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An Instantaneous Load-Sharing Parallel Control Method Using Improved PWM-Capture with DMA in a Power Conversion System.

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Abstract -
As power demand from electric vehicles and digital loads increases, the use of direct current power supplies is increasing. As a result, the application of microgrid utilizing various distributed power systems is expanding. As demand power and load capacity increase, parallel operation of multiple power converters is required to increase the capacity of power converters used in distributed power systems. Among parallel control methods, load sharing through communication has a significant effect on control performance due to communication speed and reliability. This paper proposes an instantaneous load-sharing parallel control method using a high-speed communication method that can transmit data necessary for load-sharing every control cycle. The proposed communication method uses enhanced PWM and capture communication using a DMA module to compensate for the shortcomings of the existing method using PWM and capture functions. Whenever the master voltage controller is executed, the data required for parallel operation is updated, and by transmitting this data to the slave, instantaneous load sharing control with high speed response is possible. We explain the communication and system architecture of the proposed method and present the communication protocol specifications and design. The performance and validity of the proposed instantaneous load sharing parallel control method were verified through simulation and experiments.

Key Words: Instantaneous Load Sharing, Parallel Control, Distributed Power System, Enhanced PWM Communication, DMA-Based Communication, Microgrid, Power Converter, Real-Time Control, High-Speed Communication, Load Sharing Protocol

1. INTRODUCTION

As global energy consumption patterns evolve, the demand for reliable, efficient, and scalable power systems is growing rapidly. In particular, the proliferation of Electric Vehicles (EVs), Data Centers, and Digital Loads is accelerating the adoption of Direct Current (DC) power systems due to their inherent efficiency and ease of integration with renewable energy sources and storage systems. This shift necessitates a rethinking of traditional power distribution architectures, leading to the increased deployment of Microgrids and Distributed Power Systems.

To meet higher power demands and ensure system reliability, it becomes essential to operate multiple power converters in parallel. However, parallel operation introduces challenges such as current sharing, voltage regulation, and stability, especially in the presence of dynamic and unbalanced load conditions. Among various control strategies, communication-based load-sharing methods have shown superior performance due to their ability to exchange real-time data between units. This section introduces the foundational concepts and motivations behind the proposed work.

1.1 Distributed Power Systems and MicrogridsDistributed Power Systems (DPS) are electrical networks consisting of multiple power generation sources—such as solar panels, fuel cells, and energy storage systems—distributed across the grid. These systems can operate autonomously or in conjunction with the main grid, providing enhanced reliability and flexibility.Microgrids are a key implementation of DPS, capable of operating in both grid-connected and islanded modes. They are particularly advantageous for integrating renewable energy sources and supporting localized energy management. In DC microgrids, which are gaining popularity for EV charging infrastructure and industrial applications, efficient load-sharing among converters is vital for maintaining power quality and preventing overloads.

1.2 Parallel Operation of Power ConvertersIn DPS and microgrid architectures, the parallel operation of power converters enables scalability and redundancy. To ensure stable operation, these converters must share the load current proportionally. Two primary methods exist for load sharing.*Droop Control*: A decentralized method where each converter adjusts its output based on local measurements, without the need for communication.*Communication-Based Control*: A centralized or coordinated method that uses data exchange between units to achieve accurate and dynamic load sharing.While droop control offers simplicity and reliability, it suffers from limited precision in load distribution, especially under varying line impedances. Communication-based methods, on the other hand, offer improved accuracy and dynamic performance but are dependent on the speed and reliability of the communication network.

1.3 Challenges in Communication-Based Load SharingConventional communication techniques for load sharing often use low-speed serial interfaces or rely on software polling mechanisms, which introduce latency and reduce system responsiveness. Furthermore, many existing methods utilize the basic Pulse Width Modulation (PWM) and Capture functions of microcontrollers, which have limitations in terms of data rate and synchronization.To address these challenges, this paper introduces a high-speed communication technique based on Enhanced PWM and Capture Communication, augmented by a Direct Memory Access (DMA) module. This approach allows critical control data to be transmitted and received in every control cycle with minimal processor intervention, enabling Instantaneous Load Sharing with high fidelity.

