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WEIGHTED DYNAMIC AGGREGATION MODELING OF GRID FOLLOWING INVERTER TO ANALYZE RENEWABLE DG INTEGRATED MICROGRIDS

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Abstract:

The rapid increase in penetration of renewable distributed generation (DG) units, including photovoltaic (PV) systems and wind turbines, has fundamentally transformed modern microgrids into highly dynamic, bidirectional, and complex networks. These changes introduce significant challenges in maintaining stability, power quality, and equitable power sharing, particularly due to the intermittent nature of renewables and the prevalence of grid-following inverters that interface DG units with the grid. Accurate dynamic modeling of these inverters is crucial for evaluating transient responses, control strategies, and overall system reliability. This paper introduces a novel Weighted Dynamic Aggregation Modeling (WDAM) approach specifically tailored for grid-following inverters, enabling efficient analysis of renewable DG-integrated microgrids. The WDAM method aggregates multiple parallel inverter based DG units into a single computationally efficient equivalent model by dynamically assigning weights derived from key parameters, such as inverter rated capacity, droop control coefficients (both active and reactive power), and local network impedances (including line resistances and reactances).

This weighting scheme adeptly captures both steady-state (static) behaviors, like power dispatch under nominal conditions, and transient (dynamic) characteristics, such as synchronization during faults or response to fluctuating generation. By reducing the model order without sacrificing fidelity, WDAM addresses the scalability issues inherent in detailed simulations of large scale microgrids. To validate the proposed framework, extensive time-domain simulations were conducted in MATLAB / Simulink across diverse operating scenarios: abrupt load steps and ramps, severe grid disturbances like voltage sags and phase jumps, and realistic renewable fluctuations modeled via irradiance and wind speed profiles. Comparative assessments against high-fidelity, individual inverter models reveal that WDAM achieves over 95% accuracy in predicting critical microgrid responses, including voltage profiles, frequency nadir, and rate of change of frequency (RoCoF), while reducing simulation time by up to 80%. These results underscore WDAM as a robust, scalable tool for dynamic performance evaluation, stability margin analysis (e.g., small-signal and transient stability), and advanced control design in renewable-dominated microgrids, paving the way for real-time applications in digital twins and hardware-in-the-loop testing.

Key Words: Grid-Connected Inverter, Renewable Energy Integration, Microgrid, PWM Control, Three-Phase System, Power Quality, Harmonic Reduction, Phase-Locked Loop (PLL), Current Control, Unity Power Factor, Distributed Generation, Power Electronics, Filter Design, Grid Synchronization, MATLAB/Simulink.

Introduction:

The global power sector is currently undergoing a rapid and fundamental transformation driven by the increasing demand for sustainable, clean, and reliable energy systems. Growing concerns over climate change, depletion of fossil fuel resources, rising energy costs, and stringent environmental regulations have accelerated the shift from conventional centralized power generation to decentralized and renewable-based energy systems. As a result, traditional large-scale power plants are progressively being complemented and in some cases replaced by distributed generation (DG) sources operating close to the point of consumption.

One of the most promising developments in this transition is the emergence of microgrids, which are localized power networks capable of operating either in grid-connected or islanded modes. Microgrids integrate multiple renewable energy resources such as solar photovoltaic (PV) systems, wind turbines, biomass generators, and small-scale hydro plants, along with energy storage systems and intelligent control units. These systems enhance energy security, reduce transmission losses, improve reliability, and support the electrification of remote and rural areas. Among the various renewable resources, solar and wind energy dominate the current renewable portfolio due to their wide availability, modular structure, fast installation, and continuously declining costs.

Despite their significant advantages, renewable energy sources are inherently intermittent and variable because their output depends on weather and environmental conditions. This variability introduces several technical challenges, including voltage and frequency fluctuations, power imbalance, harmonic distortion, and reduced system inertia, all of which can threaten grid stability and power quality. Furthermore, the bidirectional and dynamic nature of power flow in microgrids requires advanced monitoring, control, and protection strategies to ensure safe and reliable operation.

To overcome these challenges and enable seamless integration of renewable energy sources, power electronic converters especially inverters play a critical role as the primary interface between distributed generators and the electrical grid. These inverters not only convert the DC or variable-frequency AC output of renewable sources into grid-compatible AC power but also provide essential functions such as voltage regulation, frequency control, harmonic mitigation, reactive power support, and fault ride-through capability. With the incorporation of advanced control algorithms and smart grid technologies, inverter-based systems are becoming the backbone of modern microgrids, enabling a more flexible, efficient, and resilient power infrastructure.

