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RESEARCH ARTICLE **OPEN ACCESS**

DESIGN AN INTELLIGENT CONTROLLER FOR LOAD BALANCING IN WIND ENERGY SYSTEMS CONNECTED TO THE GRID

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ABSTRACT

With the rapid expansion of wind energy integration into electrical grids, there is an urgent need for an intelligent control system capable of adapting to the sharp power fluctuations caused by the ever-changing nature of wind and maintaining stable frequency and voltage to meet fluctuating load requirements. This paper aims to provide complete and intelligent control of a combined wind turbine-to-grid power generation system. The intelligent control unit can instantly estimate wind speed and rated power, thereby providing automatic adjustment mechanisms for inverters and load distribution. The system is represented by a detailed simulation in MATLAB/Simulink. The control unit can also analyze instantaneous frequency and voltage deviations, classify load conditions, and compensate for deficits or surpluses in the wind turbine's generated power. This study evaluated the typical performance of the proposed unit for various scenarios, including unexpected fluctuations in wind speed and sudden load changes. Simulation results showed that the intelligent controller eliminated a significant proportion of frequency deviations compared to conventional control systems. Furthermore, the voltage drops and rises were within acceptable specifications.

I. INTRODUCTION

Wind turbines hold a leading position in the context of environmental sustainability and meeting the growing global demand for energy. They are among the most prominent renewable energy technologies. They are used to convert wind energy into electrical power. Wind turbines can be classified based on the amount of energy derived from capturing the wind to operate them [1][2]. Wind turbines reduce dependence on fossil fuels, leading to reduced carbon emissions and combating climate change [3]. Wind turbines increase the efficiency of the electrical system when operated in parallel with the main grid [4]. Furthermore, the generated wind energy is transmitted to the electrical grid, providing greater stability to the power system, as wind turbines can supply electricity when demand is high. However, renewable energy sources, such as wind turbines, face challenges including intermittency and fluctuation due to varying wind speeds. Therefore, it is essential to develop strategies for frequency control, grid stability, and load control.

Smart control technologies can also improve turbine performance by enabling them to respond more quickly to changes in energy demand and handle disturbances such as overloads, faults, or even load shortages. With wind power having grown by an exceptional 14% since 2010, it is the second-fastest-growing new energy source after solar power. Wind power is set to become the third-largest source of global electricity generation after hydropower and solar by 2030, according to estimates by the International Energy Agency [5]. This growth is part of the global shift from using polluting resources as fuels to more efficient and environmentally friendly sources. All of these factors combined demonstrate the importance of wind power in the future energy mix. These forecasts point to profound changes coming to the energy industry as countries seek to reduce their dependence on fossil fuels and transition to a cleaner mix of sources. Improving the efficiency of wind turbines and related technological solutions enhances their ability to compete in the global energy market [6][7].

A connection of a wind power generation system (WPS) with the electrical primary grid is referred to as a GRID-on connection. Grid-tied connectivity refers to how a WPS integrates with load-only devices or an energy storage system. When connected to the grid, it needs to meet synchronisation conditions because the three-phase inverter (VSI) voltage and frequency must be equal to the grid's voltage, since that remains constant. On the other hand, the voltage and frequency of the WECS change with wind speed, which requires the development of a robust and reliable controller to reach synchronisation. The voltage at the DC link should be stable; this is the main goal of grid-side control, and we also need monitoring of DC link input voltage to VSI & power transfer active/reactive power into the grid. To achieve this, there is a need to use advanced control technologies to guarantee the stability of the electrical system and an even better plant performance.

These results are important because the wind power generation system can successfully help to achieve an efficient development of energy budgets, and at the same time ensure the stability in the electric system [8]. All these features and more can be achieved by using a three-level inverter as an interface to the grid, ensuring the quality of the output signals and, in general, the durability and responsiveness of the entire system [9]. Given the importance of maintaining constant voltage and frequency, in addition to all the other advantages of connecting renewable energy systems to the grid, many advanced algorithms are emerging to achieve this. In this paper [10], the researcher used the Wind Driven Optimization Algorithm and the Firefly Algorithm together to balance loads and maintain system stability, in addition to comparing them with another group of algorithms. All of this opens up future horizons for hybrid systems and smart cities. While this study deals with a proposal for a fuzzy logic algorithm to track the maximum point of a hybrid renewable energy system consisting of a wind turbine and solar cells, in addition to smart control units capable of managing the power generated by the system and distributing it between the grid or charging batteries[11].

