

Holistic integration of wave energy into maritime hybrid microgrids: dynamic stability and power quality enhancement strategies

Rebin Mohammad Amini^{a,*}, Rasool Kazemzadeh^{a,*}, Javad Morsali^b

^a Power Engineering Department, Electrical Engineering Faculty, Sahand University of Technology, Iran

^b Electrical Engineering Department, Engineering Faculty of Khoy, Urmia University of Technology, Iran

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ABSTRACT

This paper presents a detailed dynamic-stability analysis of a novel configuration maritime hybrid microgrid (MG) that integrates an Archimedes wave swing (AWS)-based wave power generation system (WPGS), photovoltaic (PV) technology, a solid-oxide fuel cell (SOFC), a synchronous generator (SG), and a dedicated battery energy storage system (BESS). To address the significant fluctuations of ocean wave conditions and evaluate their effect on the performance of the MG, a high-fidelity nonlinear model of the complete generation system has been developed. Dynamic stability analysis is used to find the dominant oscillatory modes of the system. Then, root loci analysis is utilized to evaluate the sensitivities of these modes and stability margins to wave excitation amplitudes, solar insolation levels, and operating conditions of the SOFC. The feedforward decoupling controllers have been designed for power electronic interfaces to enable seamless integration of distributed energy resources (DER) into the MG. The overall power fluctuations and dynamic stability of the MG have been improved by the novel integration of WPGS with BESS and the design of a dedicated controller for the BESS bidirectional converter. Comprehensive time-domain simulations under various operating conditions confirm that the proposed control scheme can suppress peak-to-peak (P2P) power fluctuations by 41%, restore the DC-link voltage to its required setpoint, and reduce total harmonic distortion (THD) below 5%. Frequency-domain analysis of the PV controllers confirms phase margins of 45° at $\approx 1 \times 10^4$ rad/s and 58.75° at $\approx 3 \times 10^3$ rad/s, verifying inherent stability. Furthermore, the control scheme demonstrates robust performance under sensor noise, battery degradation, and temperature variations, and its computational burden scales linearly ($O(n)$) with the number of active controllers, ensuring practical deployability. In comparison to baseline solutions without direct BESS control, this in turn results in a higher level of damping and increased power quality, and enhanced overall system reliability through multifaceted stabilization mechanisms. These results validate the feasibility of high-penetration WPGS integration in MG and provide a practically oriented control solution for secure operation under variable marine and solar conditions.

Introduction

Global energy production and management are undergoing a structural change, primarily due to the pressing need to address climate change and ensure a secure energy supply, as well as reducing economic volatility caused by fossil fuels [1]. This change is affecting power systems, as distributed energy resources (DERs) are increasingly being installed in the microgrid (MG) at the distribution level [2]. Since the output power of DERs is inherently stochastic in nature, the integration of these resources comes with serious concerns over grid intermittency, stability issues, power quality, and operational reliability [3].

Ensuring this reliability requires a control framework that not only manages power flow but also guarantees stability and power quality under realistic conditions such as component aging, sensor noise, and computational constraints.

MGs have become an attractive option as a managed framework for the integration of diverse DERs; they help improve disturbance resilience and support the development of more decentralized and sustainable energy systems [4,5]. The configuration of the hybrid MG is established by combining hybrid power generation systems (HPGSs) with conventional energy sources. Furthermore, incorporating energy storage systems (ESS) into the hybrid MG helps balance the power supplied to consumers and improves overall system stability [6–8].

* Corresponding author.

E-mail addresses: r.amini97@sut.ac.ir (R.M. Amini), r.kazemzadeh@sut.ac.ir (R. Kazemzadeh), j.morsali@uut.ac.ir (J. Morsali).

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Nomenclature	
i_{aw}, i_{bw}, i_{cw}	Phase currents of the LPMSG
$e_{a,b,c}$	Values of induced electromotive force in the phase winding due to the translator motion
$v_{aw,bw,cw}$	The generator terminal phase voltage for each phase
$Z, v_w(t)$	Displacement and vertical velocity of the buoy
K_E	Voltage constant
v_{av}	Average buoy speed ($v_{av} = 2v_m/\pi$)
v_m	Vertical speed amplitude
$N_{ph} = N_c \cdot p \cdot q$	Number of turns per coil for each phase
u_m	Maximum vertical speed of the wave
ω_{wr}	Electrical angular speed
C_{DCw}	DC-link capacitor
i_o, i_{sc}	Saturation current and short-circuit current
i_{pd}	Current flowing through the diode
i_{rs}	The diode's reverse saturation current
i_{sh}	Current flowing through the shunt resistor
k_{iph}	A cell's short-circuit current temperature coefficient at 1000 W/m ² and 25 °C
T, T_n	Operating and nominal temperature
G, q	Solar irradiation and electron charge
V_{oc}, n and K	Open circuit voltage, ideality factor of the solar cell and Boltzmann constant
E_{g0}	Semiconductor gap energy
N_s, v_{pv}	Number of series cells and PV cell voltage
C_p	Capacitance of the input filter
L_p, r_{pap}	Inductance and parasitic resistance of the DC/DC boost converter
i_{LP}	Inductor current
i_{pd}	Current supplied to the DC link from the DC/DC boost converter
V_{DCp}	DC-link voltage
D_p	Duty ratio of the boost converter
V_{DCf}	Stack output voltage, which is the thermodynamic potential of the cell
p_i	Partial pressures of hydrogen, oxygen, and water
E_0	Ideal standard potential
E	Open-circuit reversible potential
i_{fc}	Stack output current
U_{fH2}	Hydrogen utilization factor
U_{fo2}	The oxygen utilization factor
R, T	Universal gas constant and absolute temperature
K_i	Valve molar constants for hydrogen, oxygen, and water
K_r	Constant with the value of $N_0/4F$
N_{H2}^{in}	Hydrogen input flow rate (fuel flow rate or $Fuel_{fr}$)
N_{O2}^{in}	Oxygen input flow rate (air flow rate or Air_{fr})
N_0, r	Number of cells in the stack and ohmic loss
i_{fcref}	Reference SOFC current
z	Number of electrons involved in the electrochemical reaction
v_f, i_{fc}	SOFC voltage and SOFC current
V_{DCf}	Polarization voltage of the capacitor C_{DCf}
$x\%, y\%$	Mole fractions of hydrogen and oxygen in their respective input streams
$\tau_{H2}, \tau_{O2},$ and τ_{H2O}	Respective temperature-dependant time constants for hydrogen, oxygen, and water, respectively
i_{fL}	Current of inductor L_f
i_{ft}	Output current of the buck converter
F	Faraday constant, plays a fundamental role in charge transfer
P_{fuel}, P_{air}	Pressures of the fuel and air
δ, ω, ω_0	Load angle, angular speed of the generator, and synchronous speed, respectively
P_m, P_e, D	Mechanical power input to the generator, the electrical power output of the generator, and the damping coefficient, respectively
H	Inertia constant of the generator
T_{do}, E_q, E_{fd}	D-axis transient time constant in the generator's dynamic model, the q-axis transient voltage component, and the field excitation voltage, respectively
x_d, x_d', i_d	Synchronous reactance, the transient reactance in the d-axis of the generator, the current in the d-axis, respectively
T_a	Time constant of the excitation system
k_{avr}, v_{tref}, v_t	Gain of the AVR amplifier, the reference terminal voltage, and the generator terminal voltage, respectively
i_b, R_b	Denotes the BESS current, ohmic internal resistance
E_{bat}, E_0	Nonlinear and constant voltage of the BESS
$Exp(s)$	Exponential zone dynamics
$Sel(s)$	BESS mode ($Sel(s) = 0$ during BESS discharge, $Sel(s) = 1$ during BESS charging)
Q, A	Maximum BESS capacity, exponential voltage
B, i	Exponential capacity and BESS current
i^*	Low-frequency current dynamics
it, v_b	Extracted capacity and BESS voltage
i_b	Denotes BESS current
V_{DCp}	Polarization voltage of the capacitor C_{DCb}
i_{bL}	Current of inductor L_b
i_{bt}	Output current of the bidirectional converter
i_{dpt}, i_{qpi}	Output currents of the VSI
i_{dpt1}, i_{qpt1}	Output currents of the filter
V_{dcp}, V_{qcp}	Voltages of point A (Fig. 2)
i_{dg}, i_{qg}	Currents of the connection line
V_{dPCC}, V_{qPCC}	Voltage of the point of common coupling (PCC)
V_{dg}, V_{qg}	Voltage of power grid
ω	Electrical angular frequency (in rad/s)

HPGSs, including photovoltaic (PV) [9–11], wave power generation system (WPGS) [12–14], and fuel cells (FCs) [15–17], have been widely studied. Recent studies have focused on the dynamic modeling and control of both grid-feeding and grid-forming systems, including the battery energy storage system (BESS) for ancillary services and power balance [18–20]. Furthermore, recent works have optimized BESS dispatch to reduce power exchange with the main grid [21] and have proposed energy management systems (EMS) that account for BESS degradation and real-time electricity prices [22]. While wave energy has a high power density and good predictability, as well, when compared to solar and wind, and is therefore a promising resource for decreasing the dependence on large-scale storage technologies for long-term balancing

[23]; despite these advantages, ocean wave energy has not yet been widely deployed in grid-connected hybrid MG.

Among wave energy conversion (WEC) technologies, the Archimedes wave swing (AWS) device is particularly attractive due to its high power extraction efficiency, its submergence that limits both visual and environmental impacts, and its direct-drive generator configuration [24,25]. Foundational research has produced detailed models for standalone AWS-based WPGS [26–28] and has begun to study their integration into basic hybrid configurations (e.g., PV–wave systems) [29,30];

A critical synthesis of the existing literature reveals that while foundational models and preliminary integration studies exist, they often operate in methodological or configurational silos. Research on

Table 1

Comparative analysis of research gaps and novel contributions.

