

Intelligent IoT-Based Smart Grid Monitoring and Adaptive Power Management System

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ABSTRACT: The increasing integration of renewable energy sources into the power grid demands an efficient monitoring and control system to ensure stability and reliability. Traditional grid systems lack real-time data acquisition and predictive maintenance, leading to inefficiencies and power losses. This project addresses these challenges by implementing an IoT-based smart grid monitoring system that enables real-time monitoring, optimal power management, and seamless integration of renewable energy with the grid. This project proposes an IoT-Based Smart Grid Monitoring System that integrates a photovoltaic (PV) system, a three-phase AC source, and a battery energy storage system (BESS) for efficient power management. The system employs DC-DC boost and bidirectional buck-boost converters to regulate power flow, while a three-phase voltage source inverter (VSI) converts DC power into AC for grid integration. Proportional-Integral (PI) controllers ensure voltage and current stability by generating reference signals for precise power control. The system is implemented using a dSPIC30F4011 microcontroller, which generates PWM pulses to drive switching circuits. To enhance monitoring and control capabilities, an IoT-based architecture is integrated using a NodeMCU Wi-Fi module. Real-time parameters such as PV voltage, PV current, battery state of charge, battery voltage, grid voltage, and grid current are transmitted to a remote monitoring platform. This enables predictive maintenance, fault detection, and optimal energy management. The proposed system ensures smooth power exchange between renewable sources, storage systems, and the grid, improving efficiency and reliability. The IoT framework facilitates data-driven decision-making, making the smart grid more resilient and adaptive. This work demonstrates a scalable and cost-effective solution for modern energy management, paving the way for future smart grid applications

Keywords: IoT-based smart grid monitoring system Proportional-Integral (PI) controllers , DC-DC boost and bidirectional buck-boost converters , dSPIC30F4011 microcontroller.

1. Introduction

The worldwide shift to renewable energy sources has made photovoltaic (PV) system integration with the electrical grid an essential part of contemporary energy infrastructure. PV systems provide a clean, sustainable substitute for fossil fuel-based power generation by leveraging semiconductor technology to directly convert sunlight into electricity^[1]. To guarantee grid

stability, dependability, and efficiency, a number of issues must be resolved when these technologies are deployed widely. The intermittent and variable nature of solar energy is one of the main technological obstacles to PV grid integration. Unlike conventional power plants that produce electricity on demand, solar energy generation fluctuates with weather conditions and daylight availability^[4]. The grid may experience voltage and frequency instability as a result,

necessitating sophisticated control systems to maintain supply and demand equilibrium. Grid-tied inverters are used to control power quality and transform DC output from PV panels into grid-compatible AC in order to lessen these problems.

Batteries and other energy storage technologies are essential to PV grid integration. In order to reduce unpredictability and improve grid dependability, these systems store extra solar energy produced during the hours of greatest sunlight and release it during periods of low output or high demand. Additionally, demand-side management and load-shifting strategies help optimize the use of solar energy by aligning consumption patterns with periods of high generation^[5]. The requirement for smart grid technologies is another crucial element of PV grid integration. These technologies provide more effective and adaptable grid operations by monitoring and controlling the electricity flow in real-time through digital communication and automation. Improved forecasting techniques for solar power generation are also necessary to increase supply forecast accuracy and improve energy dispatch planning^[3]. Grid operators also need to deal with the problem of grid congestion, particularly in regions where PV systems are widely installed. To avoid overloads and guarantee the power network operates safely and steadily as more dispersed PV systems are connected to the grid, significant grid planning and infrastructure enhancements are required. PV grid integration is greatly aided by legislative and regulatory frameworks^[2].

The establishment of clear technical standards for PV system interconnection, investments in grid modernization, and incentives for the use of energy storage are only a few of the favorable conditions that governments and energy regulatory agencies must establish in order to promote the growth of solar energy. PV grid integration is a complex process that need for strategic planning, regulatory backing, and technology innovation. In addition to helping the grid reach renewable energy goals, a successful

integration of solar energy lowers carbon emissions, improves energy security, and ushers in a more sustainable energy future. In the upcoming years, PV systems' share of the world's energy mix is expected to increase dramatically due to continuous improvements in grid infrastructure, storage technologies, and PV technology.

2. Recent Works

The existing system represents an autonomous DC microgrid system that integrates multiple renewable energy sources and a supercapacitor-based energy storage system to enhance grid resilience and stability^[7]. The system operates at a nominal DC bus voltage of 1200 V and supplies power to a DC load, ensuring efficient and reliable energy management^[11]. This hybrid microgrid combines a photovoltaic (PV) generation system of 50 kW, a wave power generation system of 160 kW, and a wind power generation system of 100 kW, all of which feed energy into the common DC bus. Each source is equipped with power electronic converters to regulate and optimize the power flow. The PV array is interfaced through a DC-DC boost converter that is controlled using a Maximum Power Point Tracking algorithm^[6]. This ensures that the PV system continuously operates at its maximum efficiency by adjusting the operating point in response to varying irradiance and temperature^[9]. The output from the boost converter is then fed into the 1200 V DC bus. The wave energy system, rated at 160 kW, consists of an AWS connected to a Linear Permanent Magnet Generator (LPMG). The variable output from the LPMG is rectified and stabilized using a Voltage Source Converter. Similarly, the wind power generation system, rated at 100 kW, uses a Permanent Magnet Synchronous Generator connected to a VSC2, which converts the AC output to regulated DC power compatible with the microgrid's DC bus^[12]. To cater to variable DC load requirements, a DC-DC buck converter steps down the 1200 V from the DC bus to 600 V, supplying the appropriate voltage to the connected DC load^[14].

