud server over message queuing telemetry transport or MQTT IoT protocol. MQTT is a low-weight publish-subscribe communication system which is appropriate for proposed IoT-based system control. The control parameters are displayed in a dashboard user interface which uses Blynk application for the control. These parameters are displayed and it enables system operators to view, control and modify load performance remotely. Such a closed-loop control on IoT devices authorize anticipatory regulation. When a decline in wind speed and hence generation is observed, the unimportant loads can be scheduled for turned off. With this connectivity, the supervisory system is provided with real-time information regarding the state of the loads and the generator output.

This data allows adaptive load control, where the non-priority loads may be selectively turned off or on depending on the voltage state of the IG. For instance, whenever the terminal voltage falls because of an abrupt rise in load or a drop in wind speed, IoT control logic can briefly shed low-priority appliances or postpone their operation, thereby avoiding heavy voltage sags. Alternatively, during periods of surplus generation, the controller can switch in additional loads to use surplus energy and enhance system efficiency. The IoT architecture also communicates with the IT2FLC by sharing environmental and electrical information that affects the decisions of the fuzzy controller. This involves load patterns of usage, ambient conditions, or wind predictions, which add robustness to the adaptability of the fuzzy system.

In addition, the IoT-supported system provides a remote monitoring, diagnostics, and manual override user interface that enables users to monitor performance, establish operational limits, and control system priorities. This integration significantly improves the resilience, flexibility, and intelligence of the SCIG-based off-grid wind energy system. The pseudocode for this proposed control is specified in Appendix A.2.

The IoT-based supervisory logic is implemented on an ESP32 microcontroller, interfaced with the wind-driven IG system via relay modules and voltage sensors. Sensor data including output voltage and load state is streamed in real time to a cloud dashboard using MQTT protocol. Based on dynamic thresholding and wind-voltage conditions, prioritized load shedding is performed via GPIO pin toggling in the ESP controller. The supervisory algorithm is detailed in Algorithm (specified in Appendix A.2). Similar IoT-based supervisory systems for electric machines are explored in [22, 23].

3. Simulation & Experimental Results

The simulations are done on MATLAB environment using model built in MATLAB script files (m-files). The simulation model uses a three-phase induction machine of 1.5 kW, 400 V, 50 Hz and with a stator wound for 4 poles. The load consists of 500 W AC load with a daily consumption of around 7.5 kWh. The induction machine is coupled to a wind turbine which supplies the necessary mechanical power to the IG. The turbine is directly coupled to the IG rotor shaft for simulation.

For the experimental purpose, a laboratory setup is considered with the same ratings identical to those used in the simulation. The load side inverter is operated at a fixed 50 Hz frequency maintaining the load frequency at a stable value. The system hardware details are presented in Table 1.

Table 1. System hardware details

Component	Parameters	Description
System details	Induction Generator	Induction machine, 3-phase, 1.5 kW, 400 V, 50 Hz, 4-pole
	Load (total)	500 W, 7.5 kWh daily consumption
	Prime mover	DC motor, 2 kW, microcontroller to match wind turbine characteristics
	Controller	Atmega 328P for IT2FLC-based converter control
	Circuit of converter	VS-50RIA60 SCR based, 600 V, 50 A, with driver and protection
	Circuit of inverter	K2611 MOSFET based, 9 V, 11 A
	Driver	MC33153P
	Inverter switching frequency	20 kHz
IoT control system	Controller	ESP32
	Network router	IPv6
	Broker	MQTT
	Dashboard	Blynk application
	Relay	Optically isolated, 5V, 4-channel
	Sensors	voltage ZMPT101B, current ACS712

In the laboratory setup, the loads are also connected using relays. ESP32 microcontroller is used for the IoT control logic. The IG is coupled to a DC motor wherein, the motor speed is controlled using a Atmega microcontroller. The microcontroller is driven using wind speed command fed using a real-world wind turbine characteristic. The generated voltage is converted to DC using the converter and back to AC using the fixed frequency inverter to supply the loads. The inverter is driven at fixed frequency of 50Hz as mentioned.