The use of advanced quasi-ZSI (Z-Source Inverters) technology has a significant impact on the stability of both frequency and voltage, achieving high efficiency and reducing the number of components used, unlike conventional designs, in addition to the overall conversion efficiency. Furthermore, it is possible to connect renewable energy sources directly to the grid without the need for additional conversion stages [12]. The system used in this study combines wind turbines and solar cells with a set of control units. Some of these units work to draw the maximum power generated from the system, defined as MPPT algorithms. Other units control the voltage and frequency and maintain them constant in three scenarios discussed: changing radiation intensity, changing wind speed, and load disturbances using a load-side converter (LSC) control unit [13]. The use of smart control methods and artificial intelligence strategies in renewable energy power generation systems has become a must.

Therefore, an infinite number of these strategies have emerged, all of which serve one goal: increasing the capabilities of prediction and adaptation to overcome all obstacles and achieve a faster and more accurate response for the entire system [14]. After reviewing previous research and methodologies, this research proposes a smart FPI controller that controls a VSI on the grid side to synchronize the electrical power generated by wind turbines with the grid in terms of voltage and frequency, as well as balance the supplied loads and handle additional loads treated as external disturbances. All results of the proposed controller will be compared with those of a conventional PI controller. The proposed system model comprises a wind turbine, various other components, and complex control processes, which will not be the focus of this study. This study will, however, cover an intelligent controller that controls the VSI, an isolation transformer, the grid, and loads. Figure 1 shows the system proposed in this study.

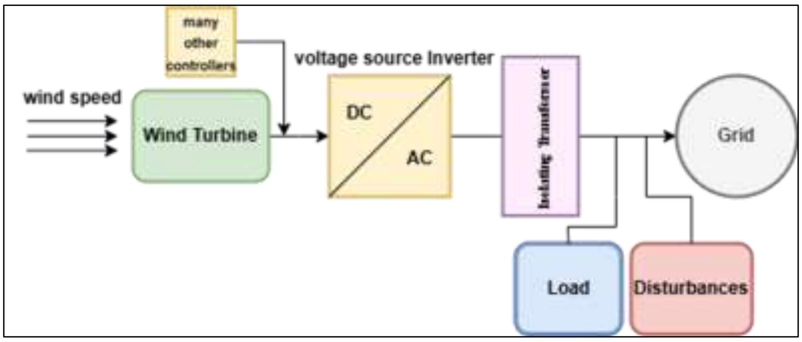

Figure 1: WECS scheme connected to the main grid and equipped with an intelligent controller.
Source: Authors, (2026).

II. THEORETICAL REFERENCE

II.1 WIND TURBINE

The power output of wind turbines varies depending on wind speed, with each wind turbine having its power performance curve. This curve enables the prediction of a wind turbine's power production without considering the technical details of its various components[15]. By analysing performance curves, operators and planners can estimate turbine efficiency under varying wind conditions, thereby contributing to improved energy management strategies and more informed electrical grid planning. Momentum theory is used to analyse the behaviour of wind turbines and make predictions about their performance. In this context, variables are analysed to ensure they have the same value over a specific portion of the air stream pipe, assuming that air is incompressible and fluid motion is constant. The resulting force is expressed by the flow of air, which is moving at a speed. The following equation expresses the mechanical power captured by a wind turbine [16][17]:

The mechanical power captured by a wind turbine

$$P_m = 0.5\rho A v^3 C_p(\beta,\lambda) \tag{1}$$

Where:

ρ = air density (Kg/m^3)
v = wind speed (m/s)
$A = \pi r^2$ (m^2)