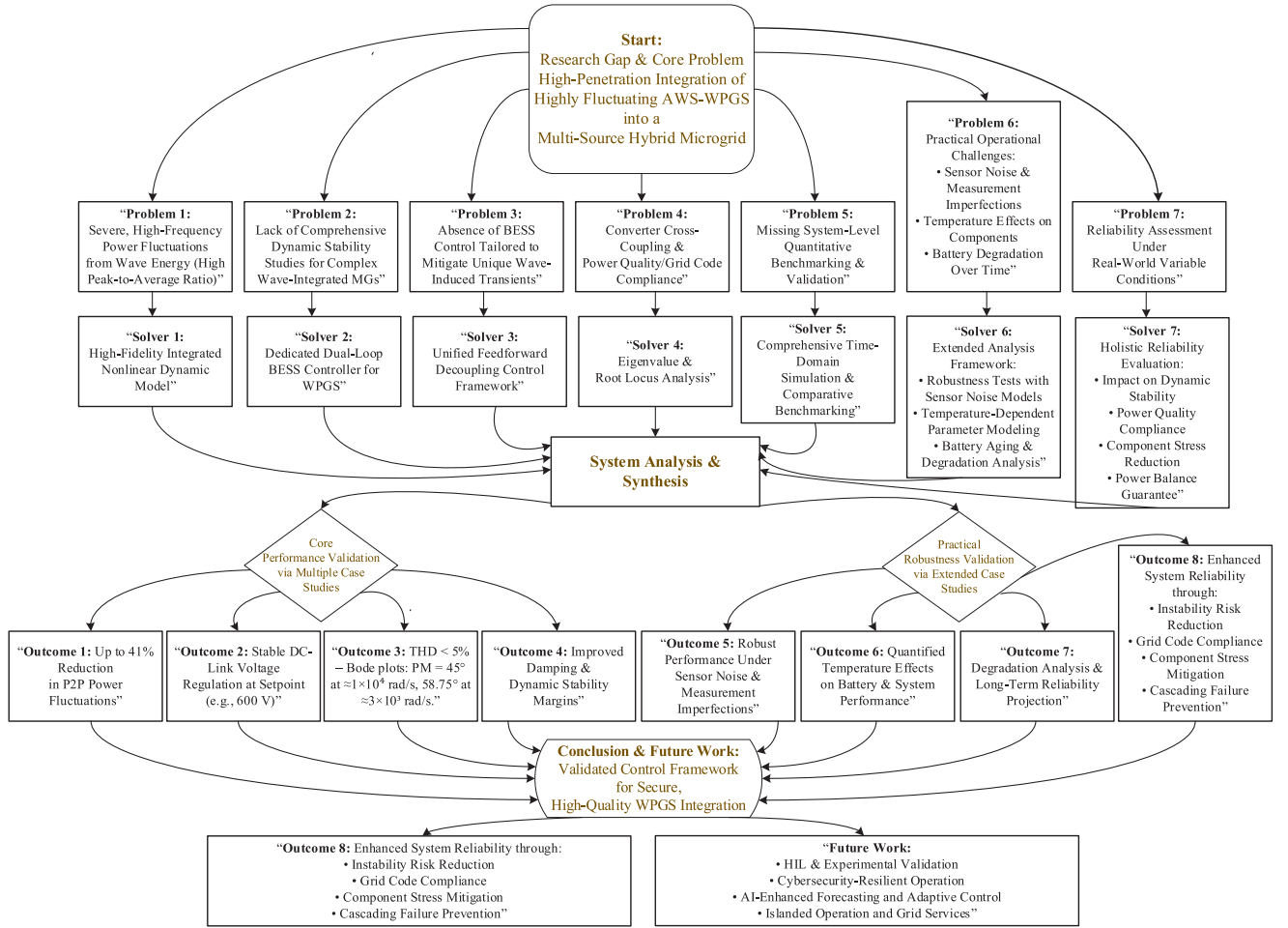
Evaluation aspect	Prior works (Literature)	Novel contributions of the present study
Integration of AWS-WPGS	Studies are limited to standalone AWS-based WPGS models [24–28,31,32,34,35,37,40–43] or basic hybrid configurations like simple solar-wave or wind-wave systems [29,30,38]. A comprehensive dynamic stability analysis of AWS-WPGS deeply integrated into a multi-DER grid-connected MG is absent.	This study presents the first comprehensive eigenvalue and root loci analysis of a grid-connected hybrid MG that incorporates an AWS-based WPGS, PV, SOFC, SG, and BESS. The analysis quantifies dynamic interactions between the WPGS and both conventional and DERs.
Control strategy for WPGS-BESS coordination	BESS control strategies are predominantly designed for smoothing PV [44] or wind power fluctuations. Dedicated control schemes for mitigating the unique high-fluctuation, high peak-to-average power ratio profile of wave energy are absent in the context of a complex hybrid MG [36].	A dual-loop BESS controller is proposed, featuring an outer voltage control loop (for DC-link regulation) and an inner current control loop, specifically tailored for the WPGS. Enables adaptive charging/discharging to mitigate wave-power transients.
Unified feedforward decoupling control	Decoupling control is commonly applied to wind or PV inverters [45–47]. A unified framework for its application across WPGS rectifiers and multiple DER's voltage source inverters (VSIs) in a wave-integrated hybrid MG has not been implemented.	A generalized feedforward decoupling control framework is developed and applied to the WPGS rectifier and all VSIs (for PV, SOFC). Effectively eliminates dq-axis cross-coupling in all power converters.
Stability under multi-source variability	Existing studies often evaluate system performance under variations of a single renewable source (e.g., solar-only [48,49] or FC-only [33]. The compound effect of simultaneous wave, solar, and fuel cell transients remains largely unexplored.	A holistic stability validation is conducted under concurrent and independent variations, including wave steps, solar ramps with noise, and SOFC current steps. Damping improvements are confirmed through eigenvalue analysis.
BESS role in wave-integrated hybrid MGs	The existing literature primarily focuses on BESS applications in solar- and wind-based MGs, with limited attention paid to wave energy integration [44,50] and to power management in generic MG configurations [21,51,52]. Although some studies have explored BESS in hybrid PV-wave systems for specific applications, such as island electrification [30], and hybrid SMES-battery systems for conditioning wave-energy-converter outputs [36], these efforts are confined to particular configurations. They fail to provide a comprehensive analysis of BESS responses to the high-frequency, rapid transients, and unique high-	A dual BESS deployment strategy with mode-specific controllers is implemented for both the PV and WPGS units. First study to implement a dedicated BESS with dual-loop control specifically designed for wave energy's unique high-fluctuation profile in a hybrid MG context. The WPGS-dedicated BESS employs a dual-loop controller (outer voltage control +

Table 1 (continued)

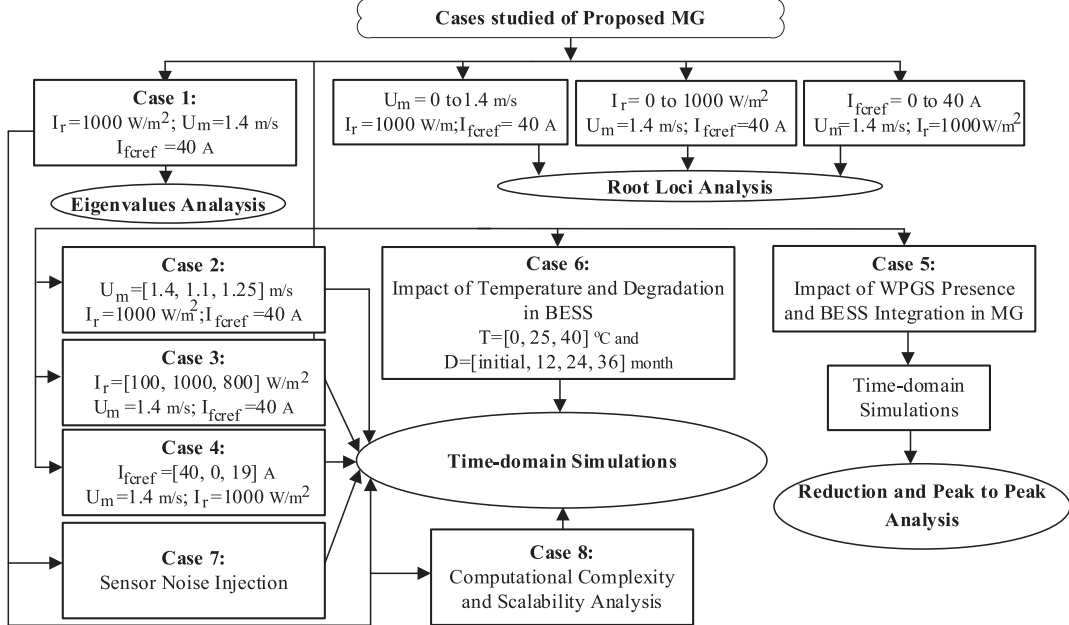
Evaluation aspect	Prior works (Literature)	Novel contributions of the present study
	amplitude power fluctuations inherent to wave energy within multi-DER, grid-connected MGs. Consequently, prior work lacks tailored BESS control mechanisms to mitigate the specific challenges posed by wave-induced power fluctuations in hybrid MGs.	inner current control) that actively mitigates wave-power fluctuations and maintains DC-link voltage stability under highly variable ocean conditions. Quantitative results demonstrate 41% Reduction in P2P power fluctuations and improved damping performance under wave transients, addressing a critical research gap identified in wave-energy integration literature.
Comparative analysis & benchmarking	A significant literature gap exists in providing comparative results against baseline scenarios to quantitatively demonstrate claimed benefits [28,29].	Explicit comparative benchmarking is provided through root loci analysis and time-domain simulations, quantifying the superiority of the proposed system in enhancing damping and reducing power fluctuations.
Power balance & practical relevance	Many studies lack a clear formulation of DC-link power balance constraints and a discussion of power mismatch management during transients, often relying solely on unvalidated simulations.	The proposed control strategy is explicitly designed to maintain DC-link voltage stability, ensuring instantaneous power balance through active BESS management in response to generation changes from WPGS and PV.