3. Proposed Work Explanation

The proposed system describes an IoT-based smart grid monitoring and adaptive power management system, integrating renewable energy sources, storage systems, and intelligent control to ensure efficient and stable grid operation. The system begins with a photovoltaic (PV) system, which generates DC power based on solar irradiance. The PV output is processed by a DC-DC boost converter to elevate the voltage to a suitable level. This converter is controlled by PWM signals generated through a PI controller and a dsPIC30F4011 microcontroller, which ensures that the output voltage stays at the desired reference level by adjusting the duty cycle of the PWM pulses. The driver circuit (TLP250) interfaces between the microcontroller and the power switch, ensuring safe and effective switching. A three-phase AC source is included as an auxiliary power input and is rectified using a diode bridge rectifier (DBR) to supply DC power to the main DC bus. All power sources feed into a centralized DC bus, which acts as a backbone for energy transfer and distribution throughout the system^[13]. A bidirectional buck-boost converter, interfaced with a battery energy storage system, allows energy to be stored or supplied back into the DC bus depending on the power flow requirements. This converter is also controlled by PWM pulses, generated using a PI controller and dsPIC controller, with additional sensing mechanisms for current and voltage feedback.

3.1 Hardware Implementation

3.1.1 DSPIC30F4011 Controller

The dsPIC30F4011 microcontroller, part of Microchip Technology's dsPIC30 series, is a versatile 16-bit device designed for high-performance digital signal processing and control applications. Its working process can be understood through its core architecture, peripherals, and the interaction between these components. At the heart of the dsPIC30F4011 is its 16-bit CPU, which operates with a Harvard architecture. This architecture features separate

data and instruction buses, allowing simultaneous fetching of instructions and data, which enhances processing speed. The CPU is capable of executing a wide range of instructions, including arithmetic, logic, and control operations. Its instruction set is designed to efficiently handle both digital signal processing (DSP) tasks and general-purpose control tasks.

3.1.2 DSPIC30F4011 Microcontroller Features

- **16-bit DSP CPU Core:** High-performance processing with Harvard architecture.
- **Memory:** Up to 64 KB Flash, 8 KB SRAM, and 2 KB EEPROM.
- **Timers:** 6 timers, including PWM modules for precise control.
- **ADC:** 12-bit resolution with up to 16 channels.
- **DAC:** 10-bit resolution for analog signal generation.
- **Communication Interfaces:** UART, SPI, and I2C for versatile data transfer.
- **Interrupt System:** Multiple sources with configurable priority levels.
- **Power Management:** Various sleep modes to conserve energy.
- **I/O Ports:** General-purpose and special function pins.
- **Debugging Support:** In-Circuit Serial Programming (ICSP) and advanced debugging features.

The microcontroller's memory system includes Flash memory for program storage and SRAM for data storage. Flash memory is used to store the firmware and program code, which is executed by the CPU. The SRAM is utilized for dynamic data storage during execution. The dsPIC30F4011 supports a range of Flash memory sizes, typically up to 64 KB, and SRAM sizes up to 8 KB, providing ample space for complex applications. One of the key features of the dsPIC30F4011 is its suite of integrated peripherals, which are essential for interfacing with the external environment and

performing specific functions. The device includes multiple timers, which can be used for generating precise time delays or for timing-related functions in applications such as motor control or waveform generation. The ADC (Analog-to-Digital Converter) is another critical peripheral, allowing the microcontroller to convert analog signals from sensors into digital data that can be processed by the CPU. This is particularly useful in applications requiring sensor interfacing, such as data acquisition systems.

The dsPIC30F4011 also features a variety of communication peripherals, including UART (Universal Asynchronous Receiver/Transmitter), SPI (Serial Peripheral Interface), and I2C (Inter-Integrated Circuit). These communication interfaces enable the microcontroller to exchange data with other devices, such as sensors, displays, and other microcontrollers. UART is commonly used for serial communication, while SPI and I2C are used for high-speed data transfer and inter-device communication. Pulse Width Modulation (PWM) modules in the dsPIC30F4011 are used for generating precise control signals, which are crucial for applications like motor control and signal modulation. PWM signals can be adjusted in terms of frequency and duty cycle, allowing for flexible control over external devices.

Interrupt handling is another significant aspect of the dsPIC30F4011's operation. The microcontroller supports multiple interrupt sources with programmable priority levels. When an interrupt occurs, the CPU can suspend its current operations, service the interrupt, and then resume normal processing. This feature is critical for real-time applications where timely response to events is essential. Power management features of the dsPIC30F4011 include various sleep modes that help reduce power consumption during periods of inactivity. These modes are essential for battery-powered or energy-sensitive applications, allowing the microcontroller to conserve power while remaining responsive to wake-up events. Programming and debugging of the dsPIC30F4011 are facilitated by tools such as the

MPLAB X IDE and the XC16 compiler. In-circuit programming and debugging capabilities allow developers to write and test code efficiently. The microcontroller's debug features, such as breakpoints and watch variables, assist in troubleshooting and optimizing application performance. The dsPIC30F4011 microcontroller operates through its combination of a powerful 16-bit CPU, extensive memory, and a rich set of peripherals. Its ability to perform digital signal processing tasks, coupled with flexible I/O and communication options, makes it suitable for a wide range of applications, from motor control to data acquisition systems. The integration of advanced features and peripherals, along with robust programming and debugging support, ensures that the dsPIC30F4011 can meet the demands of complex embedded systems.