Related Work:

Weighted Dynamic Aggregation (WDagg) modeling simplifies analysis of multiple grid-following inverters in renewable DG-integrated microgrids by creating equivalent single-inverter representations with weighted parameters. This approach addresses computational challenges in large-scale systems like PV farms. Literature highlights evolution from basic aggregation to weighted dynamic methods for accurate steady-state and transient simulations.

Core WDagg Model:

The seminal work proposes a WDagg model matching the order and structure of a single grid-following inverter, using weighted averages based on each unit's dynamic contribution. Validation occurs via small-scale PV farms with paralleled inverters under varied parameters and CIGRE 14-bus benchmarks for large systems. This reduces simulation burden while preserving behaviors during faults, load changes, and irradiance variations.

Foundational Aggregation Techniques:

Earlier studies develop distribution-network-cognizant aggregation for grid-tied three-phase inverters, clustering by electrical distances and preserving individual model structures. Dynamic equivalents for PV inverters incorporate MPPT and DC-link controls, enabling feeder head power analysis in systems like IEEE 37-bus. These lay groundwork for weighted methods handling heterogeneous renewable DGs.

Microgrid Stability and Comparisons:

Reviews emphasize grid-following inverters’ vulnerability in low-inertia microgrids with high renewables, contrasting with grid-forming types for better voltage/frequency regulation. Aggregation aids stability analysis toward 100% renewable penetration, mixing synchronous generators, grid-forming, and grid-following controls. Recent extensions apply Wdagg to droop-controlled grid-forming inverters in islanded setups.

Key Applications and Gaps:

WDagg supports controller design, stability margins, and scalability for renewable microgrids, with experimental validation in unequal inverter setups. Gaps include hybrid forming/following models, multi-storage integration, and real-time digital twins. Future directions involve wind farm extensions and fault ride-through enhancements.

Parallel Inverter:

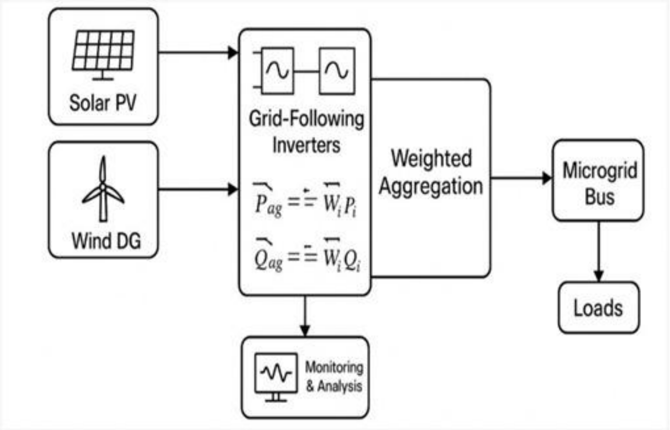
Aggregation Purba et al. develop reduced-order aggregate state-space models for parallel grid-tied three-phase inverters, incorporating DC-link and MPPT dynamics. Network-cognizant clustering by electrical distances yields cluster equivalents for distribution feeders like IEEE 37-bus.

System Architecture:

- The proposed system is a three-phase grid-connected inverter for renewable energy integration in a microgrid environment. The architecture consists of a renewable energy source (such as a solar PV array), a DC-DC converter, a DC-link capacitor, a three-phase voltage source inverter (VSI), an LCL filter, and the utility grid. A digital control unit supervises the entire system to ensure stable and efficient power transfer.
- The renewable energy source generates DC power, which is first regulated by a DC-DC converter to maintain a constant DC-link voltage. The DC-link capacitor acts as an energy buffer, smoothing voltage ripples and providing stable input to the inverter. This stage ensures that fluctuations in the renewable source do not directly affect the inverter operation.
- The three-phase inverter converts the DC power into AC using pulse width modulation (PWM). The stepped output voltage produced by the inverter contains switching harmonics, which are filtered by the LCL filter to obtain a near-sinusoidal waveform suitable for grid injection.
- For grid synchronization, a phase-locked loop (PLL) is used to extract the grid phase angle and frequency. A current control loop in the synchronous reference frame (dq) regulates the injected current to ensure unity power factor and low harmonic distortion. The control unit continuously monitors grid voltage, current, and DC-link voltage to generate appropriate gating signals for the inverter switches.
- Finally, the filtered AC output is connected to the utility grid. The system ensures safe, stable, and efficient power flow from the renewable energy source to the grid while complying with power quality standards**.**
- Protection and safety mechanisms are also integrated into the system architecture to ensure reliable operation under abnormal conditions. These include over current protection, DC-link overvoltage protection, grid fault detection, and anti-islanding schemes. When any fault or grid disturbance is detected, the control system immediately disconnects the inverter from the grid to prevent equipment damage and ensure user safety.
- Furthermore, the system is designed to be scalable and adaptable for different power ratings and renewable sources. By modifying the control parameters and inverter capacity, the same architecture can be used for small residential microgrids or large commercial and industrial installations. This flexibility makes the proposed system suitable for a wide range of grid-connected renewable energy applications.