The Betz coefficient represents the maximum theoretical value of C_p where:

$$C_{pmax} = 0.593 = 59.3\% \quad (2)$$

II.1.1 Intelligent Controller

A power converter is known as a device that converts DC power into AC power. This device consists of six power switches that utilise IGBT technology with anti-feedback diodes. These keys are divided into two groups: the upper group, which includes keys S1, S2, and S3, and the lower group, which consists of keys S4, S5, and S6[18]. To avoid short circuits, the switching technology used must be intelligent so that two switches on the same terminal do not operate at the same time. As one of the most common methods of switching signal generation, PWM is increasingly used in VSI because it controls the voltage and suppresses the third harmonic of the inverter's output voltage, improving the quality of the generated power [19]. PI controllers remain the most widely used controllers in the wind energy conversion system (WECS) industry due to their robustness and high stability margins. However, to achieve optimal performance from these controllers, tuning key parameters is essential to ensure correct operation and reliable control of the system [20].

Tuning PI controller parameters is a significant challenge in nonlinear or complex systems, where even minor adjustments are difficult for these controllers to handle. In recent years, PI controllers have been replaced by fractional proportional integral (FPI) controllers as a means of overcoming the problems described above. Additional benefits of FPI controllers are based on their ability to adapt to dynamic changes within the system, which in turn makes control more effective and better responsive to changes. The FPI controller is the next generation of PI controllers, offering excellent system performance. FPI controllers have the benefits of increased system stability and reduced sensitivity to parameter changes, making them more suitable for dynamic systems. Moreover, FPI controllers respond faster to reach zero crossing time to dampen oscillation, which directly helps increase the efficiency and stability of the entire system [2][21]. Figure 2 shows how the smart control unit works to enable the effective coordination and work synchronisation between the grid and the wind generator.

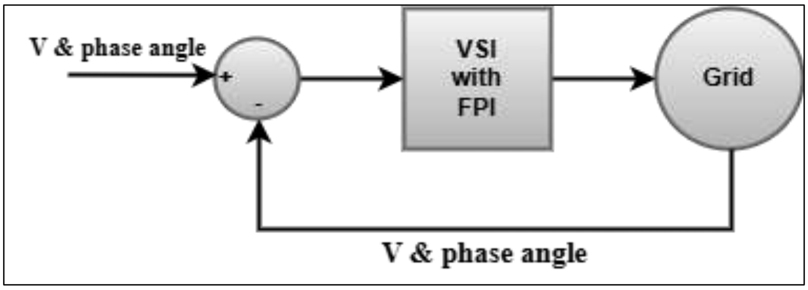

Figure 2: Operation of the intelligent control unit.
Source: Authors, (2026).

Figure 3 demonstrates the load balance between the grid and the wind turbines and how the intelligent unit controls the loads. Rated loads are fed from the wind turbines, and any additional load that introduces disturbances is fed from the grid. When there are no loads, all the power produced by the turbines is transmitted to the grid, maintaining the stability of the electrical system and improving energy efficiency.

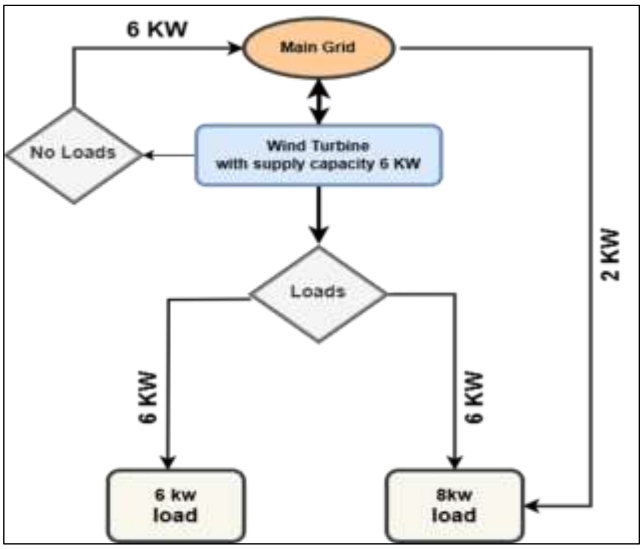

Figure 3: The distribution of loads between the wind turbine and the grid, prioritised according to the diagram, is shown.
Source: Authors, (2026).