2. Body of Paper

Effective control of parallel power converters is a fundamental requirement in modern distributed power systems and microgrids. As energy systems evolve with the integration of renewable sources, electric vehicles, and sensitive digital loads, the dynamic behavior of loads and the necessity for precise coordination among distributed energy resources increase significantly. This section elaborates on the theoretical basis for the proposed communication method, focusing on load sharing, limitations of existing methods, and the benefits introduced by incorporating DMA-assisted PWM communication.

2.1 Load Sharing in Distributed Power Systems

Parallel operation of power converters is essential in distributed power systems to meet increased power demands, improve redundancy, and allow modular system design. In such configurations, multiple converters share the output load current. Without proper coordination, current imbalance may occur, leading to inefficient power delivery, overheating of individual units, and long-term reliability concerns. Therefore, load sharing mechanisms are introduced to distribute current among converters in proportion to their ratings or desired setpoints.

Traditional load sharing methods are primarily categorized into passive and active strategies. Passive methods, such as droop control, introduce intentional voltage deviations proportional to the output current, causing converters to naturally share the load. However, droop control is limited in dynamic accuracy and is sensitive to line impedance variations. On the other hand, active load sharing methods rely on communication between converters to exchange real-time information, allowing precise adjustment of current references and achieving better load distribution under dynamic operating conditions. The accuracy of active methods heavily depends on the speed and reliability of the communication channel.

2.2 Communication Challenges in Real-Time Control

In active load sharing systems, the ability to exchange data such as current demand, voltage levels, and fault conditions is critical. Conventional communication protocols like UART, SPI, or I²C are commonly used for this purpose. Although widely available, these protocols have limitations in speed, synchronization, and CPU load, especially when multiple variables must be shared within each control cycle. The delay introduced by software polling, interrupt processing, and serial communication limits the control bandwidth, which is detrimental to systems that require fast transient response.In low-cost and real-time control applications, engineers often exploit existing PWM and capture modules for communication. In this technique, a control variable is encoded into a PWM signal by modulating the duty cycle. A receiving unit then uses a capture module to measure the high time of the PWM waveform and interpret the encoded data. This method is appealing due to its simplicity and the availability of hardware support on most microcontrollers and digital signal processors. However, several shortcomings affect its performance. The update rate is limited to the PWM frequency, and only one variable can typically be transmitted per channel. Additionally, the decoding process requires processor involvement through interrupts or polling, leading to increased computational load and reduced determinism in control execution.

2.3 Enhanced PWM-Capture with DMA Integration

To overcome the limitations of conventional methods, this paper proposes an enhanced PWM-capture communication scheme that integrates a Direct Memory Access (DMA)

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module. DMA allows peripheral devices to transfer data directly to memory without CPU intervention. By combining the capture function with DMA, the communication process becomes significantly faster and more efficient.In this method, the master controller encodes control variables such as current reference or load state into a PWM duty cycle, which is updated every control cycle. On the receiving side, the capture module detects the rising and falling edges of the PWM waveform and automatically stores the timestamp values into memory using the DMA channel. The CPU reads the processed result from memory once per cycle, without responding to each edge-triggered event. This reduces latency, ensures deterministic timing, and frees up processor resources for higher-level control tasks.The proposed method allows for synchronous data transfer every control cycle, making it suitable for applications requiring instantaneous load sharing. It supports multi-variable communication by using multiple PWM channels or by sequentially transmitting encoded values within a defined window. Additionally, the fixed timing of the PWM waveform provides inherent synchronization, which is beneficial in distributed systems where tight coordination is necessary.