An Atmega328P controller is programmed the IT2FLC for control for the converter switching maintaining the bus voltage. For load monitoring and control, ESP32 communicates key controller parameters to a cloud-connected Blynk dashboard using MQTT.

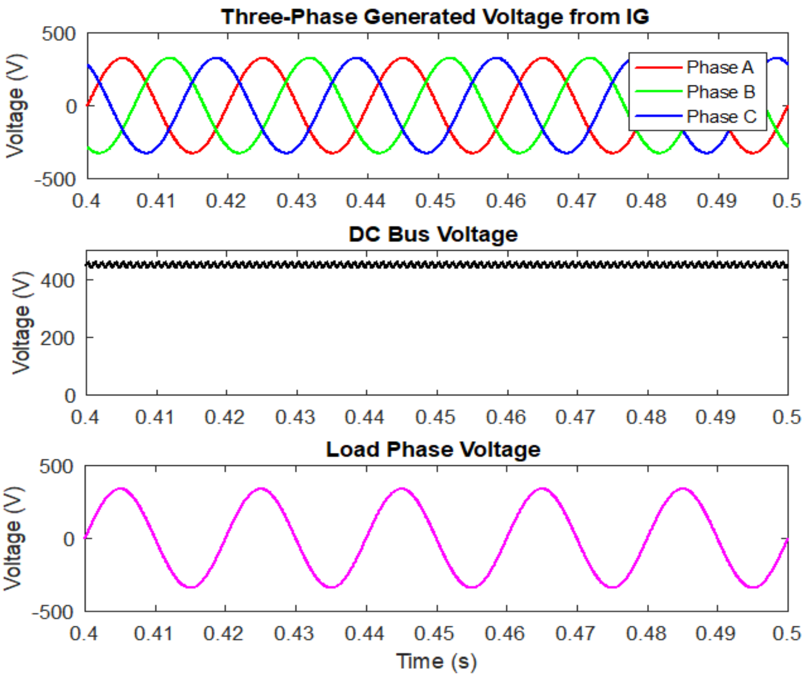

Fig. 3. Simulated IG voltage, DC bus voltage and phase voltage of load.

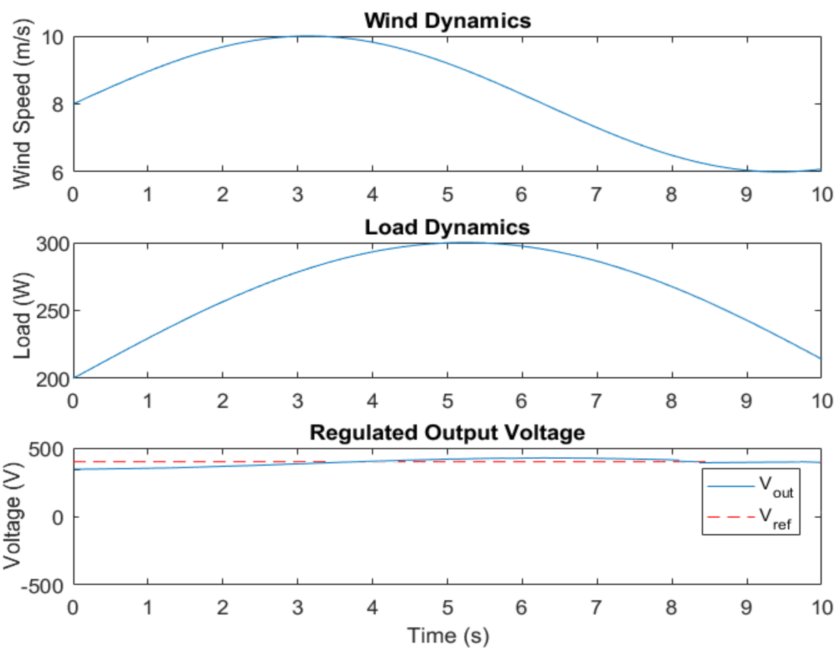

Fig. 4. Simulated wind dynamics, load dynamics and regulated output voltage with the proposed control.