II.1.2 Isolating Transformer

Isolation Transformers are utilized to protect sensitive devices from electrical noise and to provide step-up or step-down as required, in addition to coupling two circuits together that cannot be connected directly. These converters remove the DC, while allowing the AC to pass. The proposed three-phase isolation transformer concept is emerging in renewable power system applications due to the improvements in energy transmission and the stability of the electric system [22].

II.1.3 Grid and Loads

The national grid is a complex system designed to transmit and distribute electrical power across large geographic areas, ensuring that consumers' energy needs are met efficiently and reliably. It consists of a group of power plants, transmission lines, and transformer stations, working together to provide electricity to homes, businesses, and industries. Renewable energy sources are often integrated into the national grid, enhancing the sustainability of the electrical system and reducing dependence on fossil fuels. When wind turbines are connected to the grid, they supply the necessary electrical power to the loads. However, it is undeniable that wind turbines alone are insufficient to cover all loads. This is where the intelligent control unit comes in to balance the load distribution between the two sources. Wind turbines supply loads within their rated electrical capacity, while excess or unexpected loads are considered disturbances and are supplied from the main grid, which in turn generates electricity using other sources [23].

III. MATERIALS AND METHODS

This study aims to analyze the performance of a grid-tied wind energy conversion system (WECS) under variable conditions, including changes in load and wind speed, and to demonstrate the adaptability of the control used in the system. During the simulation period ($0 < t < 10$) seconds, the load was constant at 6 kW. Then, in the period ($10 \leq t \leq 12$) seconds, the load was increased by about 34% before returning to its original value. The entire system was modeled using MATLAB, as shown in Figure 4.

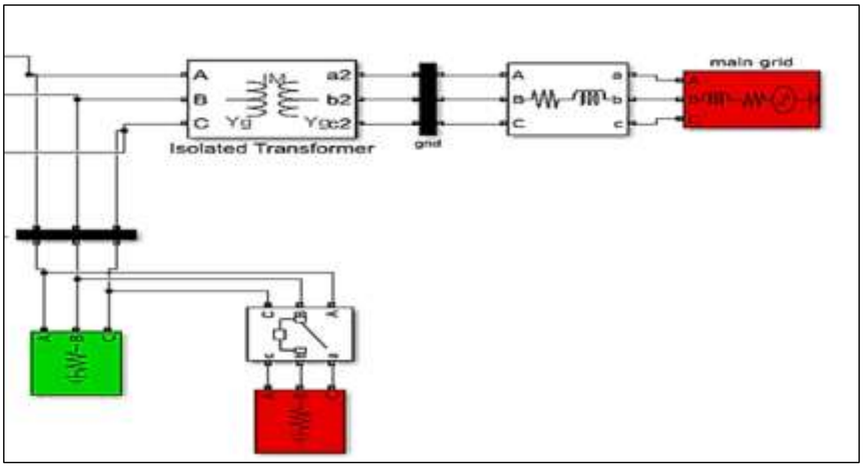

Figure 4: Simulation model of the main grid and loads.
Source: Authors, (2026).

IV. RESULTS AND DISCUSSIONS

The maximum output capacity of the wind turbine is estimated at 6 kW. Therefore, any load exceeding this limit is considered a disturbance and cannot be handled effectively, which is classified as an overload that requires the intervention of additional power sources to ensure the stability of the electrical supply. The wind speed was adjusted according to the step size as shown in Figure 5. This type of wind speed change is considered unrealistic, as it represents a significant challenge for a grid-tied (WECS) due to sudden and rapid transitions between wind speeds. Through this scenario, the effectiveness and efficiency of the proposed adaptive control system can be evaluated.

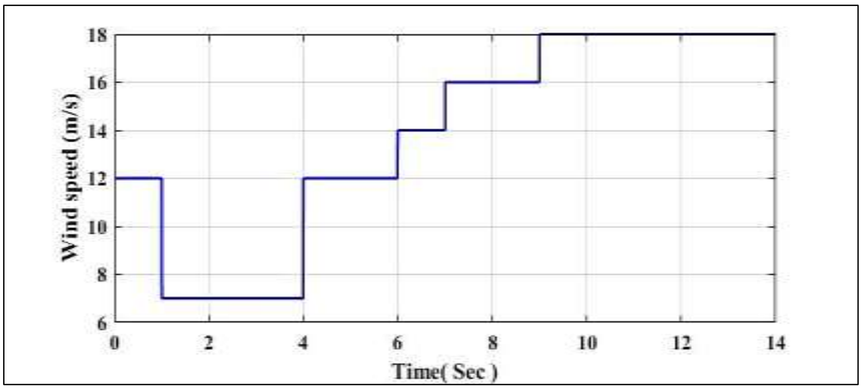

Figure 5: Wind speed variation with time.
Source: Authors, (2026).