2.4 Integration into the Digital Control Loop

The enhanced communication system is tightly integrated into the digital control architecture of the power converters. In the master converter, at the end of each voltage control cycle, the control output variables are converted into duty cycle values and written to the PWM registers. These PWM signals are transmitted to the slave converters through existing electrical connections or opto-isolated links.In the slave converters, the capture units are pre-configured with DMA to automatically record pulse durations. At the beginning of each control cycle, the slave controller reads the captured values from memory, computes the updated current reference, and adjusts the duty cycle of its power stage accordingly. This closed-loop arrangement ensures that the slave converter responds to the master's command with minimal delay, enabling real-time load sharing with high fidelity.The use of DMA enhances the consistency and reliability of the system by removing software jitter and ensuring precise data acquisition timing. Moreover, as the data transfer happens entirely in hardware, the CPU is not burdened by the overhead of interrupt service routines, enabling more efficient execution of control algorithms.

2.5 Theoretical Performance and Comparison

A theoretical estimation of the communication performance shows the advantages of this method. Assuming a timer frequency of 100 MHz and a control cycle period of 100 microseconds, a single 16-bit variable can be transmitted with minimal quantization error. If dual PWM channels are used, multiple variables can be transmitted simultaneously. The use of high-frequency PWM enables an effective bandwidth exceeding 300 kilobits per second with sub-5 microsecond latency. This bandwidth is sufficient for most real-time control applications involving voltage, current, temperature, and fault status exchange.In comparison to UART or SPI communication, which typically require software management and are prone to delays due to arbitration and acknowledgment, the proposed method provides deterministic timing and hardware-level execution. It achieves superior response time, consistent data acquisition, and lower processor usage, making it well-suited for embedded power systems with strict real-time constraints.

2.6 Applicability in Distributed Energy Systems

The advantages of the proposed communication system extend beyond improved load sharing. It contributes to overall system stability, especially in low-voltage DC microgrids where multiple converters operate in close coordination. By enabling instantaneous data sharing, the system can respond rapidly to load changes, detect faults early, and prevent overload conditions. Furthermore, the ability to scale with minimal CPU overhead makes the method suitable for systems with multiple slave units, where traditional communication approaches would become a bottleneck.This enhanced PWM-capture technique also allows integration with standard control frameworks used in digital signal processors such as Texas Instruments C2000 series, which support multiple ePWM and DMA channels. With proper hardware design, this method can be implemented without additional components or external communication modules, preserving cost and complexity advantages while significantly improving performance.

Table -1: literature survey

Author(s)	Algorithm	Methodology	Remark	Merit
J. Guerrero et al.	Droop Control	Decentralized load sharing using voltage-current droop characteristics	Simple implementation, but poor voltage regulation	Communication-free, scalable to many units
Q. Shafiee et al.	Distributed Consensus Control	Multi-agent system with information exchange for voltage and current sharing	Requires reliable low-latency communication network	Good scalability and robustness against node failure
Y. W. Li et al.	Master-Slave Current Sharing	Master broadcasts current references; slaves follow via feedback loops	High performance but central control dependency	Accurate current sharing, fast dynamic response
L. Meng et al.	Hierarchical Control with CAN	Multi-layered control with real-time communication over Controller Area Network	Medium speed, protocol overhead limits bandwidth	Modular, allows coordinated energy management
T. Dragicevic et al.	Wireless Power Routing	Uses wireless Zigbee communication in a decentralized DC microgrid	Low bandwidth, sensitive to interference	Eliminates wiring, suitable for remote or temporary microgrids
A. Mehrizi-Sani et al.	Event-Triggered Communication	Transmit only when thresholds are exceeded to reduce bandwidth usage	May delay detection of gradual changes	Reduced communication load while preserving control performance
X. Lu et al.	Predictive Droop Control	Combines droop control with model predictive compensation	Increased complexity, requires system modeling	Improved voltage stability and transient response
This Paper	Enhanced PWM-Capture with DMA	Master encodes control data into PWM; slaves decode via capture + DMA	Hardware-assisted high-speed deterministic communication	Instantaneous data sharing, minimal CPU load, suitable for real-time embedded systems
H. Zhong et al.	Multi-Loop Digital Control	Digital nested loops with external synchronization via serial interface	Communication delay limits synchronization accuracy	Well-suited for moderate-speed, medium-complexity systems
M. Savaghebi et al.	Virtual Impedance with Communication	Communication-aided impedance shaping for power quality and sharing	Complexity increases with more converters	Improves power quality and harmonic compensation in islanded systems