The system simulated generated voltage, DC bus voltage and load voltage at steady state is shown in Fig. 3. T steady state, the generated voltage is steadier with constant wind speeds. Accordingly, the bus voltage is also stable. The load phase voltage from the fixed frequency inverter is at 50Hz as shown in the figure. To test the simulation system with the proposed IT2FLC based control, at first, a change in system speed and load is considered. The wind dynamics considered for the variation is increasing speed and decreasing thereafter. The loads are also varied to create a 20% increase and subsequently a decrease in load. The regulated voltage of output is shown to closely follow the reference voltage as observed form the simulation diagram of Fig. 4 with the proposed control.

For the hardware implementation of the Internet-of-Things (IoT) application, microcontroller ESP32 is used which is also used to obtain real time measurements. The loads are controlled ON/OFF using the controller signals via relay modules. The non-critical loads are turned off depending on the necessity and power consumption. The block diagram of the hardware setup is shown in Fig. 5. For the IoT system, Blynk application is used as dashboard for real-time control of the loads and generation as shown.

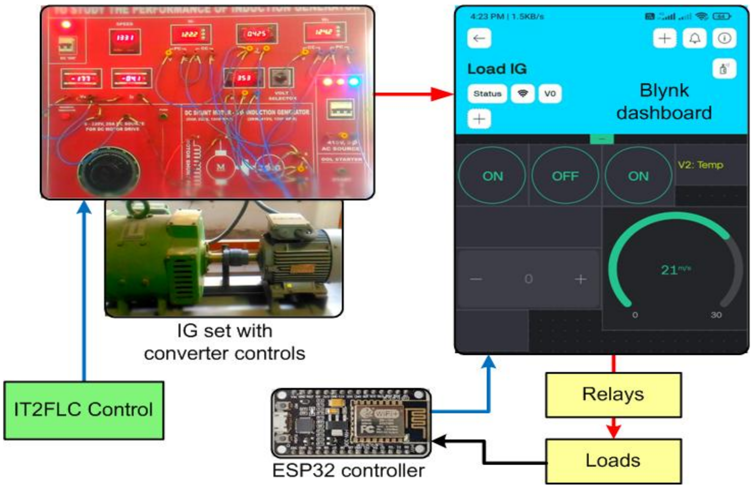

Fig. 5. Experimental block diagram with IoT-based real-time dashboard for monitoring and controlling generator voltage, DC link, and connected loads.

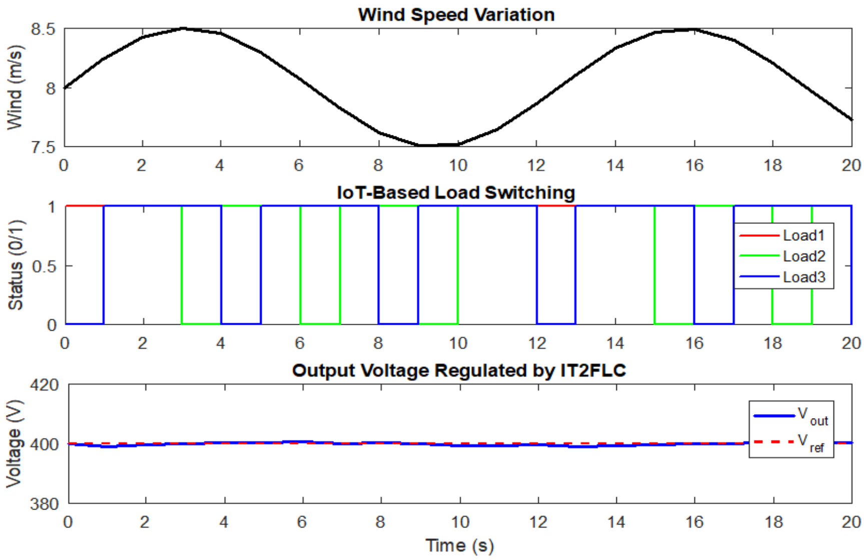

Fig. 6. Experimental wind dynamics, load status and regulated voltage output.