AWS-WPGS has predominantly advanced its standalone modeling and control [25–27,31], whereas studies on hybrid microgrids have frequently centered on more established renewables like PV and wind, incorporating BESS for smoothing their characteristic fluctuations [32,33]. This parallel progression has left a discernible disjunction: the deeply integrated dynamics of a high-fidelity wave generator within a complex, multi-source, grid-connected MG—a scenario approaching practical deployment—have not been subjected to a rigorous system-level stability interrogation. Consequently, the translation of component-level advancements into a validated, coordinated control framework capable of ensuring reliable operation under the compound variability of marine and solar resources remains an unmet requirement in the field. Furthermore, there is a lack of analysis on the computational scalability of such integrated control systems and their long-term reliability under practical imperfections like sensor noise and BESS aging. This disconnect between component innovation and system-level integration analysis forms the core motivation for the present investigation.

Nevertheless, important research gaps remain. These gaps are multifold. First, a comprehensive dynamic stability study of grid-connected MGs comprising an AWS-based WPGS, a SG, PV technology, solid-oxide fuel cell (SOFC), and specific BESS is not well covered by the literature. The unique dynamics of electro-mechanical systems and stability issues posed by waves, unlike solar and wind integration, include challenges stemming from the oscillatory character and high power peak-to-average ratios characteristic of wave energy [34,35].



a) Problem-solution flowchart for stability analysis and control design



b) Case studies structure flowchart for comprehensive system validation

Fig. 1. Research framework flowcharts.

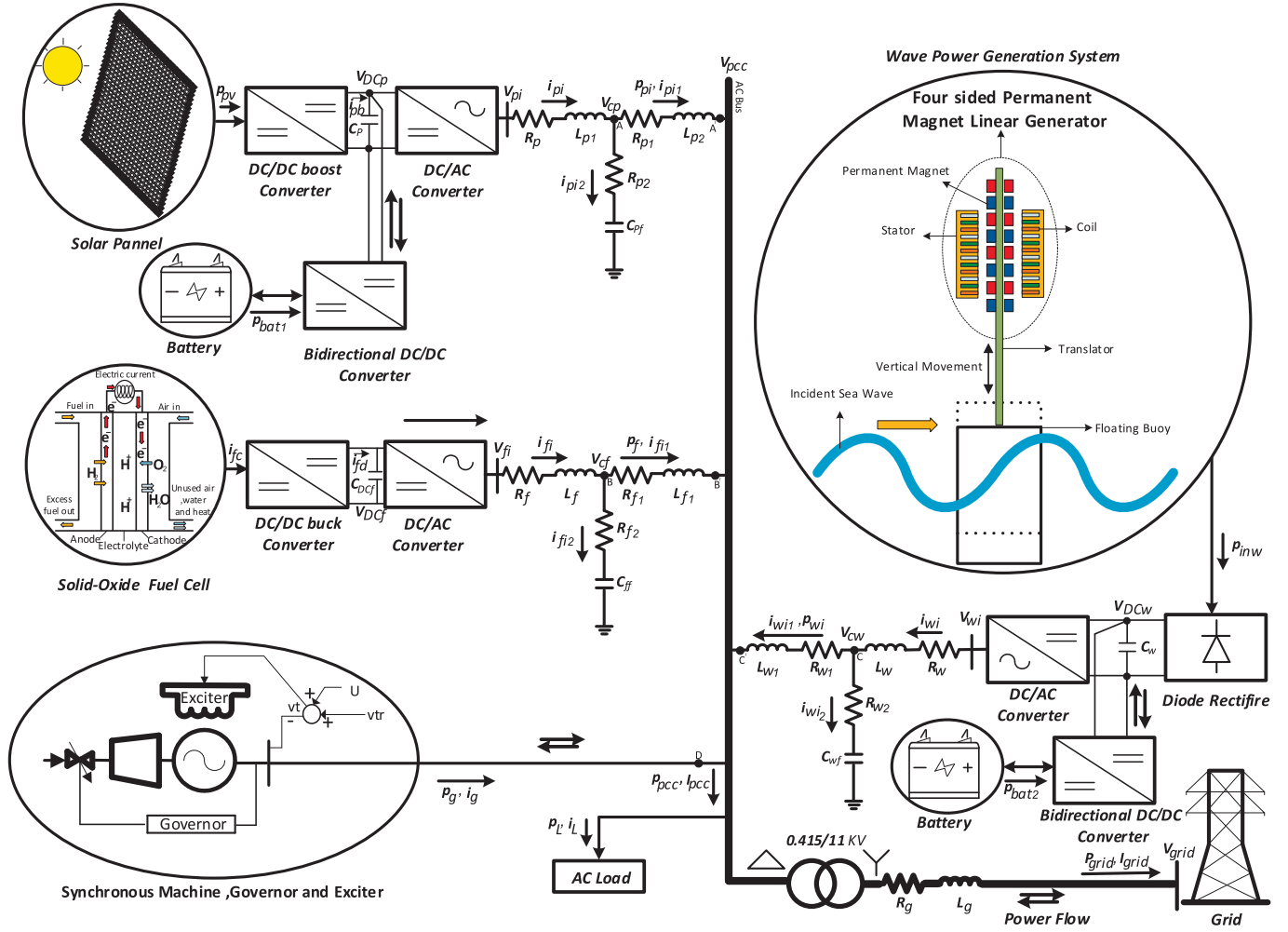


Fig. 2. Configuration of the studied MG integrated into a distribution network.

Second, although there have been many attempts on optimal unified control strategies for BESS across a wide variety of scenarios [36,37], it remains unclear how these strategies should be configured to mitigate the unique power fluctuations caused by AWS. Third, MG-level quantitative investigations that clearly shows those improvements in dynamic performance and power quality due to these integrated complex systems (compared to its counterpart without WPGs and their associated BESS control systems) remain insufficient [38]. Additionally, validation is often limited to simulations without direct verification of compliance with actual grid codes. For example, in [39], the performance requirements for harmonic distortion as defined by IEEE Std 519 were not evaluated. Crucially, assessments of the control system's practical feasibility, such as its computational burden and its robustness to real-world non-idealities, are consistently absent.

Table 1 presents a systematic comparison of limitations in the existing literature alongside novel findings from this study. It provides six critical reviewing components in relation to the dynamic stability and control of WPGS-integrated hybrid MGs. The table compares with the state-of-the-art, extracted from past works, for each aspect along with the novel methods and analyses proposed in this work. These comparative approaches demonstrate how this study integrates into the broader literature stream, which helps to highlight emphasize the first several key contributions in the areas of advanced modeling, development of control strategies, dynamic stability analysis, and stability assessment in the presence of multiple sources, along with detailed quantitative benchmarking. To address the remaining research gaps identified, this paper offers a systematic and comprehensive

investigation of dynamic stability issues in a grid-connected hybrid MG along with AWS-based WPGs, PV array, SOFC, and conventional SG operating together with an integrated BESS.

The main novelties and contributions presented in this paper are as follows:

1. **Design of a High-fidelity Integrated Model:** For the first time, a complete nonlinear dynamic model of the hybrid MG is developed where the electromechanical interactions of the AWS-based linear generator, power electronic interfaces, BESS, and other DERs are among the most critical dynamics.
2. **Design of a Coordinated Control Scheme:** A dedicated control strategy utilizing bidirectional converters is proposed for the BESS. The controller mitigates the high variability in the power output of the WPGs, regulates the DC-link voltage, and reduces fluctuations in the power transferred to the main grid.
3. **Detailed Dynamic Stability Analysis:** Eigenvalue and root loci analysis are used to determine significant system oscillatory modes and study how their damping rates change with wave input, solar irradiance levels, and the SOFC operating point.
4. **Comprehensive Performance Validation:** Numerous simulations have been performed in the time-domain, as well as under various scenarios, confirming that the proposed system enhances overall stability and improves power quality. The results show that the power fluctuations are significantly reduced and THD is always kept below 5%, which means that the output has met the standard of IEEE Std 519. This validation is extended to include robustness tests under

sensor noise, battery degradation, and temperature variations (Cases 6 & 7). Frequency-domain analysis of the PV system controllers further confirms their inherent stability, with phase margins of 45° at $\approx 1 \times 10^4$ rad/s and 58.75° at $\approx 3 \times 10^3$ rad/s.

5. **Quantitative Benchmarking:** Comparative studies are presented to demonstrate the effectiveness of the proposed BESS control in minimizing P2P power fluctuations at several WPGS operating points, and to show its superiority over the scenario where no BESS is present in the WPGS. Furthermore, the computational scalability of the control hierarchy is rigorously evaluated, demonstrating linear O(n) complexity with the number of active controllers (Case 8), which is critical for practical deployment.
6. **Explicit Reliability Enhancement Analysis:** A dedicated discussion (Section IV.H) synthesizes the results to demonstrate how the proposed scheme enhances system reliability through improved dynamic damping, guaranteed power quality, fluctuation mitigation, and robust power balance, addressing a key gap in existing studies.