Despite fluctuations in wind speed and varying loads, the single-phase voltage waveforms of the load and grid, as shown in Figures 6 and 7, show outstanding performance using both FPI and conventional PI controllers. Voltages remain constant in both methods, but the use of an FPI controller provides better control, as the system exhibits a larger and smoother damped response, reducing oscillations and overshoots in the voltage waveform.

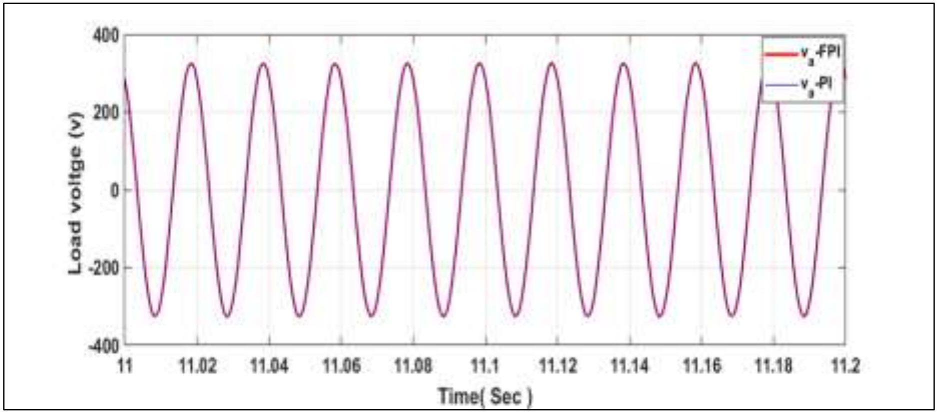

Figure 6: Single-phase load voltage under the intelligent controller.
Source: Authors, (2026).

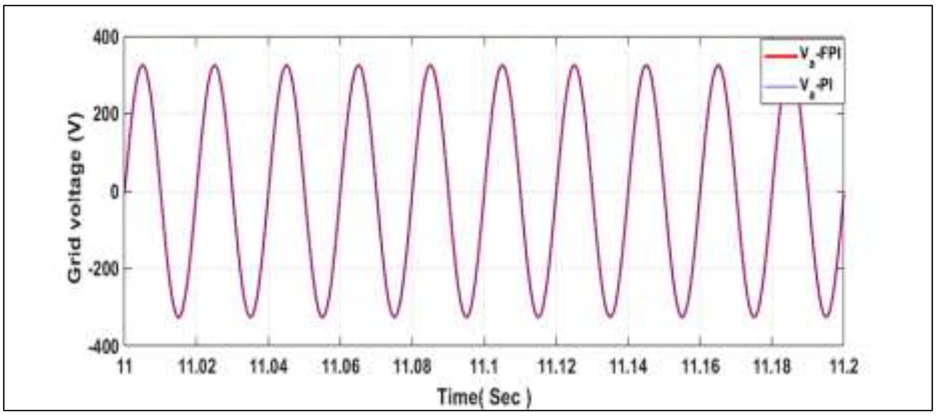

Figure 7: Single-phase grid voltage under the intelligent controller.
Source: Authors, (2026).

Figure 8 shows the single-phase load current. From this figure, it can be seen that the current remains constant at its rated value during the simulation period from (0 to 10) seconds, where the load is 6 kW and is fed entirely from the wind turbine. When the load increases during the simulation period from (10 to 12) seconds to reach 8 kW, this increases the drawing current from the electrical grid, which means that the system draws an additional 2 kW from the grid. The system shows a significant improvement in reducing oscillations and over- and undershoots when using the intelligent controller in the presence of FPI.