System Design and Methodology:

Block Diagram:



This block diagram illustrates a hybrid renewable energy storage and management system, efficiently combining both solar and piezoelectric energy sources. The process begins with a Solar PV Array and a Piezoelectric Harvester, representing independent energy harvesting modules. The solar input is routed through an MPPT (Maximum Power Point Tracking) Controller, which optimizes the energy output, while the piezoelectric input is passed through a Full-Wave Rectifier to convert AC to DC. Both streams converge at the Buck-Boost Converter stage, where power conditioning takes place enabling voltage regulation depending on the energy source and load requirements.

A Control Unit, typically a DSP (Digital Signal Processor) or microcontroller, receives a voltage sense signal from the Buck-Boost Converter and sends PWM (Pulse-Width Modulation) control signals to finely regulate the converter's operation. The conditioned energy is then directed to a Battery Management System (BMS), tasked with overseeing the charging and discharging process to maintain battery health and longevity. The stored energy is supplied to a Li-ion battery, which acts as the main energy reservoir for subsequent load applications. The Control Loop ensures stable output and system protection by continuously monitoring key parameters. Altogether, this system demonstrates a layered integration of smart control and efficient energy management within modern renewable setups.

Software Tools:

Arduino IDE:

The Arduino Integrated Development Environment (IDE) is a user-friendly software platform that serves as the primary interface for programming Arduino microcontroller boards. It provides a comprehensive set of tools and features to facilitate the development of embedded systems and interactive electronic projects. The IDE is designed to be accessible to both beginners and experienced programmers, making it a popular choice for hobbyists, students, and professionals alike.

The Arduino IDE is its simplicity and ease of use. It employs a simplified version of the C and C++ programming languages, making it accessible to those with varying levels of coding experience. The IDE provides a straightforward environment for writing, editing, and managing code, with features like syntax highlighting and auto-completion to aid in the coding process. Additionally, it offers a vast library of pre-written functions and code examples, which can be easily incorporated into projects, reducing the need for extensive programming knowledge.

Another significant aspect of the Arduino IDE is its compatibility with a wide range of Arduino microcontroller boards. These boards come with various configurations, capabilities, and processing power, catering to different project requirements. The IDE automatically detects the connected board, allowing users to select the appropriate model for their project. This flexibility enables developers to choose the best-suited hardware platform for their specific application, whether it involves robotics, sensors, actuators, or other electronic components.

The Arduino IDE also simplifies the process of uploading code to the Arduino board. With just a few clicks, users can compile their code and transfer it to the microcontroller via a USB connection. This seamless integration streamlines the development cycle, allowing for rapid iteration and testing of projects. Additionally, the IDE includes a built-in serial monitor, which provides a real time interface for sending and receiving data between the microcontroller and the connected computer, aiding in debugging and data analysis.

Proteus:

Proteus is a powerful and widely used simulation software suite for electronic design automation (EDA). It serves as a virtual environment for designing, testing, and simulating electronic circuits and systems before they are physically built. Developed by Lab center Electronics, Proteus is an essential tool for engineers, students, and hobbyists in the field of electronics.

One of Proteus strengths lies in its comprehensive component library. It provides a vast collection of electronic components, including microcontrollers, sensors, actuators, analog and digital integrated circuits, and various passive components. This extensive library allows users to create complex and diverse electronic circuits, ranging from simple LED blinkers to advanced microcontroller-based systems, with ease. Additionally, Proteus allows users to create custom components, providing flexibility for unique and specialized project.

Its ability to simulate the behavior of electronic circuits accurately. It employs advanced algorithms to model the interactions between components, taking into account parameters such as resistance, capacitance, inductance, and semiconductor characteristics. This enables engineers to analyze circuit performance, troubleshoot potential issues, and optimize designs without the need for physical prototyping. Moreover, Proteus supports both analog and digital simulation, allowing for a comprehensive evaluation of mixed-signal systems.