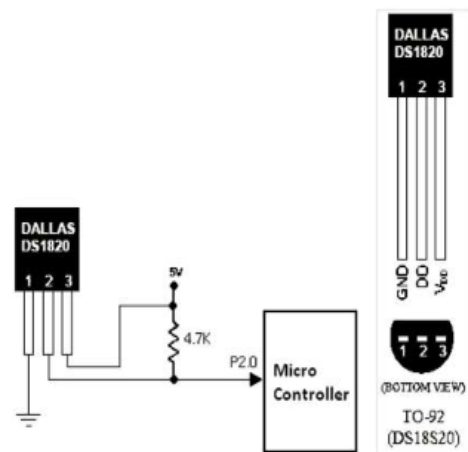


Figure 1: *DSPIC30F4011 Controller*

The dsPIC30F4011 microcontroller, part of the dsPIC30 family, stands out due to its blend of high-performance DSP capabilities and traditional microcontroller functions. Its working process is a synthesis of its advanced CPU architecture, rich peripheral set, and sophisticated control mechanisms, designed to address a diverse array of applications.

3.1.3 CPU and Core Architecture

The dsPIC30F4011 features a 16-bit DSP CPU core that combines the benefits of both general-purpose microcontrollers and specialized digital signal processors. This core operates on a Harvard architecture with separate data and instruction

memory buses, allowing for concurrent instruction fetches and data access. The CPU supports a range of instructions optimized for high-speed arithmetic operations, making it particularly effective for tasks involving complex mathematical computations, such as filtering or signal processing.

3.1.3 Memory and Data Handling

Memory management in the dsPIC30F4011 includes up to 64 KB of Flash memory for storing program code and up to 8 KB of SRAM for data storage. Flash memory is non-volatile, meaning it retains its contents even when power is lost, which is ideal for firmware storage. SRAM, on the other hand, provides fast, volatile storage for runtime data. This architecture allows the microcontroller to execute complex algorithms and handle substantial amounts of data efficiently.

3.1.4 Peripheral Integration

A key strength of the dsPIC30F4011 is its comprehensive set of peripherals, which are crucial for interfacing with the external world and executing specific functions. Key peripherals include:

- **Timers:** The dsPIC30F4011 includes multiple timers that can be used for generating precise time delays, event counting, and waveform generation. These timers are flexible, with options for both 16-bit and 32-bit modes, enabling precise control over timing applications.
- **Analog-to-Digital Converter (ADC):** The integrated ADC allows for the conversion of analog signals from sensors into digital data. With up to 16-bit resolution, the ADC provides high accuracy for applications such as sensor data acquisition and analog signal processing.
- **Digital-to-Analog Converter (DAC):** The DAC can generate analog output signals from digital data, useful in applications requiring analog signal generation, such as waveform generation or modulation.

- **Communication Interfaces:** The dsPIC30F4011 includes UART, SPI, and I2C interfaces. UART supports serial communication for tasks like debugging and communication with other serial devices. SPI and I2C facilitate high-speed data transfer and inter-device communication, essential for complex systems requiring multiple peripherals.
- **Pulse Width Modulation (PWM):** The PWM modules are used for generating control signals with precise frequency and duty cycle control. This is particularly valuable in motor control applications, where PWM can control motor speed and direction with high accuracy.

3.1.5 Interrupt Handling

The microcontroller supports a sophisticated interrupt system with multiple interrupt sources and programmable priority levels. Interrupts allow the CPU to respond promptly to external events or internal conditions by pausing its current tasks, servicing the interrupt, and then resuming normal operations. This capability is vital for real-time systems where immediate response to events is crucial.

3.1.6 Power Management

Power efficiency is addressed through various sleep modes, which reduce power consumption during periods of inactivity. These modes help extend battery life in portable applications and reduce energy consumption in energy-sensitive systems. The microcontroller can wake up from sleep modes in response to external interrupts or timers, ensuring that it remains responsive while conserving power.

3.1.7 Development and Debugging

Programming and debugging of the dsPIC30F4011 are facilitated by development tools like MPLAB X IDE and XC16 compiler. In-circuit programming and debugging capabilities allow developers to upload firmware, test code, and debug in real-time. The microcontroller's integrated debugging features, such as breakpoints

and watch variables, assist in identifying and resolving issues, optimizing performance, and ensuring the reliability of applications.

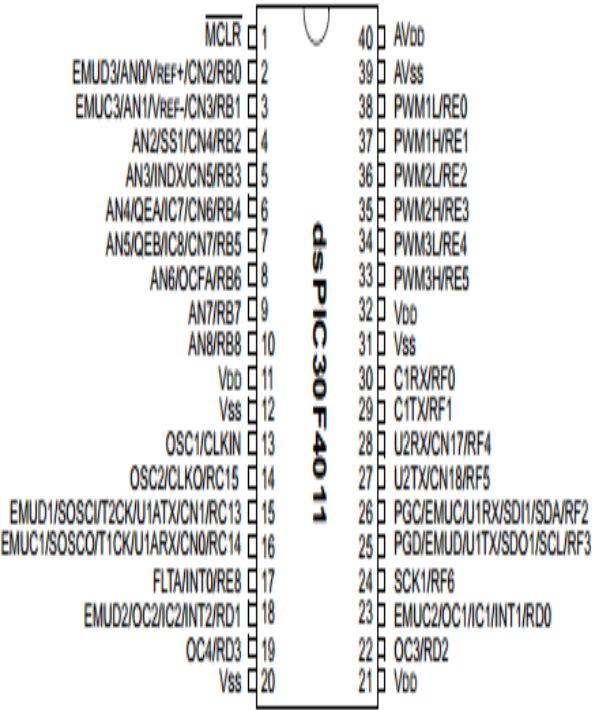


Figure 2: DSPIC30F4011 Controller Pin Diagram

The dsPIC30F4011 operates through a sophisticated combination of its 16-bit DSP CPU, extensive memory, and versatile peripherals. This microcontroller is designed to handle complex processing tasks, manage data efficiently, and interface with a wide range of external devices. Its robust set of features, coupled with advanced programming and debugging support, makes it suitable for a broad spectrum of applications, from precision motor control to intricate signal processing and communication systems.