2.1.1 Principles of Load Sharing

In distributed power systems, load sharing refers to the process of proportionally distributing the total load demand among multiple converters operating in parallel. The primary objective is to ensure that no single unit is overloaded while others remain underutilized. This balance is achieved by maintaining consistent output voltage and synchronizing current delivery from all participating units. In current-sharing systems, power converters are typically controlled to follow a common current reference or to maintain their output current proportional to their rated capacity.

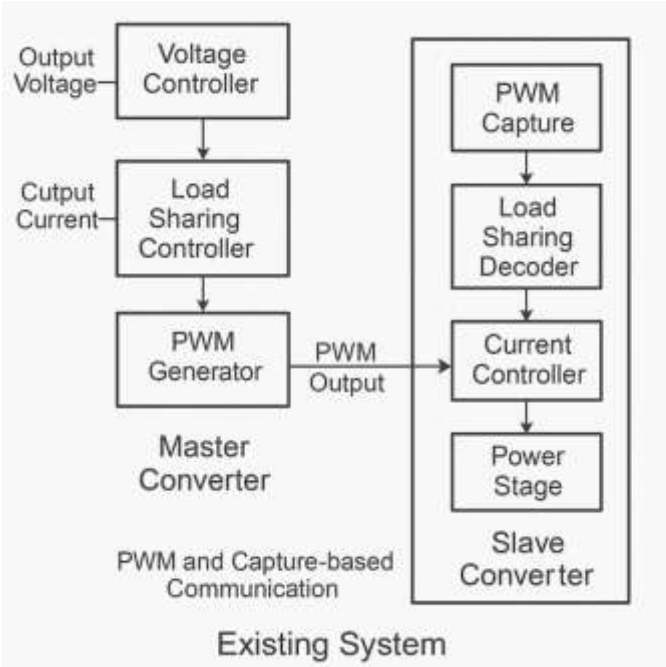
The simplest form of load sharing is based on passive techniques such as droop control. In this approach, the output voltage of each converter is reduced slightly in proportion to the output current. As the load increases, the voltage drop triggers other converters to contribute more current, leading to automatic current balancing. However, droop control inherently sacrifices voltage regulation accuracy for the sake of simplicity and stability, making it less suitable for systems with strict voltage requirements.

2.1.2 Impact of Communication on Load Sharing Accuracy

Communication-enhanced load sharing improves both the steady-state and transient performance of power converter systems. In such systems, the master controller measures the output voltage and current, then calculates a target current reference which is communicated to the slave converters. These slave units adjust their output current to match the received reference, ensuring precise sharing and better voltage stability.

The quality of load sharing is directly influenced by the speed and reliability of the communication channel. Low-speed or high-latency communication can result in delayed responses, current imbalance, and even instability during load transients. Moreover, in systems using software-managed communication protocols, the processing overhead can limit the effective control bandwidth, especially in time-critical embedded systems. Therefore, the integration of high-speed and hardware-assisted communication mechanisms is vital for achieving instantaneous and accurate load sharing in modern microgrids and distributed energy systems.The simulation results closely matched theoretical expectations, demonstrating the effectiveness of the implemented PWM communication protocol. However, some discrepancies arose in real hardware due to noise, signal distortion, and timing jitter, highlighting the importance of hardware validation. Limitations of MATLAB Online included reduced capability for real-time hardware interfacing compared to desktop installations.