The enumerated contributions are designed as a cohesive and direct response to the identified research gaps. The integrated high-fidelity model (Contribution 1) provides the necessary analytical foundation to address the lack of comprehensive dynamic stability studies in complex, wave-integrated MGs. Building upon this model, the dedicated WPGS-BESS control strategy (Contribution 2) and the unified decoupling framework (implicit in Contribution 2 & 3) are conceived specifically to mitigate wave-induced fluctuations and converter interactions, filling the gap for tailored control solutions. The in-depth eigenvalue analysis and root loci techniques (Contribution 3) offer the methodological tool to quantitatively probe stability under multi-source variability, while the extensive time-domain simulations and explicit benchmarking (Contributions 4 & 5) are deployed to furnish the missing system-level, comparative performance validation against realistic grid-code standards. The added analyses on computational scalability and explicit reliability impact (Contributions 5 & 6) directly address the gaps concerning practical feasibility and holistic reliability assessment. Thus, each proposed novelty is architected not in isolation, but as an integral component of a holistic framework aimed at bridging the specific knowledge gaps that currently impede the reliable integration of AWS-based wave power into modern hybrid microgrids.

The remainder of this paper is organized as follows. Section II details the configuration and mathematical modeling of all studied system components. Section III describes the proposed control strategies. Section IV presents and discusses the dynamic stability analysis and time-domain simulation results. Section V concludes the paper and outlines directions for future work.

Fig. 1 provides a unified visual summary of the research methodology employed in this study. Part (a) presents a comprehensive problem–solution–outcome flowchart that structures the entire investigation. It begins by mapping the core research challenge—integrating a high-variability AWS-based WPGS into a hybrid MG—onto seven specific technical gaps (P1–P7). These gaps are systematically addressed through a corresponding set of tailored solutions (S1–S7), including the development of a high-fidelity model, the design of dedicated control strategies (e.g., a dual-loop BESS controller and unified feedforward decoupling), and advanced stability analyses. The flowchart culminates in the validated outcomes (O1–O8), demonstrating enhanced dynamic stability, power quality, and system reliability. To empirically validate this framework, part (b) details the architecture of the case studies through a dedicated flowchart.

It outlines the seven structured simulation scenarios (Cases 1–7), designed to progress from steady-state analysis to tests under independent resource variations (wave, solar, fuel cell), comparative BESS performance assessment, and finally, robustness evaluations concerning battery degradation, temperature effects, and sensor noise. Collectively, these two flowcharts illustrate the holistic and systematic approach adopted to bridge theoretical control design with practical performance

validation for secure wave energy integration.

MG configuration and mathematical models

Configuration of the proposed MG

Fig. 2 shows the configuration of the proposed MG connected to a distribution power grid. The MG mainly includes an SG with an exciter and governor, PV, SOFC, WPGS, BESS, and alternating current (AC) load. The SG, WPGS, PV, and SOFC are the power sources of the MG. The WPGS is integrated to the grid through an AC/DC rectifier, a common DC-link, a VSI, and an inductor-capacitor-inductor passive filter known as LCL, respectively. The LCL filter reduces harmonics and improves the output signal quality of grid-connected inverters by filtering out high-frequency components and noise. The WPGS comprises a linear permanent magnet synchronous generator (LPMSG) powered by AWS.

The comprehensive design details and operational principles of the AWS-based WPGS have been elucidated in [26,27,38,42]. It is assumed that the WPGS produces only active power. The PV is connected to the grid through a DC-DC boost converter, a common DC-link, a VSI, and an LCL filter.

The boost converter of the PV system has an MPPT function to extract maximum power. The PV is tasked solely with supplying active power support. The SOFC is integrated into the grid through a DC-DC buck converter, VSI, and LCL filter. Similarly, the SOFC also generates only active power. The SG is directly connected to the grid. Due to the intermittent nature of DERs, Energy Storage Device (ESD) is generally needed in HPGS to ensure power backup and to facilitate the management and smoothing of power fluctuations [29]. An ESD is needed to reduce these fluctuations in generated power and stabilize the DC-link voltage.

Among the various ESD technologies, BESS is more favorable in renewable energy applications for several reasons. These include high energy density, relatively low capital cost, and engineering feasibility [36,50,53]. Due to the inherent power fluctuations injected into the DC-link by PV and WPGS, the integration of a BESS is imperative to ensure stable and continuous power delivery.

Furthermore, given that the wave power output is characterized by a high peak-to-average power ratio, the selected BESS must exhibit a long operational lifespan, significant cycle life, high round-trip efficiency, and low maintenance requirements; rapid response capabilities during both charging and discharging operations are also critical to effectively compensate for the transient power imbalances introduced by the WPGS. Consequently, in this work, each system (PV and WPGS) is integrated with a dedicated BESS, interfaced through a bidirectional DC-DC converter. The following section provides a detailed description of the mathematical models utilized for each subsystem, as depicted in Fig. 2. It then elaborates on the control scheme employed for the proposed MG.

Mathematical model of studied MG

The comprehensive mathematical model of all equipment, as shown in Fig. 2, is presented in the following subsequent sections.

Model of WPGS

To model the incident ocean wave and the response behavior of the LPMSG, a set of differential equations has been presented. Furthermore, the incoming ocean wave is assumed to follow a sinusoidal pattern. The configuration of the LPMSG is shown in Fig. 2. It contains four flat primary elements and four secondary elements compassed within one housing. The primary elements, corresponding to the stator windings depicted in Fig. 2, remain stationary and are named stators, while the secondary elements, referred to as translators in Fig. 2, move with the buoy and are called translators. The translator constitutes a non-stationary component within a generator. An equivalent circuit

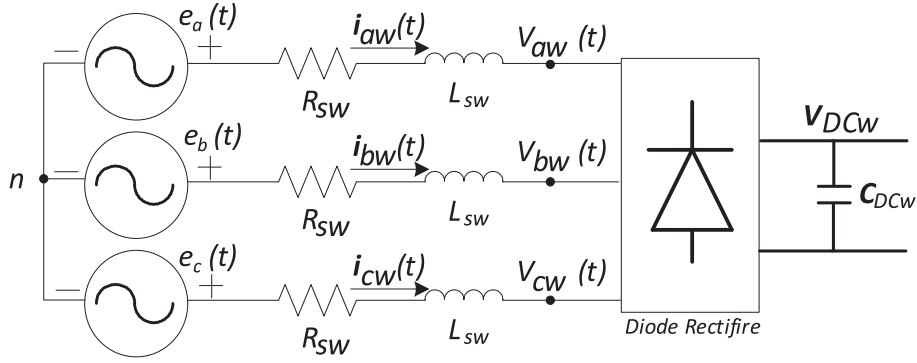


Fig. 3. Equivalent circuit diagram of a three-phase winding of an LPMSG connected to a rectifier.

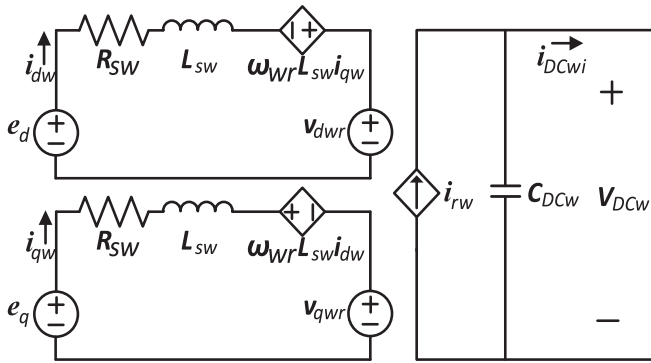


Fig. 4. Dynamic average-value model of WPGS and active rectifier [45,54].

diagram of a three-phase winding of an LPMSG is shown in Fig. 3 [54].

The differential equations of the three-phase circuit model of the LPMSG are [54]:

$$L_{sw} \frac{di_{aw}}{dt} = e_a - v_{aw} - i_{aw} R_{sw}$$

$$L_{sw} \frac{di_{bw}}{dt} = e_b - v_{bw} - i_{bw} R_{sw}$$

$$L_{sw} \frac{di_{cw}}{dt} = e_c - v_{cw} - i_{cw} R_{sw}$$

Where,

$$e_a = K_E \cos(z_w \pi / \tau) v_w(t) \quad (4)$$

$$e_b = K_E \cos(z_w \pi / \tau - 2\pi/3) v_w(t) \quad (5)$$

$$e_c = K_E \cos(z_w \pi / \tau - 4\pi/3) v_w(t) \quad (6)$$

$$v_j = i_j R_L \quad j = aw, bw, cw \quad (7)$$

$$v_{av} = 2u_m / \pi \quad (8)$$

$$K_E = M_s \cdot W_s \cdot N_{ph} \cdot \phi \cdot v_{av} \quad (9)$$

It should be noted that in this model, the buoy position tracks the wave ocean elevation, precisely:

$$\frac{dz}{dt} = v_w \quad (10)$$

The function $v_w(t)$ will coincide with the wave elevation equation defining ocean wave elevation ($v_w(t) = u_w(t)$) as a function of time $u_w(t)$ and also is presented as [54]:

$$u_w(t) = u_m \sin(2\pi t / T) \quad (11)$$

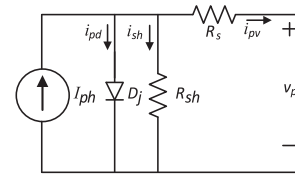


Fig. 5. Single-diode equivalent circuit model of a PV cell.

The power balance of the DC-link is ensured at each moment by matching the power provided from both WPGS and BESS with the power drawn by the inverter (P_{inv}):

$$P_{inv} + P_{bat} = P_{inv} + C_w V_{DCw} \frac{dV_{DCw}}{dt} \quad (12)$$

Where in this framework, the power losses (P_{loss}) are assumed to be zero in the ideal lossless case, besides, BESS power is treated as positive when the BESS discharges to the DC-link and negative when it is charging.