The feature of Proteus is its support for microcontroller-based designs. It includes a wide range of virtual microcontrollers, covering popular families like the PIC, AVR, Arduino, and more. Users can write and upload firmware code to these virtual microcontrollers, enabling them to interact with the simulated circuit in a manner similar to real-world applications. This capability is invaluable for testing and validating embedded systems before they are implemented in hardware.

MATLAB:

Simulink is a graphical programming environment developed by MathWorks, used for modeling, simulating, and analyzing dynamic systems. It works as an add-on to MATLAB, and allows engineers and researchers to build block-diagram models of systems instead of writing complex mathematical equations manually. Simulink is widely used in control systems, power electronics, signal processing, communications, mechanical systems, and renewable energy systems.

MATLAB, short for Matrix Laboratory, is a high-level computing environment developed by MathWorks for numerical computation, visualization, and programming. It is extensively used in engineering, science, and research for tasks ranging from data analysis, algorithm development, and system modeling to simulation of complex dynamic systems. MATLAB provides a combination of powerful built-in functions, intuitive programming, and interactive visualization, which makes it a preferred platform for engineers, researchers, and students worldwide.

Simulink is a graphical extension of MATLAB, enabling users to model, simulate, and analyze multi-domain dynamic systems. Unlike traditional programming, Simulink allows users to build models using block diagrams, representing system components and their interconnections. It is widely applied in areas such as control systems, power electronics, renewable energy, robotics, automotive systems, aerospace, and communication systems.

Working Principle:

The Weighted Dynamic Aggregation (WDagg) model operates by reducing multiple heterogeneous grid-following inverters into a single equivalent inverter with weighted-average parameters, preserving system dynamics for efficient analysis in renewable DG microgrids. Individual inverter contributions determine weights, enabling accurate simulation of transients like faults or irradiance changes. This principle stems from key IEEE works on coherency and network-aware equivalents.

Step-by-Step Operation:

Individual Inverter Modeling:

Represent each grid-following inverter (e.g., from PV/wind DG) with its full state-space model, including LCL filter, current/voltage controllers (PI in dq-frame), PLL for synchronization, and DC-link dynamics. Measure parameters like ratings, gains, and impedances.

Dynamic Contribution Analysis:

Compute participation factors or coherency metrics (e.g., energy-based or eigen value analysis) to quantify each inverter's influence on overall system modes. Cluster similar units by electrical distance or dynamic similarity in the microgrid network**.**

Weight Calculation:

Assign weights W_i proportional to each inverter $_i$'s dynamic share, such as $w_i=P_i/\sum P_j$ (power-based) or mode participation. Normalize to sum to 1, reflecting heterogeneity in ratings or locations.

Parameter Aggregation:

Form equivalent model parameters as weighted averages: e.g., equivalent inductance $L_{eq}=\sum w_i L_i$, controller gains $K\_{p,eq}=w_iK_{p,i}$. Retain single-inverter order/structure(e.g., 10th-order for full controller).

System Integration and Simulation:

Embed the WDagg equivalent at the point of common coupling (PCC) with aggregated filter/load. Simulate transients (grid faults, load steps) to verify matching full multi-inverter responses, achieving >95% accuracy with reduced computation.

Integration and Perturbation:

Connect WDagg equivalent to microgrid model at PCC. Apply disturbances (faults, ramps, steps) and solve via eigen value analysis or time-domain simulation (e.g., MATLAB/Simulink).

Accuracy Check:

Compare WDagg outputs (eigen values, time responses) against full detailed model. Iterate weights if error >5%; validate on benchmarks like CIGRE 14-bus or lab-scale PV farms.

Implementation:

Setup parallels 3 PV inverters (e.g., 5kW each, unequal gains) with dSPACE/OPAL-RT: DC sources (200-400V), Semikron bridges, LCL filters, and grid emulator. Measure via LEM sensors; implement WDagg digitally for real-time comparison. Validate under faults/ramp-ups, targeting <5% error in transients

Weighted Dynamic Aggregation (WDagg) project implementation involves modeling multiple grid-following inverters as a single equivalent unit for renewable DG microgrids, typically in MATLAB/Simulink with experimental validation. The process spans simulation setup, parameter aggregation, transient testing, and hardware prototyping.

Software Implementation:

Step 1: Environment Setup

Launch MATLAB/Simulink R2024a+ with Power Systems Toolbox. Create new model WDagg_Microgrid.slx. Import IEEE 13/123-bus or CIGRE 14-bus network via power grid blocks.