3.2 DSP Engine

The dsPIC30F4011 microcontroller features a specialized DSP (Digital Signal Processing) engine that enhances its ability to perform complex mathematical operations efficiently. Here's a brief overview of the DSP engine within the dsPIC30F4011.

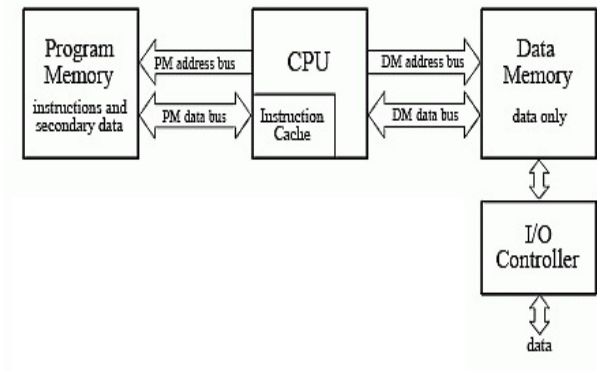


Figure 3: DSP Engine

3.2.1 DSP Engine Features

- **16-bit DSP Core:** Designed for high-performance digital signal processing tasks, it provides a robust foundation for processing and manipulating digital signals.
- **Hardware Multiplier/Accumulator:** Supports fast multiplication and accumulation operations, which are essential for tasks such as filtering, Fourier transforms, and other signal processing algorithms.
- **Single-Cycle Instructions:** The DSP engine includes instructions that execute in a single cycle, significantly speeding up operations like multiplication, addition, and shift operations.
- **Dedicated DSP Instructions:** Includes a range of instructions optimized for common DSP tasks, such as MAC (Multiply-Accumulate) operations, which are crucial for implementing filters and other signal processing functions.
- **Addressing Modes:** Offers specialized addressing modes for efficient data access and manipulation, enhancing the performance of DSP algorithms.
- **Circular Buffers:** Supports circular buffer operations, which are commonly used in real-time signal processing applications to handle data streams efficiently.
- **Dual Data Paths:** Allows simultaneous operations on multiple data paths, improving throughput and performance in signal processing applications.

- **Interrupt Handling:** Provides mechanisms for handling interrupts efficiently, enabling real-time processing and response to external events.

The DSP engine in the dsPIC30F4011 allows for advanced signal processing tasks to be executed with high speed and precision, making it suitable for applications such as audio processing, motor control, and data acquisition.

3.3 Multiplier

The dsPIC30F4011 microcontroller integrates a sophisticated multiplier within its Digital Signal Processing (DSP) engine, designed to handle complex mathematical computations efficiently. This multiplier is a critical component that enhances the microcontroller's ability to perform high-speed arithmetic operations, essential for various digital signal processing tasks.

3.3.1 Overview of the Multiplier

The multiplier in the dsPIC30F4011 is a 16-bit hardware multiplier that operates as part of the DSP engine. Its primary function is to perform multiplication of two 16-bit numbers, which is a fundamental operation in many DSP algorithms. The results of these multiplications can be used in a wide array of applications, including filtering, signal modulation, and data transformation.

3.3.2 Operation and Performance

The hardware multiplier in the dsPIC30F4011 supports a range of operations, including single-cycle and double-cycle multiplication. This hardware acceleration allows the microcontroller to perform these operations significantly faster than software-based multiplication, which is crucial for real-time processing applications. One of the key features of the dsPIC30F4011's multiplier is its ability to perform Multiply-Accumulate (MAC) operations. The MAC operation multiplies two numbers and then adds the result to an accumulator. This feature is particularly useful in implementing digital filters and other signal processing algorithms where repeated multiplication and accumulation are

required. For instance, in a Finite Impulse Response (FIR) filter, the MAC operation can efficiently compute the weighted sum of input samples.

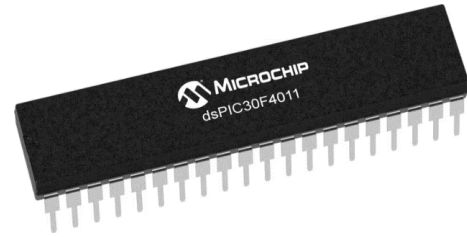


Figure 4: Multiplier

3.3.3 Single-Cycle Execution

The multiplier in the dsPIC30F4011 can execute multiplication operations in a single cycle, which optimizes performance and reduces the computational delay. This single-cycle execution is critical for maintaining high processing speeds and ensuring that real-time applications operate smoothly. By minimizing the number of cycles required for multiplication, the microcontroller can handle more complex tasks and achieve higher throughput.

3.3.4 Specialized Instructions

The dsPIC30F4011 includes specialized instructions that leverage the hardware multiplier. These instructions are designed to maximize the efficiency of arithmetic operations and reduce the overhead associated with performing complex calculations. For example, the MUL instruction performs a multiplication operation, while the MAC instruction combines multiplication with accumulation, streamlining the execution of common DSP algorithms.

3.3.5 Integration with Other DSP Features

The multiplier is integrated with other DSP features of the dsPIC30F4011, such as the hardware accumulator and specialized addressing modes. This integration allows for seamless data processing and manipulation, as the results of multiplication can be directly fed into the accumulator or used in conjunction with other DSP instructions. The multiplier also works in tandem with circular buffers and dual data paths,

further enhancing the efficiency of data handling and processing.