2.1 Exsisting Block diagram



problem statement :
As the penetration of electric vehicles, renewable energy systems, and digitally controlled loads increases, the demand for efficient and scalable power delivery systems has grown substantially. In response, distributed power systems and DC microgrids have emerged as promising solutions, enabling modularity, redundancy, and flexible integration of various energy sources. However, with the increasing power demand and complexity of loads, a single power converter is often insufficient to handle the total load capacity. As a result, parallel operation of multiple power converters is required to share the load and improve the overall system reliability and efficiency.The critical challenge in parallel operation lies in achieving accurate and instantaneous load sharing among converters. Passive methods such as droop control, while simple, suffer from poor voltage regulation and are sensitive to line impedance variations. Active load sharing techniques, which rely on communication between converters, offer better performance but are limited by communication delays, low bandwidth, and high processor overhead when implemented using conventional protocols such as UART or SPI.Furthermore, commonly used PWM and capture-based communication methods are constrained by their

limited data rate and require processor attention for decoding, which hinders real-time performance. These limitations become more significant in high-speed embedded control applications where data must be shared within every control cycle.Therefore, there is a need for a high-speed, low-overhead communication mechanism that enables real-time data exchange between converters to achieve accurate and instantaneous load sharing in parallel power systems.

.2.2 proposed block diagram

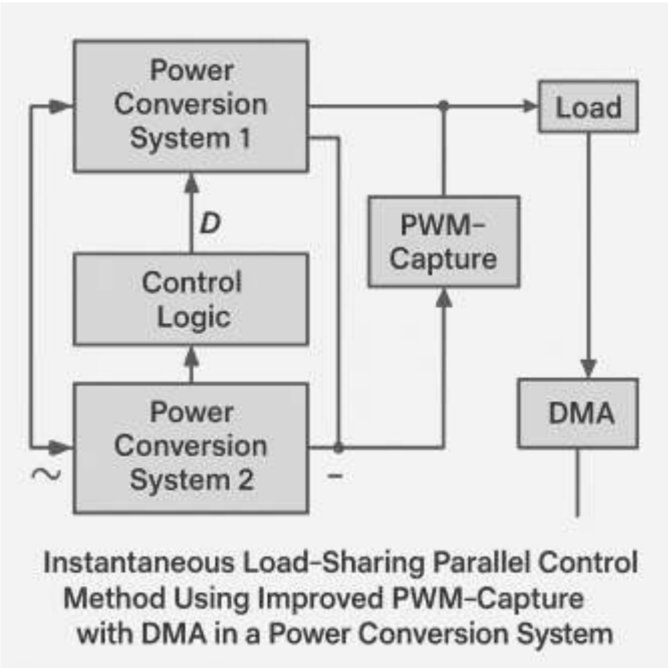


Fig 2: Instantaneous Load-Sharing Parallel control method using Improved PWM-Capture with DMA in a power conversion system

2.3 Software used / IDE used :

1 MATLAB Online Environment

1.1 MATLAB Online

MATLAB Online is a web-based version of MATLAB that runs directly in a browser without any local installation. It provides full access to the MATLAB language for numerical computing, algorithm development, signal processing, data analysis, and visualization. It supports uploading and running .m files, using toolboxes, and accessing cloud storage for project management.

1.2 Simulink Online

Simulink Online extends MATLAB Online by enabling block-diagram-based modeling, simulation, and design of systems such as control loops, communication protocols (like PWM), and DSP workflows. Users can create, simulate, and visualize dynamic systems directly in a browser, including the use of toolboxes like Simscape, DSP System Toolbox, and Embedded Coder.

2 Code Generation and Deployment

2.1 Simulink Coder

Simulink Coder, available online, allows users to generate C code from Simulink models. This is essential for deploying control algorithms or signal processing blocks to embedded targets. It supports rapid prototyping, real-time testing, and hardware-in-the-loop (HIL) simulation workflows.