According to the dynamic average-value model shown in Fig. 3, the differential equations for the WPGS and the active rectifier in the dq reference frame are given in Eqs. (13)–(16) [45,54].

$$L_{sw} \frac{di_{dw}}{dt} = e_d - R_{sw} i_{dw} + \omega_w L_{sw} i_{qw} - v_{dwr} \quad (13)$$

$$L_{sw} \frac{di_{qw}}{dt} = e_q - R_{sw} i_{qw} - \omega_w L_{sw} i_{dw} - v_{qwr} \quad (14)$$

where $[e_d, e_q]$, $[i_{dw}, i_{qw}]$, and $[v_{dwr}, v_{qwr}]$ transformed results of the $e_{a,b,c}$, $i_{aw,bw,cw}$, and $v_{awr,bwr,cwr}$, respectively, into the dq frame. The following equation is applied to the DC side of the WPGS:

$$C_{DCw} \frac{dV_{DCw}}{dt} = i_{rw} - i_{DCwi} \quad (15)$$

The principle of instantaneous power balance ($P_{DCw} = P_{ACw}$) governs the relationship between the AC side and the DC side as follows:

$$i_{rw} = 3(i_{dw} v_{dwr} + i_{qw} v_{qwr}) / (2V_{DCw}) \quad (16)$$

Model of PV

A PV module functions as an instantaneous converter reliant on solar radiation for active power supply, exhibiting nonlinear electrical characteristics under varying solar irradiance levels. In the absence of solar radiation, a cell behaves passively, and this source is distinct from conventional DC power generators; it also does not function as a constant voltage source nor as a constant current source. The output current (power) of a PV array is contingent upon various factors, primarily including solar irradiation, temperature, the size of the panels, the efficiency of PV panels, and other parameters associated with panel

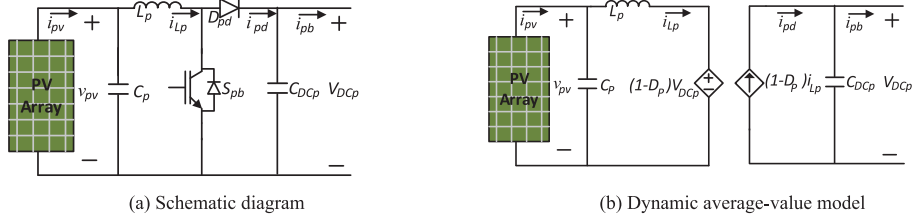


Fig. 6. Schematic diagram and dynamic average-value model of the DC/DC boost converter.

manufacturing, as outlined in [55]. The mathematical model of the PV cell, as depicted in the equivalent circuit model of Fig. 5, contains a current source in parallel (as shown by I_{ph}) and two resistors to describe losses that are shown by R_s and R_{sh} in series and shunt, respectively.

The mathematical equation representing the output current of the PV cell is as follows [55–57]:

$$i_{pv} = I_{ph} - i_{pd} - i_{sh} \quad (17)$$

The mathematical equations of the output current of the PV module are formulated as follows [55–57]:

$$I_{ph} = [i_{sc} + k_{iph}(T - 298)]G/1000 \quad (18)$$

$$i_{pd} = i_0 \left[\exp \left(\frac{q(v_{pv} + R_s i_{pv})}{nKT} \right) - 1 \right] \quad (19)$$

$$i_{rs} = i_{sc} / \left[\left(\exp \left(\frac{qV_{oc}}{nN_sKT} \right) - 1 \right) \right] \quad (20)$$

$$i_{sh} = (v_{pv} + R_s i_{pv}) / R_{sh} \quad (21)$$

$$i_0 = i_{rs} \left(\frac{T}{T_n} \right)^3 \exp \left(\frac{qE_{g0}(1/T_n - 1/T)}{nK} \right) \quad (22)$$

From the mentioned equations, the implicit expression for the output current of the PV cell has been derived as follows [56,57]:

$$i_{pv} = I_{ph} - i_0 \left[\exp \left(\frac{q(v_{pv} + R_s i_{pv})}{nKT} \right) - 1 \right] - i_{sh} \quad (23)$$

The power balance of the DC-link can be formulated as follows:

$$P_{pv} + P_{bat} = P_{inv} + C_p V_{DCp} \frac{dV_{DCp}}{dt} \quad (24)$$

Fig. 6(a) illustrates the schematic representation of the examined DC/DC boost converter for interfacing the PV array with the DC link. In the context of the schematic presented in Fig. 6(a), it is assumed that the switching operations of switch S_{pb} and diode D_{pd} are disregarded, and the DC/DC boost converter is delineated using the dynamic average-value model depicted in Fig. 6(b). As a result, references [58] detail the development of the differential equations used in simulating the behavior of the DC/DC boost converter, which are represented as follows:

$$C_p \frac{dv_{pv}}{dt} = i_{pv} - i_{Lp} \quad (25)$$

$$L_p \frac{di_{Lp}}{dt} = v_{pv} - (1 - D_p) V_{DCp} - r_{pqp} i_{Lp} \quad (26)$$

$$C_{DCp} \frac{dV_{DCp}}{dt} = i_{pd} - i_{pb} \quad (27)$$

$$i_{pd} = (1 - D_p) i_{Lp} \quad (28)$$

Model of SOFC

SOFC is a high-efficiency cell when compared to other FC types. They offer several advantages over low-temperature cells, which has

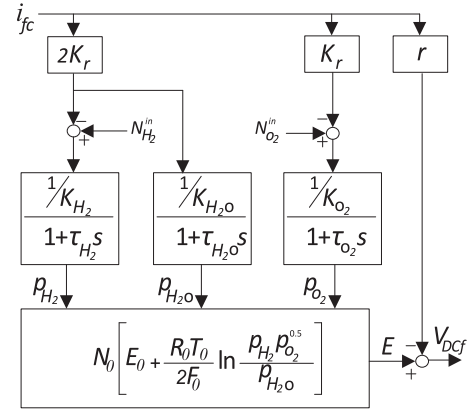


Fig. 7. Dynamic model of SOFC.

increased its attractiveness. Additionally, these cells easily achieve higher electrical efficiencies. These properties, therefore, result in a more straightforward system configuration compared to low-temperature FCs, which need additional units for hydrogen generation [59].

Due to the difficulty in shutting down high-temperature FCs, they find acceptance primarily used in stationary applications. Their extended operational lifespan is the reason behind using SOFCs in commercial systems [59]. Furthermore, any excess water can be recycled through a steam turbine to generate additional electricity, thereby increasing the overall system efficiency.

An SOFC consists of an anode and a cathode with an electrolyte layer between them. Hydrogen is supplied to the anode, while oxygen is supplied to the cathode terminal and this favors the necessary electrochemical processes for electricity generation [60]. As a result, the oxidation occurs at the anode, while reduction occurs at the cathode. The electrolyte allows the transfer of electrons and ions formed during oxidation to transfer from the anode to the cathode. This basic mechanism is common to all FC types. [61]. The corresponding reactions are shown as follows [62]:



The SOFC system, comprising hundreds of cells connected in series or parallel, allows for adjusting fuel input by regulating the fuel valve, thereby enabling precise control of the system's output voltage. The dynamic model of SOFC has been shown in Fig. 7. The average voltage magnitude of the SOFC stack, as determined by the Nernst equation and Ohm's law, including considerations of ohmic losses, can be modeled by the following equations [63]:

$$V_{DCf} = E - r_{fc} \quad (30)$$

$$E = N_0 E_0 + (N_0 RT / 2F) \ln(p_{H_2} p_{O_2}^{0.5} / p_{H_2O}) \quad (31)$$

Wherein,

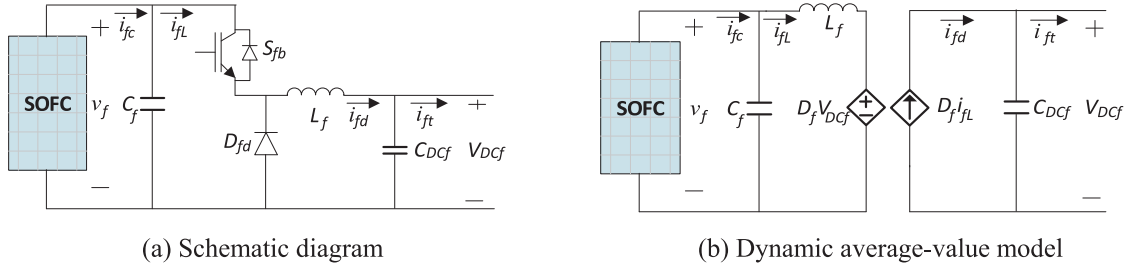


Fig. 8. Schematic diagram and dynamic average-value model of the DC/DC buck converter.

$$p_{H_2} = \frac{1/K_{H_2}}{1 + \tau_{H_2}s} (N_{H_2}^{in} - 2K_r i_{fc}) \quad (32)$$

$$p_{O_2} = \frac{1/K_{O_2}}{1 + \tau_{O_2}s} (N_{O_2}^{in} - K_r i_{fc}) \quad (33)$$

$$p_{H_2O} = \frac{1/K_{H_2O}}{1 + \tau_{H_2O}s} 2K_r i_{fc} \quad (34)$$

$$N_{H_2}^{in} = \frac{60000RT i_{fc,ref}}{U_{H_2} z F P_{fuel} x\%} \quad (35)$$

$$N_{O_2}^{in} = \frac{60000RT i_{fc,ref}}{2U_{O_2} z F P_{air} y\%} \quad (36)$$