3.3.6 Applications

The multiplier’s capabilities make it suitable for a wide range of applications that require intensive arithmetic computations. In audio processing, for instance, it can be used to implement effects such as equalization and reverb by efficiently processing audio signals. In motor control applications, the multiplier can handle the complex calculations needed for control algorithms and signal processing. Additionally, its use in communication systems for modulation and demodulation tasks highlights its versatility and importance in embedded systems.

3.4 Data Spaces

The dsPIC30F4011 microcontroller, data spaces are organized to facilitate efficient storage and access of program code and runtime data, which is critical for high-performance operation in embedded systems. The dsPIC30F4011 employs a Harvard architecture, distinguishing between program memory (Flash) and data memory (SRAM). This separation allows simultaneous access to both instruction and data, optimizing execution speed. The program memory in the dsPIC30F4011 is composed of up to 64 KB of Flash memory. This non-volatile memory is used to store the microcontroller’s firmware, including the application code and any constants or lookup tables. Flash memory retains its data even when power is off, ensuring persistent storage of the program.

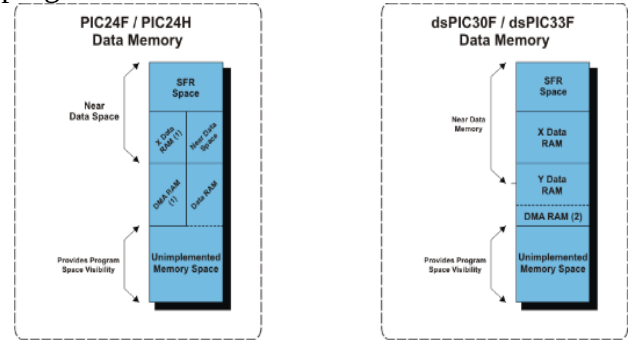


Figure 5: Data Spaces

3.4.1 Data Memory

Data memory consists of up to 8 KB of SRAM. This volatile memory is used for runtime data

storage, including variables, stack, and dynamic data structures. SRAM is accessed quickly, providing efficient data manipulation and handling during program execution. In addition to general-purpose data memory, the dsPIC30F4011 includes special function registers (SFRs) that are mapped into the data space. These registers control and monitor the microcontroller's peripherals and internal functions, such as timers, ADCs, and communication modules. SFRs are crucial for configuring and interacting with the microcontroller’s hardware.

3.4.2 Memory Organization

The memory space is organized with a separate address space for program and data memory, which enhances data access efficiency. The microcontroller supports direct and indirect addressing modes, providing flexibility in accessing data memory. The dsPIC30F4011’s data spaces are designed to ensure efficient program execution and data handling, with distinct areas for Flash program memory, SRAM data memory, and special function registers. This architecture supports the microcontroller’s high performance in complex embedded applications.

Modulo addressing in the dsPIC30F4011 microcontroller is a technique utilized for efficient memory management, particularly in circular buffer applications. In this addressing mode, the modulo operation ensures that memory accesses wrap around within a specified range, facilitating seamless data handling in scenarios where the data structure cycles through a fixed size. For the dsPIC30F4011, modulo addressing is often employed in conjunction with its peripherals, such as timers and UARTs, to manage data streams efficiently. The address calculation uses the formula $\text{Address} = (\text{Base Address} + \text{Offset}) \% \text{Buffer Size}$, where Buffer Size is the total number of entries in the circular buffer. This method helps in keeping track of current positions and automatically wraps addresses when they exceed the buffer's limit, thus simplifying buffer management and enhancing real-time performance. By leveraging modulo addressing,

developers can efficiently handle repetitive data processing tasks, crucial for high-performance embedded systems.

3.6 Driver Circuit (TLP250)

The TLP250 is a popular opt coupler used for interfacing microcontrollers with high-voltage circuits. In the context of the dsPIC30F4011 microcontroller, the TLP250 acts as a driver circuit to safely connect the low-voltage digital logic of the dsPIC30F4011 with high-voltage loads, such as relays or MOSFETs. The TLP250 opt coupler includes an integrated transistor driver that provides electrical isolation between the low-voltage side (where the dsPIC30F4011 operates) and the high-voltage side.

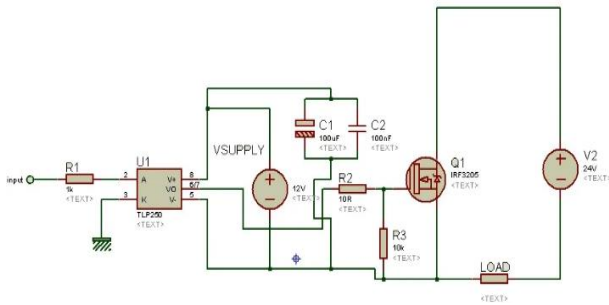


Figure 6: Driver Circuit (Tlp250)

This isolation protects the microcontroller from high-voltage spikes and transients, which could otherwise damage sensitive components or disrupt operation. In practical terms, the dsPIC30F4011 controls the TLP250 by sending a control signal to its input LED. When this LED is illuminated, it activates the internal phototransistor, which then switches the high-voltage side. The TLP250 can drive high-current loads, making it suitable for switching relays or driving gate signals for MOSFETs used in power electronics. To use the TLP250 with the dsPIC30F4011, you typically connect a digital output pin from the DSPIC to the LED input of the TLP250. The output of the TLP250 then drives the gate or base of a power transistor or relay, which controls the high-voltage load. This configuration ensures that the dsPIC30F4011 remains isolated from high voltages while effectively controlling high-power devices. Integrating the TLP250 with the dsPIC30F4011 provides a robust and safe method

for interfacing with high-voltage circuits, essential for reliable operation in embedded systems.