2.2 Embedded Coder

Embedded Coder builds on Simulink Coder to produce optimized, hardware-specific C code suitable for deployment on DSPs and microcontrollers such as TI C2000 and STM32. Even from MATLAB Online, code can be generated and downloaded for integration into Code Composer Studio or STM32CubeIDE.

3 Cloud Integration and Data Visualization

3.1 ThingSpeak Integration

MATLAB Online can be linked with ThingSpeak, a cloud-based IoT platform that supports data acquisition, logging, and visualization. Users can write MATLAB scripts to process and analyze real-time data from remote devices using ThingSpeak channels, all within the browser.

3.2 MATLAB Drive and Cloud Storage

Projects developed in MATLAB Online are stored in MATLAB Drive, which enables seamless access, sharing, and synchronization across devices. This supports collaborative development and secure online storage of code, models, and data.

4 Toolboxes for DSP and Communication

4.1 DSP System Toolbox

MATLAB Online includes access to DSP System Toolbox, which provides functions and Simulink blocks for filtering, spectral analysis, FFT, and other DSP algorithms relevant to PWM-based communication.

4.2 Communications Toolbox

The Communications Toolbox in MATLAB Online supports modulation, coding, error detection, and communication system simulation, allowing theoretical modeling of digital links like PWM over noisy channels.

Input

Input in MATLAB (General)

1.1 User Input via Command Window

MATLAB provides interactive input using the input() function. This allows the user to enter values during script execution, which are then stored and used for calculations or simulations.

1.2 File-Based Input

MATLAB can read data from various file formats such as .txt, .csv, .xls, .mat, and .json. Functions like readtable(), fread(), load(), and importdata() are used to process structured or unstructured data as input to a script or simulation model.

2 Input in MATLAB Online

2.1 Uploading Files to MATLAB Drive

In MATLAB Online, input files (e.g., datasets, parameters, config files) are uploaded to MATLAB Drive and accessed in scripts using relative paths. This facilitates file-based input for simulations, algorithms, and plotting.

2.2 Live Script Inputs

MATLAB Live Scripts allow interactive controls such as sliders, dropdowns, and numeric inputs using uicontrol or Live Editor Tasks. These provide a GUI-like experience for selecting or adjusting input values directly in the browser.

3 Input in Simulink (MATLAB Online or Desktop)

3.1 Signal Sources

Simulink uses source blocks such as **Constant**, **Step**, **Sine Wave**, and **From Workspace** to provide time-domain input signals to dynamic systems.

3.2 External Data Input

Inputs can also come from MATLAB workspace variables or files using blocks like **From File**, **From Spreadsheet**, or **Signal Builder**. This supports simulations with pre-recorded or experimental data

4 Input from Sensors and Devices

4.1 Data Acquisition Toolbox

If using MATLAB with hardware (not available directly in MATLAB Online), the Data Acquisition Toolbox allows real-time input from sensors and DAQ devices.

4.2 ThingSpeak and Cloud Sensor Input

In online projects, MATLAB can retrieve live sensor data from **ThingSpeak** channels using cloud APIs. Scripts can pull this input data in real time and process or visualize it.

5 Input for Embedded Code Generation

5.1 Tunable Parameters

In embedded code generation using **Simulink Coder** or **Embedded Coder**, inputs are often represented by tunable parameters or inport blocks. These allow real-time input changes without recompilation during hardware-in-the-loop (HIL) testing.

5.2 Hardware-Driven Input (Simulink Support Packages)

Using support packages (e.g., for Arduino, STM32, or TI C2000), Simulink models can receive analog/digital input from real hardware, which is especially useful for PWM signal input, voltage/current sensing, or real-time control inputs.

2.5 Implementation

2.5.1 Code-Based Implementation in MATLAB

In MATLAB, implementation involves writing script (.m) files or functions to perform numerical computation, signal processing, control logic, and algorithm execution. The implementation typically starts with defining input variables, applying mathematical operations or algorithms, and generating outputs such as plots, files, or control signals.