The power balance across the DC-link is given by:

$$P_f = P_{inv} + C_{DCf} V_{DCf} \frac{dV_{DCf}}{dt} \quad (37)$$

As shown in Fig. 8(a), the schematic diagram illustrates the analyzed DC/DC buck converter used as an interface between the SOFC and the DC-link. This schematic considers the case when the switching actions of the switch and the diode are assumed to be neglected. Instead, the DC/DC buck converter is represented using the dynamic average-value model illustrated in Fig. 8(b). Accordingly, the differential equations governing the operation of the DC/DC buck converter can be formulated based on [58,64] as follows:

$$C_f \frac{dv_f}{dt} = i_{fc} - i_{fL} \quad (38)$$

$$L_f \frac{di_{fL}}{dt} = v_f - D_f V_{DCf} - r_{paf} i_{fL} \quad (39)$$

$$C_{DCf} \frac{dV_{DCf}}{dt} = i_{fd} - i_{ft} \quad (40)$$

$$i_{fd} = D_f i_{fL} \quad (41)$$

Model of SG

The mathematical model of the synchronous generator (SG), excitation system, and automatic voltage regulator (AVR) has been considered as follows [65]:

$$\frac{d\delta}{dt} = \omega_0(\omega - 1) \quad (42)$$

$$2H \frac{d\omega}{dt} = (P_m - P_e - D(\omega - 1)) \quad (43)$$

$$T_{do} \frac{dE_q}{dt} = (E_{fd} - E_q - (x_d - x'_d) i_d) \quad (44)$$

$$T_a \frac{dE_{fd}}{dt} = (-E_{fd} + k_{avr}(v_{ref} - v_t)) \quad (45)$$

Model of BESS

The electrical model of the BESS has been shown in Fig. 9. The electrical model of the BESS is an internal resistor connected in series with a parallel RC circuit [66,67]. The mathematical equations of the exponential zone dynamics and-

function of $f_{1,2}$ for charge and discharge situations are as follows

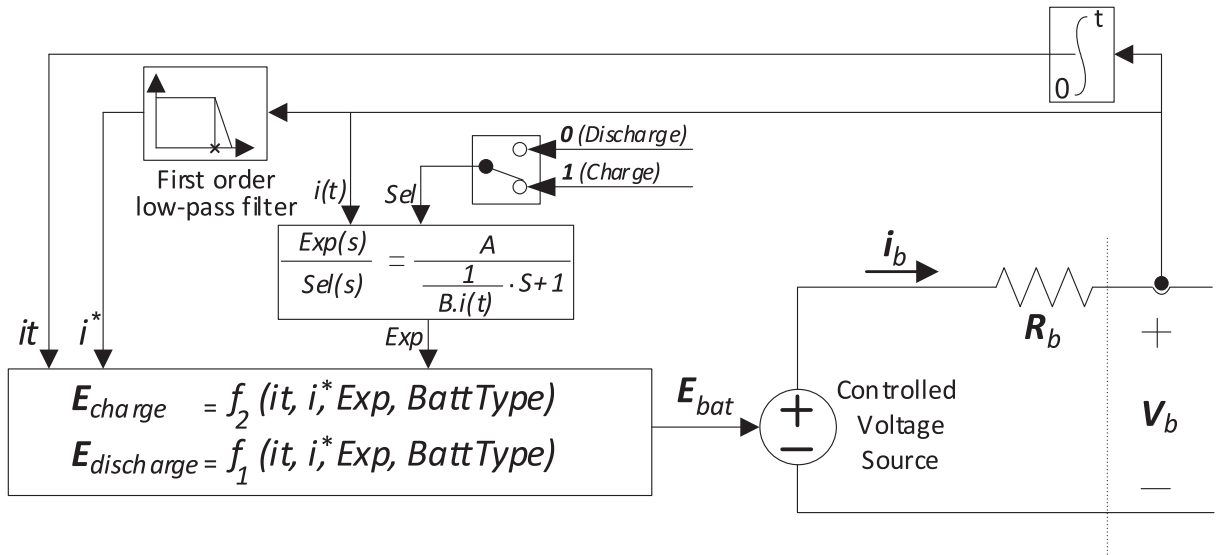


Fig. 9. Equivalent-circuit model of BESS.

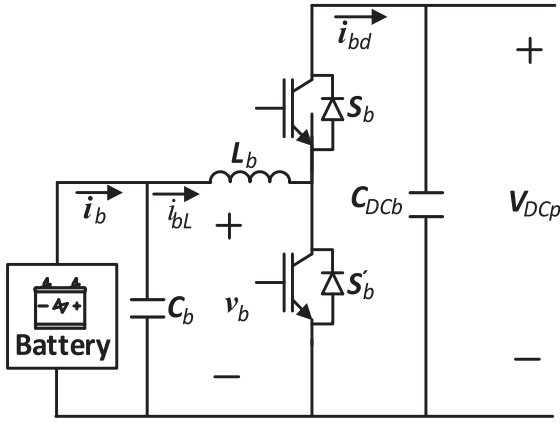


Fig. 10. Schematic diagram of bidirectional DC/DC converter.

[55,64]:

Discharge mode ($i > 0$):

$$f_1(it, i^*, Exp) = E_0 - k_b \cdot \frac{Q}{Q - it} \cdot i^* - k_b \cdot \frac{Q}{Q - it} \cdot it + Laplace^{-1} \left(\frac{Exp(s)}{Sel(s)} \cdot 0 \right) \quad (46)$$

Charge mode ($i < 0$):

$$f_2(it, i^*, Exp) = E_0 - k_b \cdot \frac{Q}{it + 0.1 \cdot Q} \cdot i^* - k_b \cdot \frac{Q}{Q - it} \cdot it + Laplace^{-1} \left(\frac{Exp(s)}{Sel(s)} \cdot \frac{1}{s} \right) \quad (47)$$

Fig. 10 represents the schematic diagram of a half-bridge bidirectional DC/DC converter. It is mainly utilized to interface the BESS with the MG. It contains two switches S_b and S'_b , two filtering capacitor C_b and C_{DCb} and an inductance L_b followed by a BESS.

Fig. 11 shows the dynamic average-value model of bidirectional DC/DC converter. The bidirectional converter's operation can switch between a buck or a boost mode depending on the direction of energy flow. The buck mode ensures adequate BESS charging, as depicted in Fig. 11 (a).

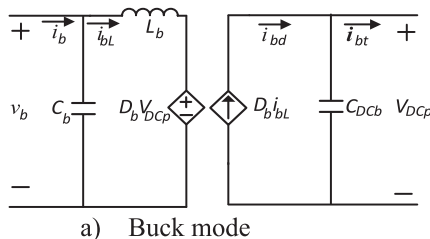
Besides, during the buck mode, the switch S'_b remains open while the control of the switch S_b is done using a pulse-width modulation (PWM) signal. Fig. 11(b) illustrates the converter's boost operating mode. The boost mode ensures the secure discharge of the BESS. During the boost mode, the switch S_b remains open while the control of the switch S'_b is done using a PWM signal.

The mathematical comprehensive model of the bidirectional buck-boost DC/DC converter connected to the BESS, based on the dynamic average-value model depicted in Fig. 11 and considering the buck-boost operating modes, using Kirchhoff's laws yields are as follows:

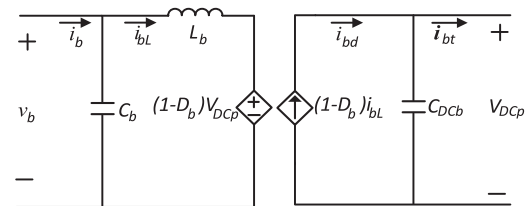
Buck mode:

$$C_b \frac{dv_b}{dt} = i_b - i_{bL} \quad (48)$$

$$L_b \frac{di_{bL}}{dt} = v_b - D_b V_{DCp} - r_{pab} i_{bL} \quad (49)$$



a) Buck mode



b) Boost mode

Fig. 11. Dynamic average-value model of the bidirectional DC/DC converter.

$$C_{DCb} \frac{dV_{DCp}}{dt} = i_{bd} - i_{bt} \quad (50)$$

$$i_{bd} = D_b i_{bL} \quad (51)$$

Boost mode:

$$C_b \frac{dv_b}{dt} = i_b - i_{bL} \quad (52)$$

$$L_b \frac{di_{bL}}{dt} = v_b - (1 - D_b) V_{DCp} - r_{pab} i_{bL} \quad (53)$$

$$C_{DCb} \frac{dV_{DCp}}{dt} = i_{bd} - i_{bt} \quad (54)$$

$$i_{bd} = (1 - D_b) i_{bL} \quad (55)$$

Model of VSI, filter, and connection line

According to Fig. 2, three VSIs and filters in the MG connect DER to the power grid. They have similar dynamic behavior and mathematical models. Hence, only a mathematical model of the PV system's VSI and filter have been presented in this paper. The PV system's VSI, depicted in Fig. 2, is linked to the distribution power grid via an LCL filter, a step-up transformer, and a connection line.