3.7 MOSFET IRF 840

Integrating the IRF840 MOSFET with the dsPIC30F4011 microcontroller is an effective strategy for controlling high-power loads in embedded systems. The IRF840 is an N-channel MOSFET designed for high-voltage and high-current applications, making it suitable for switching heavy loads such as motors, solenoids, or high-power resistors. Its key features include a maximum drain-source voltage (V_{DS}) of 500V and a continuous drain current (I_D) of 8A, which provides substantial switching capacity.

When interfacing the IRF840 with the dsPIC30F4011, it is crucial to consider the MOSFET's gate drive requirements. The dsPIC30F4011 operates at a much lower voltage (typically 3.3V) compared to the IRF840's gate threshold voltage, which ranges from 2V to 4V. This means that the dsPIC30F4011 alone may not provide sufficient gate drive voltage to fully switch the IRF840 on or off. To address this, a gate driver circuit, such as the TLP250 opt coupler or a dedicated MOSFET driver IC, can be employed to amplify the control signal from the dsPIC30F4011.

3.8 Hardware View

A solar panel harnesses solar energy, while various components like controllers, filters, and measuring devices are interconnected. An oscilloscope displays waveform signals, showcasing the system's functionality. It represents the integration of renewable energy and electronic controls.

3.9 Experimental Analysis

Figure 7 shows a steady horizontal green line, indicating a DC signal at -16.3750 mV/div, with a time base of 5.0000 ms/div,

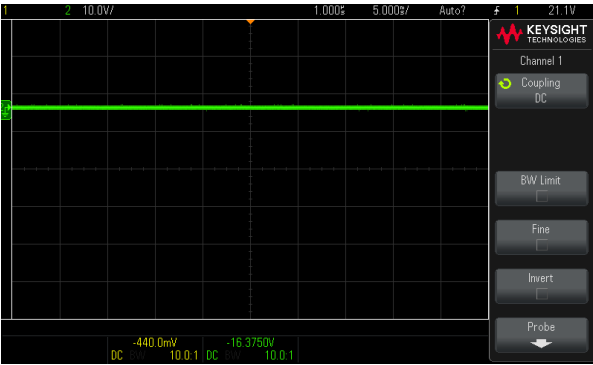


Figure 7: Input Voltage Waveform

volts. The voltage scale is set to 10.0 confirming a stable and consistent measurement.

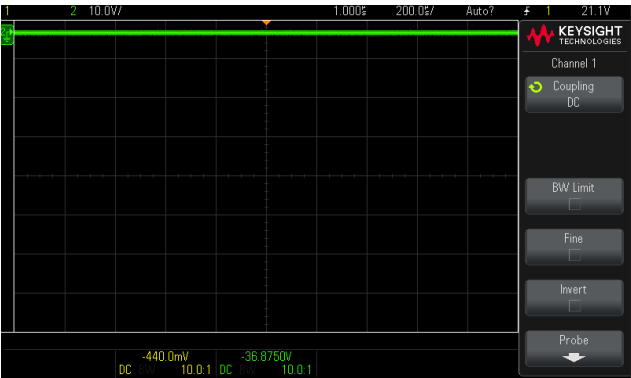


Figure 8: Output Voltage Waveform

Figure 8 displays a stable horizontal green line, representing a DC voltage of -36.8750 volts. The vertical scale is set to 10.0 mV/div, with a time base of 200 µs/div, indicating consistent and accurate signal measurement.

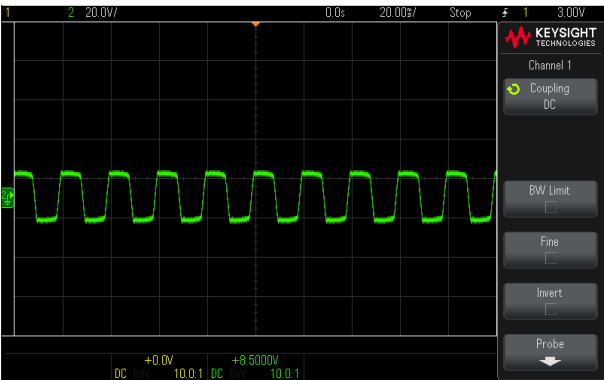


Figure 9: Converter Pulse Waveform

Figure 9 displays a periodic waveform, indicating an alternating signal oscillating between +8.5000 volts and -8.5000 volts. The vertical scale is set to 20.0 V/div, with a time base of 20.000 ms/div, showing clear waveform characteristics and stability.

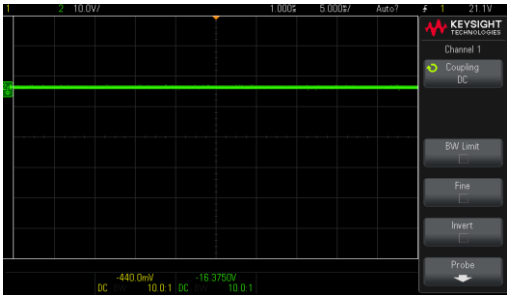


Figure 10: Battery Voltage Waveform

Figure 10 shows a steady horizontal green line, indicating a DC level at -16.3750 volts. The vertical scale is set to 10.0 mV/div, with a time base of 5.0000 ms/div, reflecting a stable and consistent measurement without fluctuations.