Fig. 6 depicts the experimental wind dynamics or variation in wind speed, load status of whether the load is switched ON (1) or switched OFF (0) and the regulated voltage output with the reference voltage. In the proposed problem, three different loads are considered as the consolidated system load. Accordingly, when the loads are turned ON/OFF and with the system variation of wind speed, with the proposed control, the output voltage from the system is remaining at a stable value and closely following the reference voltage. The proposed controller performance is compared with prevalent standard and state-of-the-art control techniques available for such generation schemes. The result is tabulated in Table 2 below. Each of the control techniques are also applied in the proposed generation system for comparison data.

Table 2. Controller Performance Comparison

Controller Type	Steady-State Error (V)	Settling Time (s)	Max Deviation (V)	Load Handling Efficiency (%)
PI Controller	15-20	3.2	±28	85
Type-1 FLC	10-15	2.5	±18	89
IT2FLC (Proposed)	2-5	1.7	±9	95

As observed from the table, the IT2FLC control performs better with lower steady state error, better settling time and low deviation than both PI and Type-1 fuzzy logic controllers. Also, with the proposed control, the load handling efficiency increases than the other two popular controllers. This is advantageous for controlling critical loads especially in a remote and grid-isolated setup.

Additionally, the proposed IT2FLC scheme also reduces Total Harmonic Distortion (THD) in output voltage, improving the output power quality. FFT analysis shows the THD reduced from 6.3% (PI control) to 3.1% (IT2FLC) under variable wind and load conditions. The voltage waveform comparison and the voltage THD plot comparison are shown in Fig. 7 below. As observed, the proposed controller obtained results are much better than without the use of this control which is evident. Table 3 provides controller performance as regards overshoot, voltage recovery time and ripple during disturbances like changes in wind speeds or loads. It is observed that the proposed controller betters the system performance in all these three cases.

Table 3. Controller Performance with Disturbances

Metrics	Without IT2FLC	With IT2FLC
Overshoot	12%	2%
Voltage recovery time	1.5s	0.5s
Maximum ripple during disturbances	18V	6V

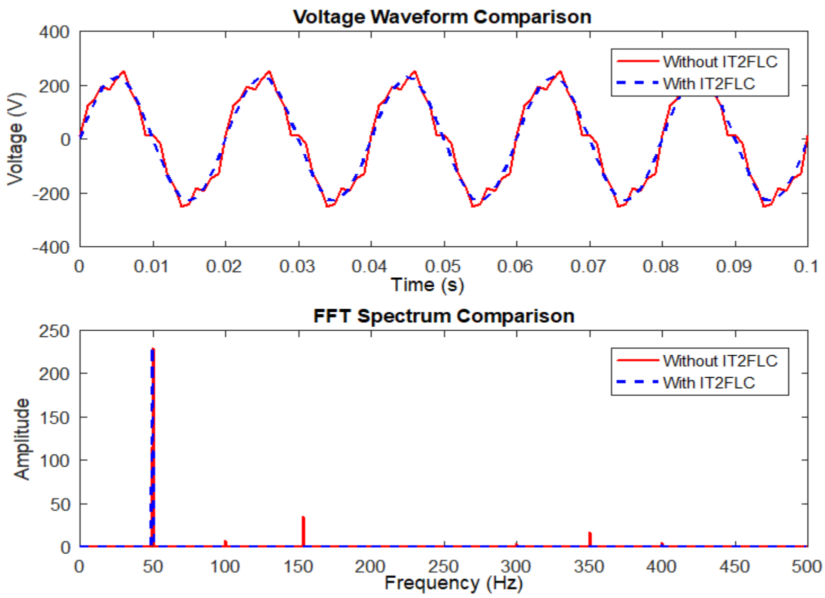

Fig. 7. Voltage waveform and THD comparison plots.

Fig. 8 depicts the controller response to step load or wind speed. This study is performed to validate controller’s dynamic adaptability. As observed, without IT2FLC the waveform shows ripple, with overshoot and slow recovery. With the proposed controller, it shows smooth adaptation with minimal ripple and fast recovery.