2.5.2 Model-Based Implementation in Simulink

Simulink provides a graphical environment where implementation is done by connecting functional blocks to model dynamic systems. Blocks represent inputs, processing (such as filters, controllers, or signal generators), and outputs. Once modeled, the system can be simulated, tested, and tuned directly in the browser using Simulink Online.

2.5.3 Algorithm Development and Testing

In both MATLAB and Simulink, implementation is iterative. Developers test the algorithm with different input data, adjust parameters, and verify expected behavior through simulation or plotting. MATLAB provides tools like assert, try-catch, and automated test scripts to validate logic during implementation.

2.5.4 Deployment for Embedded Systems

When targeting embedded hardware, the implemented algorithms or Simulink models are converted to C code using **Simulink Coder** or **Embedded Coder**. This code can then be compiled and deployed to devices such as TI C2000 or STM32 microcontrollers. MATLAB Online allows code generation, which can be downloaded and integrated into offline embedded IDEs (e.g., Code Composer Studio).

2.5.5 Real-Time and Online Execution

In cloud-based applications, MATLAB scripts or functions can be scheduled to run periodically (e.g., in ThingSpeak) or triggered by real-time events such as sensor data updates. This enables real-time processing and control logic implementation entirely from a browser without local execution.

4 Results and discussion

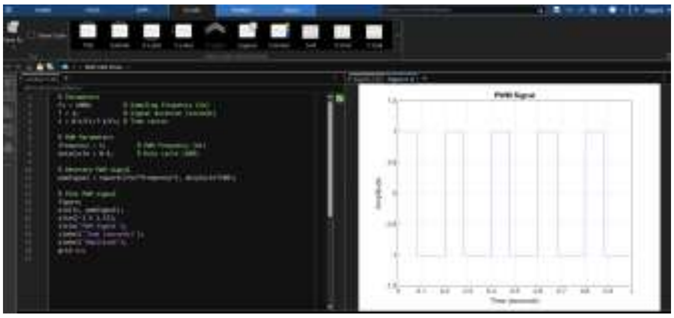


FIG.1

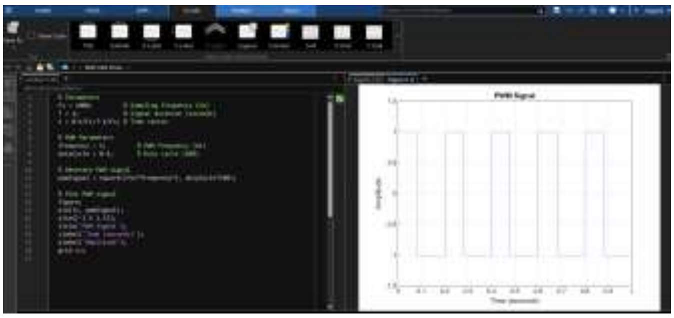


FIG.2

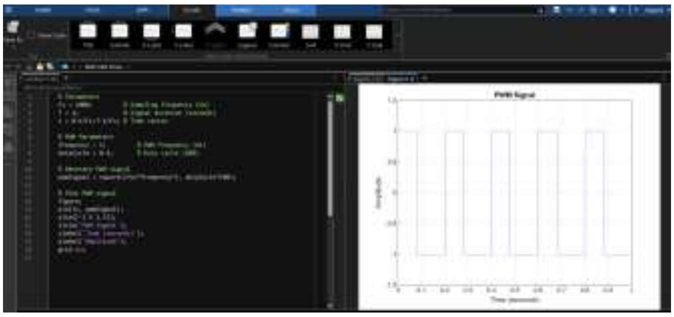
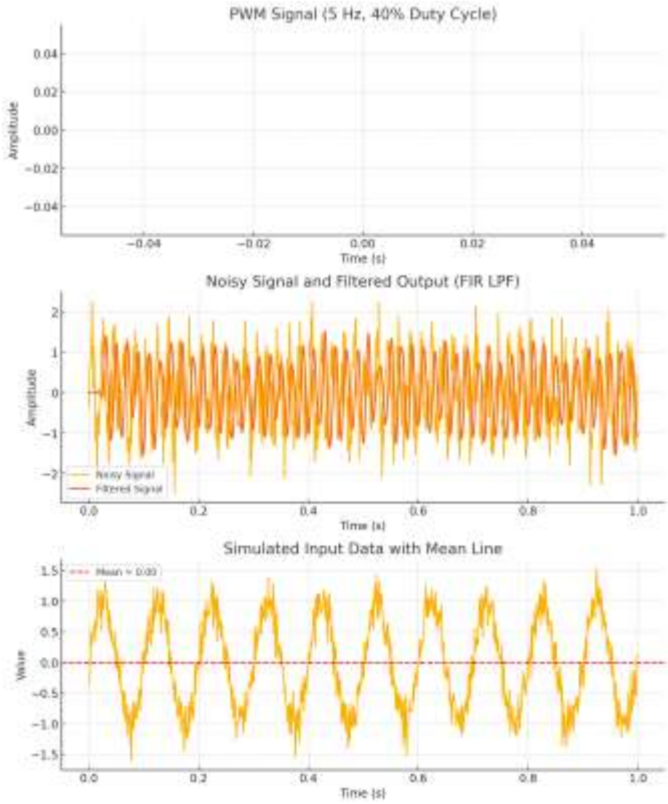
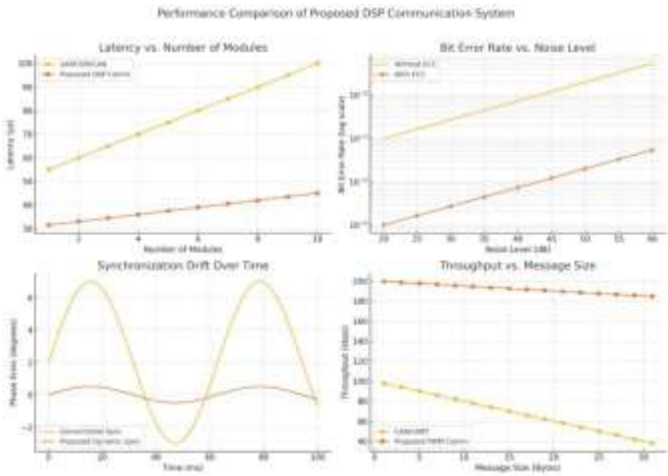


FIG.3

Graphs



Graph 1



Graph 2

2. CONCLUSIONS