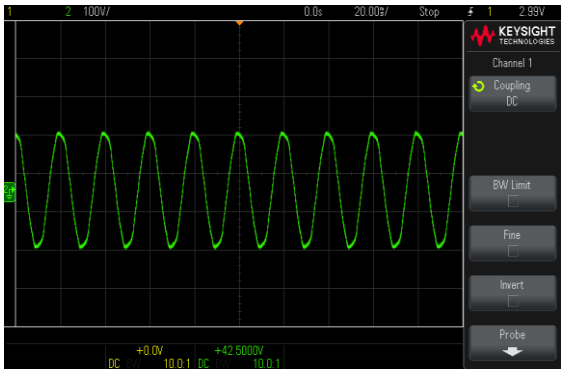


Figure 11: LC Filter Output Waveform

Figure 11 displays a sinusoidal waveform oscillating between +42.5000 volts and -42.5000 volts. The vertical scale is set to 100 V/div, with a time base of 20.000 ms/div, indicating a stable AC signal with clear amplitude and frequency characteristics.

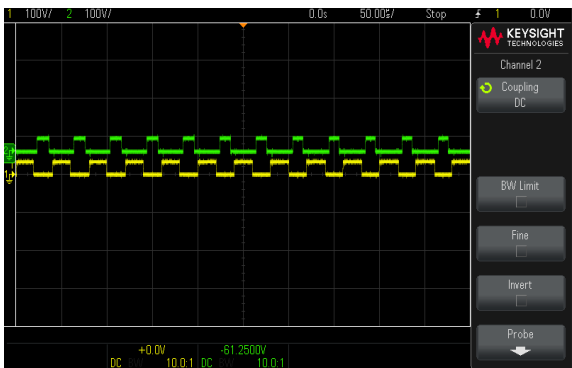


Figure 12: PWM Pulse 1 & 2

Figure 12 shows a digital pulse waveform oscillating between high and low states, centered around -61.2500 volts. The vertical scale is set to 100 V/div, with a time base of 50.000 ms/div, indicating a stable and well-defined digital signal.

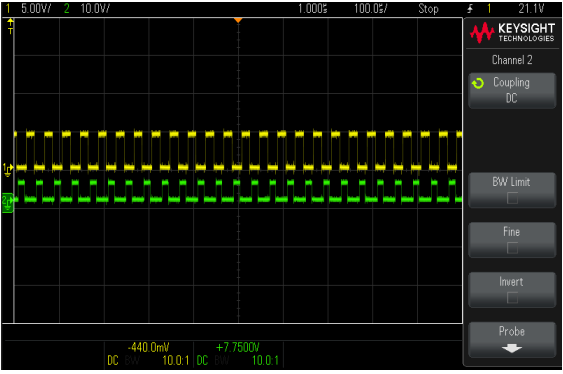


Figure 13: *PWM Pulse 3 & 4*

Figure 13 shows a digital pulse waveform oscillating between high and low states, centered around +7.7500 volts. The vertical scale is set to 100 V/div, with a time base of 50.000 ms/div, indicating a stable and well-defined digital signal.

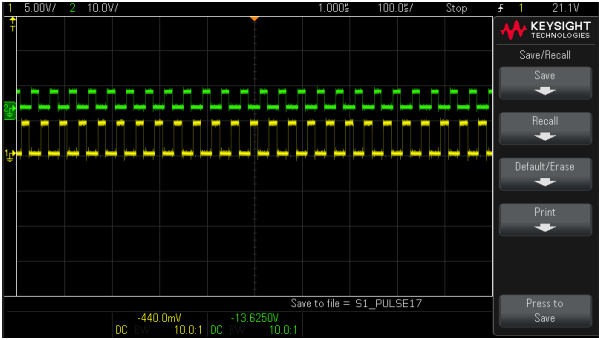


Figure 14: *PWM Pulse 5 & 6*

Figure 14 shows a digital pulse waveform oscillating between high and low states, centered around -13.6250 volts. The vertical scale is set to 100 V/div, with a time base of 50.000 ms/div, indicating a stable and well-defined digital signal.

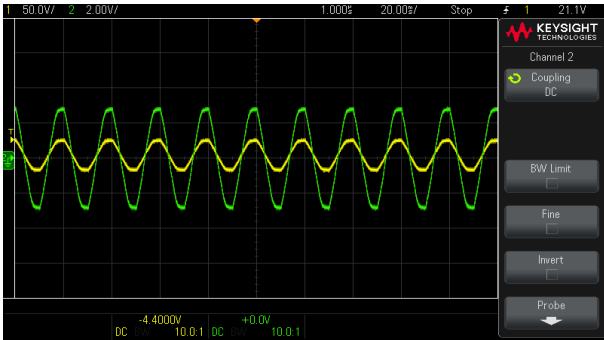


Figure 15: *Grid Waveform*

Figure 15 displays a grid waveform, shows a clear AC signal overlaid on a DC offset. The green and yellow traces shows the amplitude and frequency characteristics, highlighting distinct oscillations. This setup emphasizes precise signal

measurement and analysis critical for electrical diagnostics.

4. Conclusion

In conclusion, the proposed IoT-based smart grid monitoring system presents a comprehensive and efficient solution for modern power management challenges. By integrating a photovoltaic system, battery energy storage, and a three-phase AC source, the system ensures seamless coordination and optimal power flow. The use of DC-DC converters, a three-phase VSI, and PI controllers enhances power quality and system stability. Implementation through the dSPIC30F4011 microcontroller and NodeMCU Wi-Fi module allows precise control and real-time data transmission, enabling remote monitoring, fault detection, and predictive maintenance. This approach not only improves grid reliability and efficiency but also supports the growing penetration of renewable energy sources. The IoT framework empowers stakeholders with actionable insights for better decision-making, making the grid more adaptive and resilient to changing demands. This project offers a scalable, cost-effective model that addresses critical smart grid requirements and contributes significantly to the development of sustainable and intelligent energy infrastructures.

4.1 Future Scope

- The future scope of this project includes integrating advanced machine learning algorithms for predictive analytics, enhancing cybersecurity for data transmission, and expanding compatibility with other renewable sources like wind energy.
- Incorporating blockchain for energy transactions can further improve transparency, making the system more robust, scalable, and suitable for smart city applications.