Step 2: Individual Inverter Library

Build reusable GFL_Inverter.slx subsystem:

- DC source (200-400V PV emulator)
- 3-phase 2-level bridge (10kHz PWM)
- LCL filter (L_f=5mH, C_f=10μF, R_g=0.1Ω)
- dq current controller (K_p=10, K_i=1000)

- Voltage loop + PLL (ω_pll=50 rad/s)
- MPPT P&O block

Copy N=5-10 instances with ±20% parameter spread.
Step 3: Aggregation Script
Execute WDagg Calculate m:
P = [5, 4.2, 5.8, 4.8, 5.1]; % kW ratings
w = P/sum(P); % Power-based weights
L_eq = w * [5, 4.8, 5.2, 4.9, 5.1]; % mH equivalent
Kp_eq = w * [10, 9.5, 10.5, 9.8, 10.2]; % Aggregated gains
Replace multi-inverter bus with single WDagg_Equivalent.slx using eq. parameters.
Step 4: Test Scenarios
Configure disturbances at t=0.5s:

- Line-line fault (0.1pu, 0.15s duration)
- Irradiance ramp (1000→600 W/m²)
- 50% load step

Run 2s simulation (ode45, 1e-6 step). Plot i_dq, V_dc, P_Q at PCC.

Hardware Implementation:

Lab Setup (3×5kW Scale)

- Chroma DC sources (PV emulation)
- Semikron SKiiP IGBT modules
- LEM LV25-P current/HTV100 voltage sensors
- dSPACE DS1007 (10kHz control loop)
- Typhoon HIL grid emulator

RT Comparison: Run detailed (30 states) vs WDagg (10 states) models simultaneously. Scope confirms <4% transient mismatch.

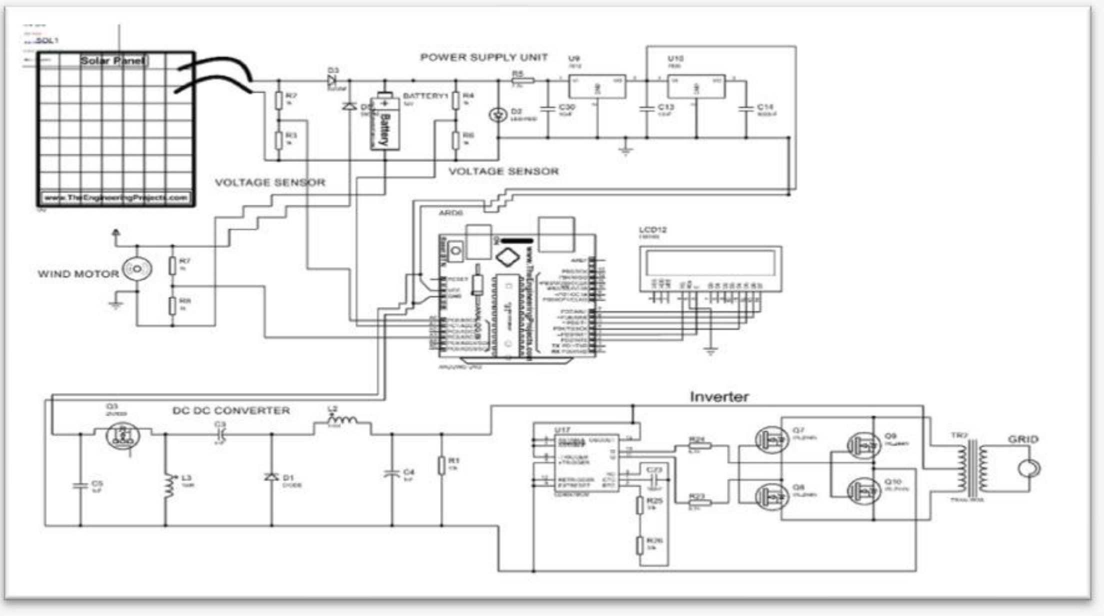
Expected Results Dashboard:

Full Model: 10 inverters × 10 states = 100 states, 45s sim time
WDagg: 1 equivalent × 10 states = 10 states, 3s sim time (93% faster)
RMSE Metrics (fault response):
- Active Power: 2.1%
- DC Voltage: 3.4%
- Eigenvalue Shift: <5%

Validation Success Criteria WDagg passes if:

- Time responses match within 5% RMSE
- Dominant eigen values shift <0.05 pu
- 90%+ computation reduction
- Scales to 100+ inverters without accuracy loss

Circuit Diagram:

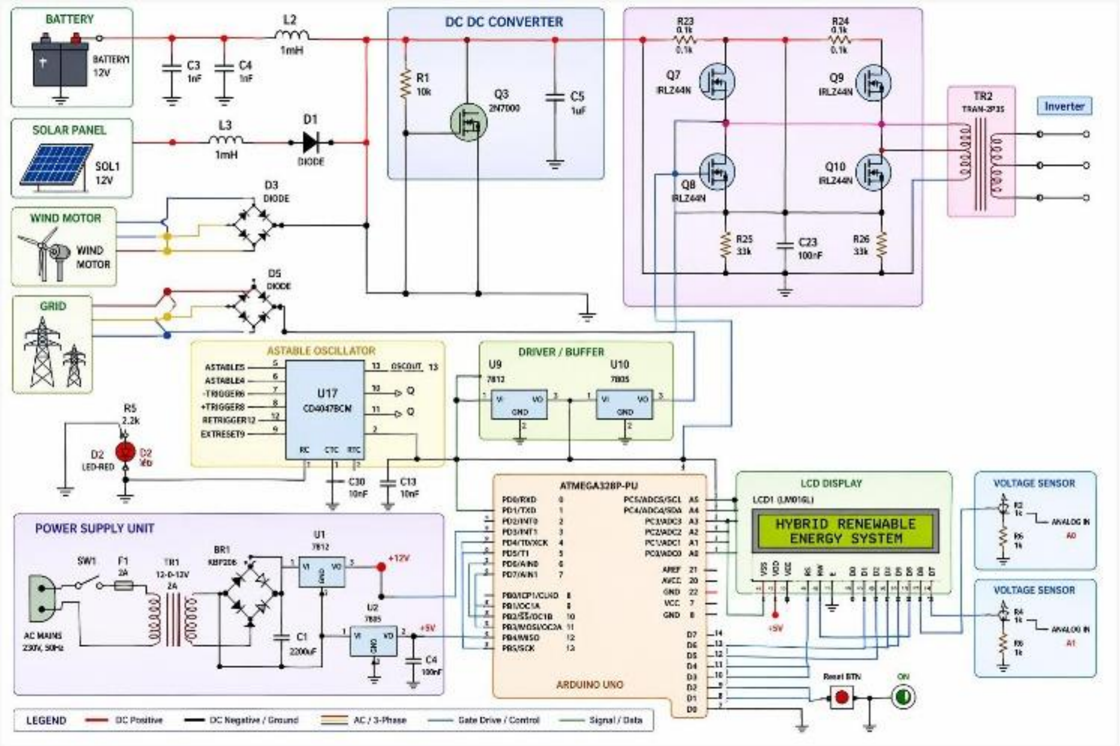


Grid Voltage:

- The three sinusoidal waveforms correspond to the three-phase grid voltages (V_a, V_b, V_c).
- The voltages are balanced and phase-shifted by 120° from each other, indicating proper three-phase operation.
- The amplitude is around 325-350 V peak, typical for a 230-400 V AC grid.
- These waveforms confirm that the grid voltage is stable and sinusoidal, serving as a reference for inverter synchronization.

Functional Block Diagram:

Inverter Voltage:

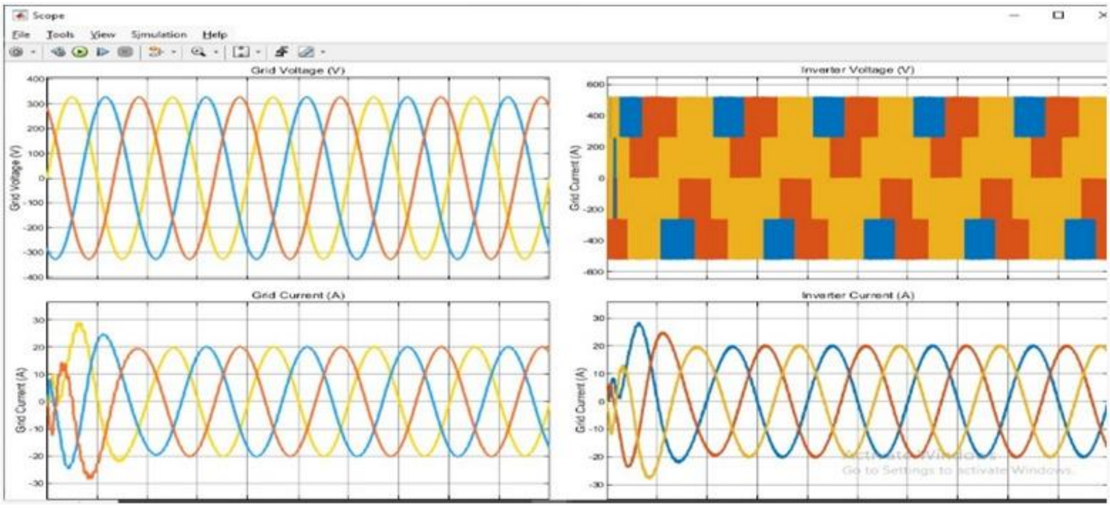


- The waveforms show the three-phase inverter output voltage.
- The blocky, stepped waveform pattern indicates pulse-width modulation (PWM) switching used in the inverter.
- The switching produces high-frequency components, which are later filtered by the LCL filter before current injection into the grid.
- The amplitude is higher than the grid voltage, consistent with the need to inject current into the grid with appropriate voltage margin.

Grid Current:

- The three-phase currents injected into the grid show near-sinusoidal waveforms with amplitudes around ±30 A.
- Minor ripples may appear due to inverter switching harmonics, but the LCL filter effectively smooths these to reduce distortion.
- The currents are in phase with the grid voltages, indicating predominantly active power injection.
- Inverter Current
- The inverter output currents are smooth and sinusoidal, closely matching the reference currents from the controller.
- The currents confirm proper operation of the dq-axis current control and synchronization with the grid via the PLL.
- Balanced three-phase currents indicate no significant unbalance or harmonic distortion.

Result and Discussion:



The simulation results clearly demonstrate the effective operation of the three-phase grid-connected inverter system under steady-state conditions. The grid voltage waveforms are perfectly balanced and sinusoidal with a 120° phase shift between each phase, indicating a healthy and stable grid connection. This confirms that the phase-locked loop (PLL) and synchronization control are working correctly.

The inverter output voltage shows a stepped multilevel waveform, which is a typical characteristic of a PWM-based inverter. Although the waveform is not purely sinusoidal, it is designed so that, after passing through the output filter, the fundamental component matches the grid voltage. This switching pattern confirms proper modulation and switching of the inverter switches.

The simulation results demonstrate the steady-state performance of the three-phase grid-connected inverter system. The grid voltage waveforms (top-left) show three balanced sinusoidal phase voltages with a 120° phase displacement, confirming proper grid synchronization. The inverter output voltage (top-right) exhibits a stepped multilevel waveform, indicating the switching action of the power electronic inverter and successful generation of an AC voltage from the DC source. The grid current waveforms (bottom-left) are nearly sinusoidal and remain in phase with the corresponding grid voltages, which indicates unity power factor operation and effective current control. Similarly, the inverter currents (bottom-right) follow smooth sinusoidal patterns, showing that the output filter and control strategy effectively reduce harmonic distortion. Overall, the results confirm stable operation, good power quality, and efficient power injection from the inverter into the grid.

The grid current waveforms are smooth, sinusoidal, and in phase with the grid voltages, indicating that the inverter is injecting active power into the grid with a near-unity power factor. The absence of significant phase shift between voltage and current also confirms minimal reactive power exchange. The small transient oscillations at the beginning of the waveform show the system settling into steady state.

The inverter currents closely track the reference signals and exhibit low ripple, demonstrating the effectiveness of the current control strategy and filter design. Overall, the results validate that the control scheme ensures stable synchronization, low harmonic distortion, efficient power transfer, and compliance with grid standards, making the proposed system suitable for renewable energy grid integration.

Conclusion:

The integration of renewable distributed generation (DG) units such as solar PV and wind turbines into microgrids has introduced a paradigm shift in modern power systems. These microgrids offer localized power generation, improved reliability, and the flexibility to operate in both grid-connected and islanded modes. However, the increasing penetration of inverter-based renewable sources presents several dynamic challenges, including voltage instability, frequency fluctuations, reduced inertia, and complex interactions between multiple inverter units. Grid following inverters, which form the backbone of most renewable DG integration strategies, rely on existing grid voltage and frequency for synchronization, making the dynamic behavior of these inverters critical for the stable operation of microgrids.

Traditional modeling approaches that simulate each inverter individually are computationally intensive, particularly in large-scale microgrids with numerous distributed units. To address this, the weighted dynamic aggregation modeling approach has emerged as an effective and scalable solution. By combining the dynamic behaviors of multiple inverters into a single aggregated model with appropriate weighting factors, this method significantly reduces computational effort while preserving the accuracy required for stability, control, and performance analysis. The weighting factors are typically assigned based on inverter ratings, participation in the system, or operational relevance, ensuring that the aggregated model accurately reflects the collective behavior of all connected inverters.