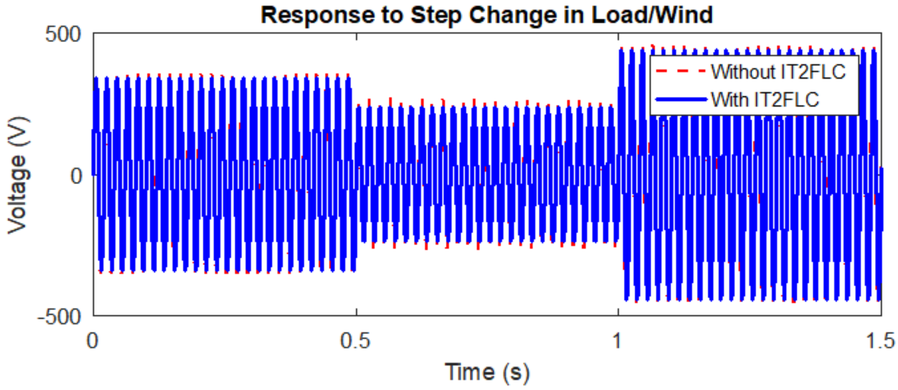

Fig. 8. Experimental response of the system to step changes in load/wind profile.

4. Conclusion

This paper presents a novel approach towards solving the issue of integrating wind energy into off-grid systems by using an IT2FLC integrated with an IoT-based supervisory control system. The proposed system is anticipated to achieve improved performance in dealing with uncertainties and dynamic loading, ensuring stable and quality power supply. The integration of IoT enables real-time monitoring, adaptive control, and improved system robustness. Additionally, comparative analysis with conventional controllers confirmed the advantage of IT2FLC in terms of accuracy, stability, and adaptability. The successful integration of IoT-based real-time load control with fuzzy logic makes this scheme a capable solution for remote and off-grid wind-based power systems.

Future work will include hybrid controller design using deep-learning-based fuzzy tuning and integration with larger microgrid testbeds. System verification through more experiments and scaling up to large-scale microgrid systems will be undertaken in future work.

Appendix A

A.1. Pseudocode: *Interval Type-2 Fuzzy Logic Controller (IT2FLC)*

```
Input: Error (e), Change in error (de)
Output: Control signal (u)
1. Normalize inputs: e_norm = e / e_max, de_norm = de / de_max
2. For each fuzzy rule:
      - Evaluate Upper MF: µ_U(e_norm), µ_U(de_norm)
      - Evaluate Lower MF: µ_L(e_norm), µ_L(de_norm)
3. Compute Footprint of Uncertainty (FOU)
      - FOU = area between µ_U and µ_L
4. Apply fuzzy inference on both bounds
      - u_U = output using upper MFs
      - u_L = output using lower MFs
5. Aggregate outputs
      - u = (u_U + u_L) / 2
6. Denormalize and clamp: u = clamp(u * gain, u_min, u_max)
Return u
```

A.2. Pseudocode: *IoT-Based Supervisory Load Control Loop*

Input: V_out, Wind_speed, Priority[1..3]
Output: Load_status[1..3]
1. Set V_ref = 240 V
2. Measure V_out and Wind_speed from ESP32
3. Compute V_error = V_ref - V_out
4. IF Wind_speed $\geqslant$ 8 AND |V_error| $\leqslant$ 5
        Set Load_status[1..3] = ON
    ELSE IF Wind_speed $\in$ [6, 8) AND V_out $\geqslant$ 230
        Set Load1 = ON, Load2 = ON, Load3 = OFF
    ELSE IF Wind_speed < 6 OR V_out < 220
        Set Load1 = ON, Load2 = OFF, Load3 = OFF
    ELSE
        Maintain previous Load_status
5. Send Load_status[i] to relay pins via ESP32
6. Repeat every 0.5 s

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

Conceptualization, methodology, analysis, and investigation for the system, A.K.M. and A.C; software, validation, and data curation, by A.K.M. and A.C.; writing—original draft preparation, review, and editing, A.C.; visualization, A.K.M.; supervision, A.C. Both authors had approved the final version.

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