References

1. Luise Middelhaue, Cedric Terrier, Francois Marechal, Year: 2022, "Decomposition strategy for districts as renewable energy hubs", IEEE Open

- Access Journal of Power and Energy, Vol: 9, pp.287-297.
2. Iram Akhtar, Mohammed Jameel, Abdullah Altamimi, Sheeraz Kirmani, Year: 2022, "An innovative reliability oriented approach for restructured power system considering the impact of integrating electric vehicles and renewable energy resources", IEEE Access, Vol: 10, pp.52358-52376.
3. Fahad R. Albogamy, Mohammad Yousaf Ishaq Paracha, Ghulam Hafeez, Imran Khan, Sadia Murawwat, Gul Rukh, Sheraz Khan, Mohammad Usman Ali Khan, Year: 2022, "Real-time scheduling for optimal energy optimization in smart grid integrated with renewable energy sources", IEEE Access, Vol: 10, pp.35498-35520.
4. Rushil Kaushikkumar Patel, Aparna Kumari, Sudeep Tanwar, Wei-Chiang Hong, Ravi Sharma, Year: 2022, "AI-empowered recommender system for renewable energy harvesting in smart grid system", IEEE Access, Vol: 10, pp.24316-24326.
5. Chitralkha Jena, Josep M. Guerrero, Abdullah Abusorrah, Yusuf Al-Turki, Baseem Khan, Year: 2022, "Multi-objective generation scheduling of hydro-thermal system incorporating energy storage with demand side management considering renewable energy uncertainties", IEEE Access, Vol: 10, pp.52343-52357.
6. Gema García Platero, Mayte García Casado, Marta Pérez García, Paula Junco Madero, David Alvira Baeza, Year: 2022, "CECRE: supervision and control of Spanish renewable energies in the last 15 years", Journal of Modern Power Systems and Clean Energy, Vol: 10, No: 2, pp.269-276.
7. Aswin Anil Bindu, KC Sindhu Thampatt, Year: 2023, "Optimal design and techno-socio-economic analysis of grid-connected hybrid renewable system", IEEE Access.
8. Xuanyi Xiao, Jianbing Yin, Lin Chen, Mingchang Wang, Yi Zhao, Zhiyi Li, Year: 2023, "Evolutionary game-theoretic modeling of massive distributed renewable energy deployment towards low-carbon distribution networks", Journal of modern power systems and clean Energy, Vol: 11, No: 5, pp.1519-1528.
9. Ashish Kumar Karmaker, Md Alamgir Hossain, Hemanshu Roy Pota, Ahmet Onen, Jaesung Jung, Year: 2023, "Energy management system for hybrid renewable energy-based electric vehicle charging station", IEEE Access, Vol: 11, pp.27793-27805.
10. Frede Blaabjerg, Yongheng Yang, Katherine A. Kim, Jose Rodriguez, Year: 2023, "Power electronics technology for large-scale renewable energy generation", Proceedings of the IEEE, Vol: 111, No: 4, pp.335-355.
11. Amir Ahmadifar, Mirko Ginocchi, Megha Shyam Golla, Ferdinanda Ponci, Antonello Monti, Year: 2023, "Development of an energy management system for a renewable energy community and performance analysis via global sensitivity analysis", IEEE Access, Vol: 11, pp.4131-4154.
12. Enrico Giglio, Riccardo Novo, Giuliana Mattiazzo, Davide Fioriti, Year: 2023, "Reserve provision in the optimal planning of off-grid power systems: impact of storage and renewable energy", IEEE Access.
13. Qing-Hua Wu, Anjan Bose, Chanan Singh, Joe H. Chow, Gang Mu, Yuanzhang Sun, Zhaoxi Liu, Zhigang Li, Yang Liu, Year: 2023, "Control and stability of large-scale power system with highly distributed renewable energy generation: viewpoints from six aspects", CSEE Journal of Power and Energy Systems, Vol: 9, No: 1, pp.8-14.
15. Chang-Hua Lin, Mohammad Suhail Khan, Javed Ahmad, Hwa-Dong Liu, Tung-Chun Hsiao, Year: 2024, "Design and analysis of novel high-gain boost

converter for renewable energy systems (RES)”, IEEE Access.

16. Teeraphon Phophongviwat, Thunwa Boonlert, Komsan Hongesombut, Year: 2024, “Enhancing Grid Stability Using a Virtual Inertia-Integrated Railway Power Conditioner in Railway Power Supplies With High Renewable Energy Penetration”, IEEE Access.

17. Nebojša Horvat, Dušan B. Gajić, Petar Trifunović, Veljko B. Petrović, Dinu Dragan, Vladimir Katić, Year: 2024, “Performance Evaluation of a Distributed Ledger-based Platform for Renewable Energy Trading ”, IEEE Access.

18. Danhu Li, Jiazhu Xu, Year: 2024, “Renewable Energy Power’s Investment and Production Strategies for a Class of Noncooperative Game Models of Power Sales with Risk Avoidance”, IEEE Access.

19. Nader Sh Abdelhakeem, Mostafa M. Hasaneen, Sherif Helmy, Mohamed M. Moenes Salama, Mohamed Zakaria Kamh, Year: 2024, “Modified Arithmetic Algorithms for Optimal Power System Operation Considering Uncertainties from Intermittent Renewable Energy and Electric Vehicles”, IEEE Access.

20. Saher Javaid, Mineo Kaneko, Yasuo Tan, Year: 2024, “Energy Balancing of Power System Considering Periodic Behavioral Pattern of Renewable Energy Sources and Demands ”, IEEE Access.