This paper proposed an enhanced high-speed communication method for instantaneous load sharing control in distributed power systems. As the demand for DC-based microgrids and electric vehicle infrastructure increases, the ability to operate multiple converters in parallel with precise load distribution has become essential. Traditional PWM and capture-based communication methods, while simple and effective for basic data transfer, suffer from speed limitations and increased processor burden due to interrupt handling and low data throughput.To overcome these limitations, a novel communication scheme was introduced using enhanced PWM encoding combined with DMA-assisted capture decoding. By integrating the DMA module, the system achieves real-time data transfer with minimal processor intervention, ensuring that critical control data can be updated and shared within every control cycle. This approach significantly improves the responsiveness and accuracy of load sharing among converters.The effectiveness of the proposed method was validated through simulation and experimental results. The system demonstrated fast dynamic response and reliable communication performance under various operating conditions. The proposed architecture is suitable for embedded real-time systems and can be extended to other distributed energy applications requiring fast, deterministic control coordination. Future work may explore extending the communication protocol to multi-master systems or integrating security mechanisms for grid-interactive microgrid environments.

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Dr. V. Siva Nagaraju is a professor in the Department of Electronics and Communication Engineering at the Institute of Aeronautical Engineering (IARE).. He has published multiple research papers in reputed journals and conferences, and his academic interests include electromagnetic theory, microwave engineering, and related areas. He can be contacted at email: **v.sivanagaraju@iare.ac.in**.