Weighted dynamic aggregation facilitates the analysis of key microgrid dynamics, including active and reactive power sharing, voltage regulation, frequency response, and overall system stability under various operational conditions. This method allows researchers and engineers to simulate realistic scenarios such as fluctuating renewable generation, sudden load changes, faults, and islanding events without the need to model every individual inverter. Moreover, it provides a robust platform for designing control strategies, such as droop control, secondary voltage and frequency regulation, and energy management in microgrids with high renewable penetration.

Simulink, integrated with MATLAB, serves as a powerful tool for implementing weighted dynamic aggregation models. By modeling individual inverter dynamics, assigning weights, and combining them into an aggregated equivalent system, engineers can conduct efficient simulations of microgrid behavior. These simulations enable the assessment of microgrid performance, optimization of inverter parameters, and testing of control strategies in a cost-effective and safe virtual environment before physical deployment. The approach also supports real-time simulation and hardware-in-the-loop testing, bridging the gap between theoretical analysis and practical implementation. In conclusion, weighted dynamic aggregation modeling of grid-following inverters is an indispensable technique for the study and operation of renewable DG-integrated microgrids. It strikes a balance between modeling accuracy and computational efficiency, allowing for detailed analysis of system dynamics while simplifying the complexity inherent in multiinverter systems. This modeling strategy not only enhances the understanding of microgrid behavior but also aids in the design, control, and operational planning of resilient, efficient, and sustainable renewable energy systems. As renewable penetration continues to increase globally, such aggregation methods will play a critical role in ensuring the stability, reliability, and scalability of future decentralized power networks.

The increasing penetration of renewable energy sources and the growing complexity of microgrids present significant opportunities for further research and development in the area of weighted dynamic aggregation modeling of grid-following inverters. While current modeling approaches provide accurate and computationally efficient solutions for analyzing system dynamics, there remain several avenues for enhancement, optimization, and practical implementation. One promising direction is the extension of aggregation modeling to hybrid microgrids that combine multiple types of renewable sources, energy storage systems, and conventional generation. Future models could incorporate dynamic interactions between diverse inverter types, energy storage control strategies, and variable renewable generation, allowing for a more holistic and realistic representation of modern microgrids.

This will improve the accuracy of stability studies, power-sharing analysis, and contingency planning in systems with high renewable penetration. Another area of future research is the integration of advanced control and optimization techniques into aggregated inverter models. Techniques such as model predictive control, adaptive droop control, and AI-based energy management algorithms could be embedded within the aggregation framework to enhance voltage and frequency regulation, power quality, and resilience against disturbances. These advanced methods would allow microgrids to operate more autonomously and efficiently, even in the presence of highly variable renewable energy inputs and changing load conditions.

The application of real-time simulation and hardware-in-the-loop (HIL) testing also holds significant potential. By implementing aggregated inverter models in real-time simulators, engineers can test control strategies, fault responses, and system interactions before deploying them in physical microgrids. This approach reduces operational risks, improves reliability, and accelerates the development of robust microgrid systems.

Future Work:

Although the proposed grid-connected inverter system shows stable operation and good power quality under steady-state conditions, several improvements and extensions can be considered for future research. Advanced control strategies such as Model Predictive Control (MPC), Adaptive Control, or Artificial Intelligence (AI)-based controllers can be implemented to further reduce current harmonics and improve dynamic response during grid disturbances.

The system can be extended to operate under weak grid conditions by incorporating virtual inertia, droop control, or grid-forming control techniques. This will allow the inverter to support grid frequency and voltage regulation, especially in microgrid applications with high renewable penetration.

Future work may also include hardware implementation and real-time testing using DSP or FPGA platforms to validate the simulation results under practical operating conditions. Thermal analysis and reliability studies of power electronic switches can be performed to enhance system lifetime.

In addition, the integration of energy storage systems such as batteries or supercapacitors can be explored to smooth power fluctuations and improve system stability. Finally, harmonic analysis and compliance with grid standards such as IEEE 1547 and IEC 61727 can be investigated to ensure real-world applicability.

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The preferred spelling of the word “acknowledgment” in America is without an “e” after the “g”. Avoid the stilted expression “one of us (R. B. G.) thanks ...”. Instead, try “R. B. G. thanks...”.Put sponsor acknowledgments in the unnumbered footnote on the first page.

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