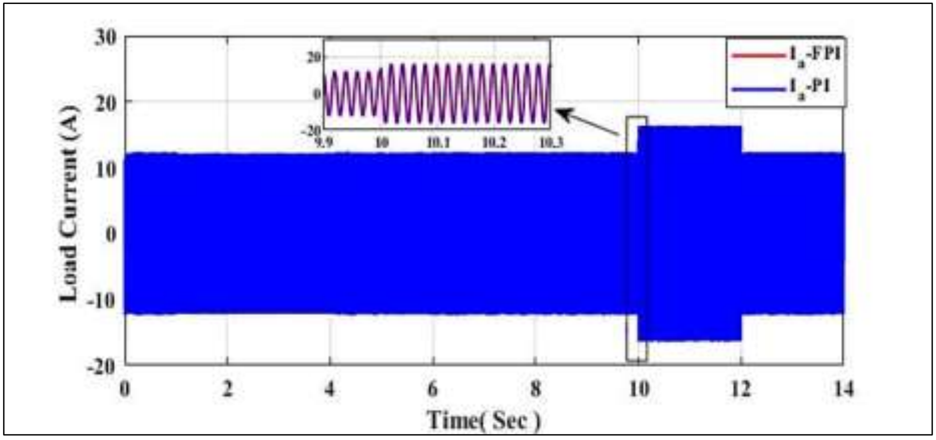

Figure 8: Single-phase load current under the intelligent controller.
Source: Authors, (2026).

Figure 9 shows the single-phase grid current, where it can be seen that the current changes depending on wind speed fluctuations and load changes. Overloads or underloads resulting from low wind speed are always compensated for by the grid, ensuring stability and continuity of electrical supply.

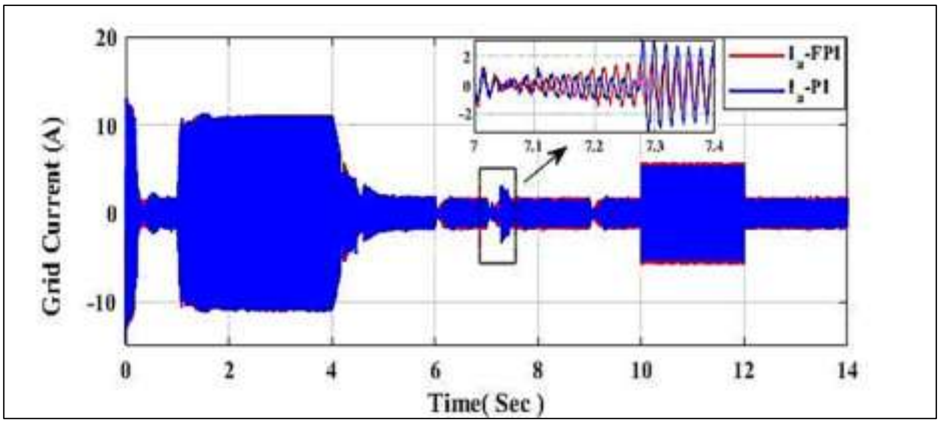

Figure 9: Single-phase grid currents under the intelligent controller.
Source: Authors, (2026).

Using intelligent control technology, the grid frequency is always stable at 50Hz despite abnormal situations. Figure 10 shows the network frequency.

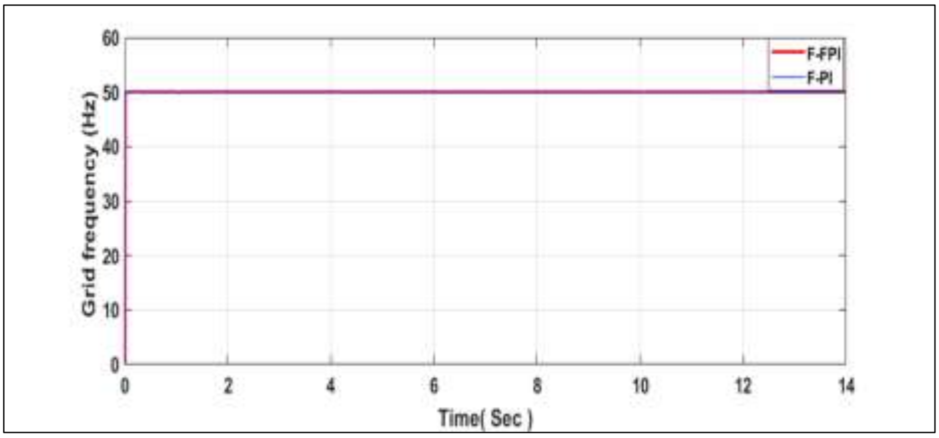

Figure 10: Grid frequency.
Source: Authors, (2026).