Their dynamic models are formulated under the dq-axis reference frame as follows:

$$L_{p1} \frac{di_{dpi}}{dt} = V_{dpi} - V_{dcp} - R_p i_{dpi} + \omega L_{p1} i_{qpi} \quad (56)$$

$$L_{p1} \frac{di_{qpi}}{dt} = V_{qpi} - V_{qcp} - R_p i_{qpi} - \omega L_{p1} i_{dpi} \quad (57)$$

$$L_{p2} \frac{di_{dpi1}}{dt} = V_{dcp} - V_{dPCC} - R_{p1} i_{dpi1} + \omega L_{p2} i_{qpi1} \quad (58)$$

$$L_{p2} \frac{di_{qpi1}}{dt} = V_{qcp} - V_{qPCC} - R_{p1} i_{qpi1} - \omega L_{p2} i_{dpi1} \quad (59)$$

$$C_{pf} \frac{dV_{dcp}}{dt} = i_{dpi} - i_{dpi1} + \omega C_{pf} V_{qcp} + R_{p2} C_{pf} (p(i_{dpi}) - p(i_{dpi1})) \quad (60)$$

$$C_{pf} \frac{dV_{qcp}}{dt} = i_{qpi} - i_{qpi1} - \omega C_{pf} V_{dcp} + R_{p2} C_{pf} (p(i_{qpi}) - p(i_{qpi1})) \quad (61)$$

$$L_g \frac{di_{dg}}{dt} = V_{dPCC} - V_{dg} - R_g i_{dg} + \omega L_g i_{qg} \quad (62)$$

$$L_g \frac{di_{qg}}{dt} = V_{qPCC} - V_{qg} - R_g i_{qg} - \omega L_g i_{dg} \quad (63)$$

Control strategy

This section describes the control strategy designed for the investigated MG. The control objective is to regulate the power delivered from the distribution power grid continuously and smoothly, maintain system performance over a wide range of operating conditions, and capture as

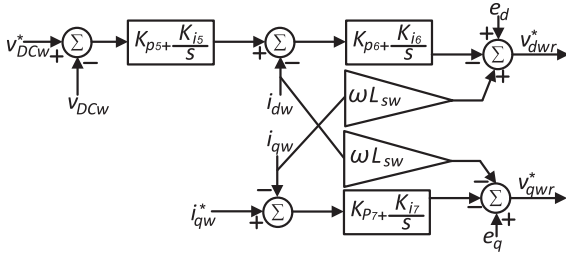


Fig. 12. Control structure of the active rectifier in WPGS.

much available output from distributed generation (DG) resources as possible.

The controller of the DC/DC boost converter maximizes power extraction from the PV system. In contrast, the active rectifier controller reduces power oscillations in the WPGS; additionally, the VSI controller regulates the power injected into the distribution network, while the bidirectional buck/boost converter controller ensures that the DC-link voltage is maintained. Therefore, effective coordination between the controllers of the bidirectional buck/boost converter and the VSI is essential. Detailed control methods for the DC/DC buck and boost converters, as well as the VSI and active rectifier, are outlined in the subsequent subsections.

Control of rectifier, bidirectional DC/DC converter, and VSI for WPGS

The three-phase circuit of LPMSG and the dynamic average-value model of WPGS are shown in Figs. 3 and 4, respectively. It can be demonstrated that if $e_{a,b,c}$ (in Fig. 3) are balanced and devoid of harmonics, then v_{dwr} and v_{qwr} of voltage source rectifier (VSR) (in Fig. 4), become DC. The equations of v_{dwr} and v_{qwr} are represented as follows:

$$v_{dwr} = S_{dw} V_{DCw} \quad (64)$$

$$v_{qwr} = S_{qw} V_{DCw} \quad (65)$$

Where $[S_{dw}, S_{qw}]$ are the switch states. Eqs. (13) and (14) clearly demonstrate the presence of cross-coupling between the d-axis and q-axis variables ($\omega_{wr} L_{sw} i_{qw}$, $\omega_{wr} L_{sw} i_{dw}$). Hence, a feed-forward decoupling controller can be designed to determine control variables $[v_{dwr}^*, v_{qwr}^*]$, which are likewise DC quantities. The feedforward decoupling control method is implemented to remove the influence of cross-coupling among the control variables of power electronic converters. Overall system performance is improved by responding to real-time disturbances rather than relying solely on feedback correction schemes. The compensation of coupled variables before their occurrence results in an improved dynamic response, minimized control effort, and increased stability under changing operating conditions [68]. To achieve this concept, the new variables $[v_{dwr}^*, v_{qwr}^*]$ are defined as follows [45]:

$$v_{dwr}^* = e_d - v'_{dwr} + \omega_{wr} L_{sw} i_{qw} \quad (66)$$

$$v_{qwr}^* = e_q - v'_{qwr} - \omega_{wr} L_{sw} i_{dw} \quad (67)$$

Where $[v'_{dwr}, v'_{qwr}]$ denote the decoupling variables for current dq components, which are:

$$v'_{dwr} = (K_{p5} + K_{i5}/s)(i_{dw}^* - i_{dw}) \quad (68)$$

$$v'_{qwr} = (i_{qw}^* - i_{qw}) \quad (69)$$

Fig. 12 represents the rectifier control structure of the WPGS. The system operates in the d-q reference frame. The d-axis and q-axis components of the current can be independently regulated. However, system dynamics induce cross-coupling terms among the components, which perturb the control precision. The decoupling controller of the feedforward structure operates to eliminate these interactions by incorporating decoupling terms with system parameters. As a result, the coupling effects are effectively canceled, enabling the PI controllers to regulate the d-axis and q-axis currents independently.

The control strategy is designed around two interaction loops to achieve efficient regulation within the system. The voltage control loop ensures that the DC link voltage remains constant by adjusting the reference current on the d-axis. This approach ensures that the rectifier operates efficiently despite variations in power generation. In addition, the current control loop ensures that the actual d-q currents accurately track reference.

This is achieved by reducing control error using PI controllers and improving tracking precision through reduced system overshoot. In order to enhance control performance, decoupling terms based on system inductances and grid frequency are incorporated into the control strategy. These terms effectively prevent cross-coupling between the d-axis component and q-axis components, allowing each control amount can be accurately controlled independently.

Fig. 13 shows the control block diagram of the bidirectional DC/DC converter that connects the BESS to the DC-link. The converter is controlled by a dual-cascaded feedback linear control structure, which improves both power management and dynamic stability. The proposed control strategy consists of an outer and an inner control loop that work in a hierarchical manner to regulate the bidirectional buck-boost converter in the WPGS. The outer loop maintains the DC bus and BESS voltage at their desired levels, ensuring stable operation under varying output power of the WPGS. This loop utilizes PI controllers to generate the reference battery current and can operate in both charging and discharging modes.

By dynamically adjusting this reference current, the outer loop ensures voltage regulation and enhances overall system stability. On the other hand, the inner loop is designed to regulate the actual BESS current by minimizing the deviation from its reference value. This regulation is achieved through an additional PI controller that processes the current error and generates the appropriate duty cycle for PWM control of the bidirectional converter. The inner loop improves the system's dynamic response and mitigates current fluctuations by enabling rapid current tracking, ensuring efficient power flow management. This hierarchical control structure enhances system performance by effectively decoupling voltage and current regulation, allowing each loop to operate within its optimized bandwidth. The outer loop, characterized by a

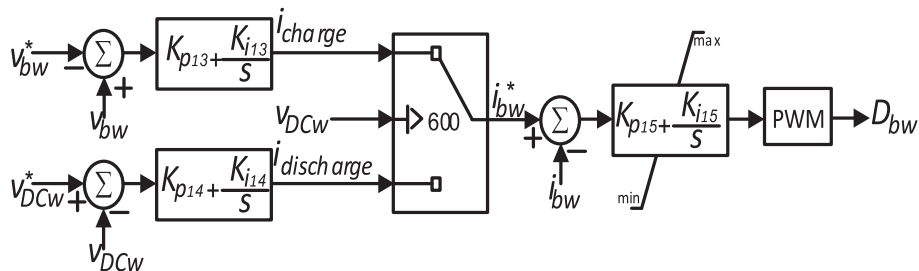


Fig. 13. Control structure of the bidirectional DC/DC converter in WPGS.

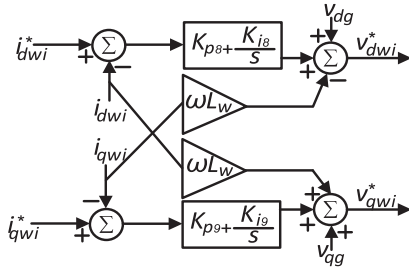


Fig. 14. Control structure of the VSI in WPGS.

lower bandwidth, ensures steady-state voltage stability, whereas the inner loop, with a higher bandwidth, provides fast and precise current control. This cascaded approach improves WPGS's power fluctuations. It should be noted that the proposed controller in Fig. 13 regulates BESS integrated within WPGS based on DC-link voltage (V_{DCw}) levels. When the voltage has exceeded 600 V, the battery has transitioned into charging mode. Conversely, if the voltage has fallen below this threshold, the battery has discharged to compensate for the voltage drop.

The proposed controller for the VSI, as presented in Fig. 14, consists of a current control loop and a feedforward compensation loop. The current control loop employs PI regulators to track the reference currents (i_{dwi}^*) and (i_{qwi}^*), ensuring precise regulation of the direct and quadrature current components, which enables effective control of active and reactive power while minimizing THD in the MG voltage and current. Simultaneously, the feedforward compensation loop incorporates decoupling terms (ωL_w) to eliminate cross-coupling effects, improving control accuracy and transient response. The integration of these loops ensures independent and stable regulation of power flow and output voltage, optimizing the performance of the grid-connected inverter.

Control of DC/DC boost converter and bidirectional buck/boost converter for PV system

The output power generated by the PV array is influenced by fluctuating solar irradiance and ambient temperature and is contingent upon the terminal voltage of the PV array. The PV array's MPPT is essential for efficient operation. This can be achieved by regulating the DC/DC boost converter within the PV system, thereby controlling the terminal voltage to reach the desired MPPT. Various MPPT techniques have been proposed in the research for implementation with DC/DC converters utilized in PV systems, including methods such as constant voltage (CV), perturb and observe (P&O), and incremental conductance (IC) [29]. The widely employed P&O MPPT technique is utilized in this paper to control the DC/DC boost converter. In [15,69], detailed principles and a flowchart for this technique have been addressed.