Figure 11 shows the power management system under variable wind speed (step size) and variable loads with the intelligent controller, where the system has minimal undershooting and overshooting as well as lower fluctuation.

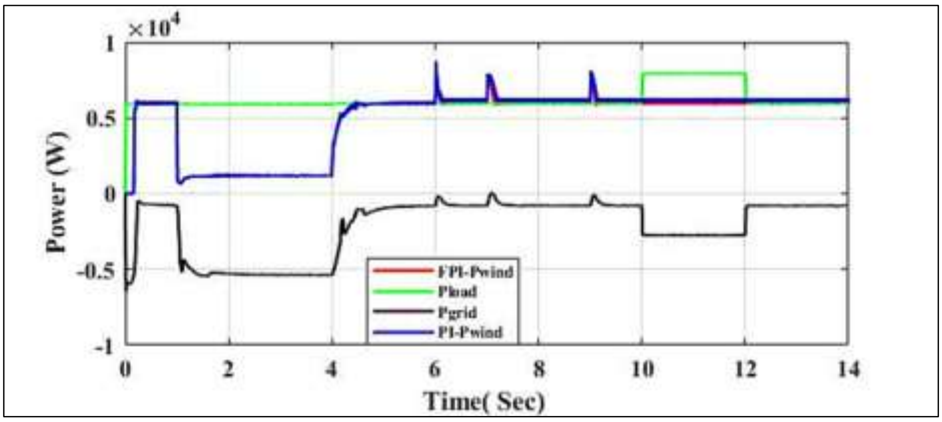

Figure 11: The power management system
Source: Authors, (2026).

V. CONCLUSIONS

This study is a complete evaluation of the performance of grid-tied WECS under variable conditions, including wind speed fluctuations and load variations. An intelligent controller was used with two strategies: A conventional PI controller and an FPI controller. The last one has been used to improve system performance and reduce oscillations and overshoots in the voltage waveform. The results showed that FPI controllers provide better performance in terms of reducing oscillations, which enhances the stability of the electrical system. Load balance has been achieved between the main grid and the wind turbines, as the rated loads are fed from the turbines, while overloads from the grid are compensated. The single-phase load current was also analyzed, and the current remained constant at its rated value during all times, indicating the effectiveness of the system in meeting the load needs. When the load increased, the draw current from the grid increased, which emphasizes the ability to handle overload. Finally, it is explained that the grid current changes with wind speed fluctuations and load changes, so overloads or lower power generated from the wind turbine are always compensated by the grid, ensuring the stability of the electrical system. These results are evidence of the effectiveness of using the smart controller unit in improving the performance of grid-connected WECS systems, which enhances the reliability of electrical supply and reduces the negative effects of wind speed fluctuations and variable loads, in addition to managing the supply of loads with power in all circumstances.

VI. AUTHOR'S CONTRIBUTION

Conceptualization: Zainab Jamal Mohammed and Mafaz Yahya Damarah.
Methodology: Zainab Jamal Mohammed and Mafaz Yahya Damarah.
Investigation: Zainab Jamal Mohammed and Mafaz Yahya Damarah.
Discussion of results: Zainab Jamal Mohammed.
Writing – Original Draft: Zainab Jamal Mohammed.
Writing – Review and Editing: Zainab Jamal Mohammed.
Resources: Zainab Jamal Mohammed and Mafaz Yahya Damarah.
Supervision: Zainab Jamal Mohammed and Mafaz Yahya Damarah.
Approval of the final text: Zainab Jamal Mohammed and Mafaz Yahya Damarah.

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