Fig. 15 presents the proposed controller designed for the BESS integrated into the PV system. Through this control strategy, the DC bus voltage (V_{DCp}) and PV-generated current (i_{pv}) are maintained at their desired values, while the BESS current follows the reference setpoint. In scenarios where i_{pv} deviates from its nominal value, the outer loop dynamically adjusts the reference battery current (i_b^*), enabling the bidirectional DC/DC converter to regulate power exchange efficiently and maintain system dynamic stability under varying operational conditions.

The block diagram of the proposed feedforward decoupling control for the VSI employed in the PV system is shown in Fig. 16. It should be noted that the VSI's current controllers are used to regulate the active power transmitted through the VSI, achieve low THD in the MG voltage and current, and also maintain voltage magnitude of the PCC at the reference value. To achieve independent control of the active and reactive components, the VSI control is presented in the dq-axis reference frame, aligning the d-axis with the V_{PCC} [70]. Therefore, the VSI regulates the active power transmitted through it and the V_{PCC} by adjusting the d-axis and q-axis currents, respectively.

Control of SOFC

From the control aspect, a fundamental characteristic of the SOFC

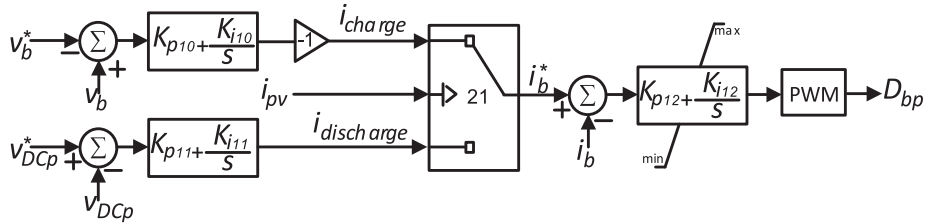


Fig. 15. Control structure of the PV system's bidirectional DC/DC converter.

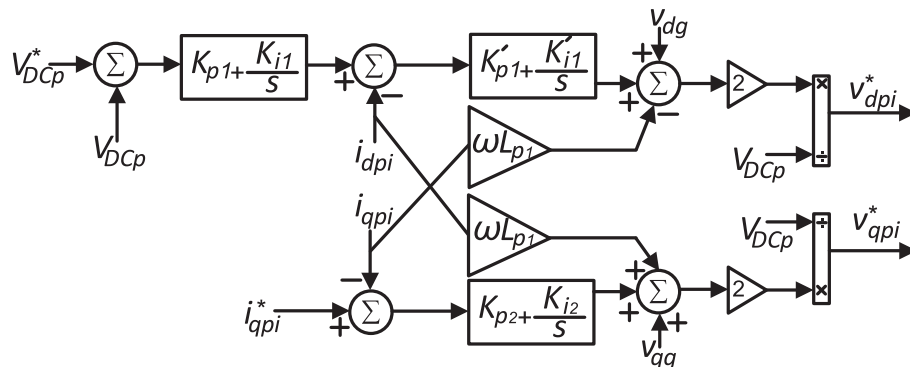


Fig. 16. Control structure of the PV system's VSI.

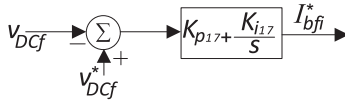


Fig. 17. Control structure of the DC/DC buck converter for SOFC.

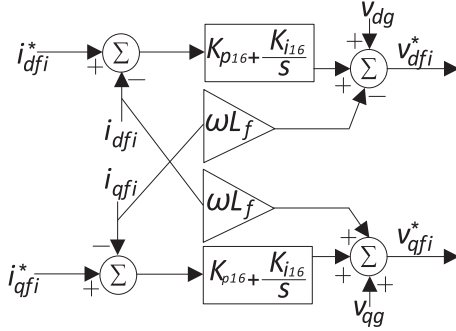


Fig. 18. Control structure of the VSI for SOFC.

Table 2

Oscillatory eigenvalues of the MG under the specified operating condition in case 1.

Mode No.	Eigenvalues	Mode No.	Eigenvalues
λ_{1-2}	$-1.3934 \pm 0.11776i$	λ_{19-20}	$-1.8746 \pm 6283.2i$
λ_{3-4}	$-2.982 \pm 442.14i$	λ_{21-22}	$-0.068242 \pm 0.005465i$
λ_{5-6}	$-1.8214 \pm 6275.3i$	λ_{23-24}	$-0.68977 \pm 1.2206i$
λ_{7-8}	$-1.817 \pm 6283.2i$	λ_{25-26}	$-26.059 \pm 14.168i$
λ_{9-10}	$-0.98301 \pm 4442.9i$	λ_{27-28}	$-25 \pm 66.144i$
λ_{11-12}	$-1.6779 \pm 6283.2i$	λ_{29-30}	$-6.8126 \pm 314.58i$
λ_{13-14}	$-1.7185 \pm 6283.2i$	λ_{31-32}	$-0.88148 \pm 4437.3i$
λ_{15-16}	$-1.0611 \pm 4442.9i$	λ_{33-80}	$-150 \pm 86.603i$
λ_{17-18}	$-1.8097 \pm 6283.2i$		

power plant is the disparity in response times between the SOFC and the VSI [62,71]. The adjustment of active and reactive powers in a VSI to attain a new steady state through PWM duty cycle modification typically

takes approximately 0.1 s, whereas achieving a new steady state for the FC requires a longer duration, typically between 5 and 10 s [62].

To achieve rapid power tracking, a widely adopted approach [72–74] involves utilizing an inverter to control active and reactive powers by adjusting the current (i_{fref}) supplied to the inverter. In Fig. 17, a controller for a buck converter connected to a SOFC is presented. The primary objective of this controller is to regulate the filtered DC voltage (V_{DCF}). In this structure, the reference voltage (V_{DCF}^*) is compared with the actual voltage, and the resulting error is processed by a PI controller. The controller's output determines the reference current (I_{bfi}^*) for the converter which plays a crucial role in power regulation and voltage stability. Fig. 18 illustrates the proposed feedforward decoupling control scheme for the VSI employed with the SOFC within the dq-axis reference frame. The VSI regulates the active power delivered through it and the V_{PCC} by manipulating the d-axis and q-axis currents, respectively.

Eigenvalues, root loci analysis, and time-domain simulations

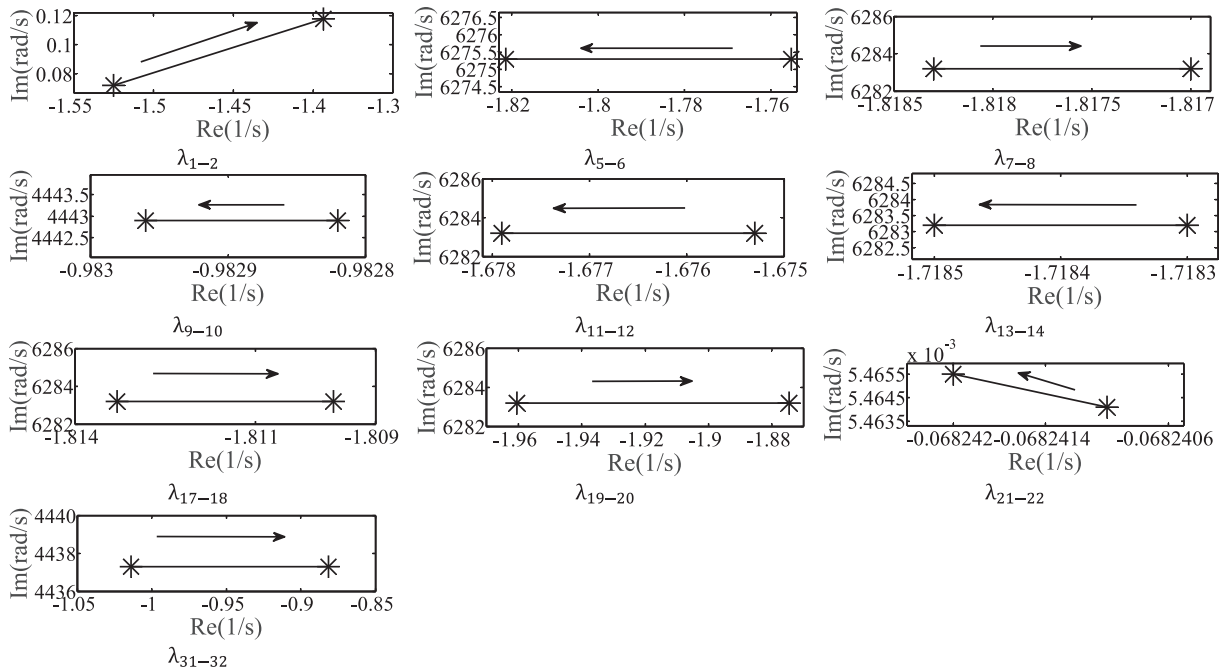
MG eigenvalues

Although the occurrence of the most intense conditions regarding DG may not be simultaneous, it is of significant-interest to investigate the MG eigenvalues under the most stringent power flow operating conditions. In doing so, as case 1, the solar irradiance is set at its highest value of 1000 (W/m^2), while u_m and i_{fref} are set at 1.4 (m/s) and 40 (A), respectively. Considering the inputs mentioned earlier, the output power of PV, WPGS, SOFC, and SG sources has been obtained as 49 (kW), 53 (kW), 50 (kW), and 148 (kW), respectively.

Table 2 presents all oscillatory eigenvalues of the investigated MG at the specified operating condition. It should be noted that the other real eigenvalues have been omitted. In addition, the table shows that all real eigenvalues are negative, confirming the overall dynamic stability of the studied MG under the considered operating conditions.

Root loci analysis

The root loci analysis for variations in PV irradiance, u_m , and i_{fref} has

Fig. 19. Root loci of the MG eigenvalues when u_m as the input of the WPGS is increased from 0.0 to 1.4 (m/s) (case 2).

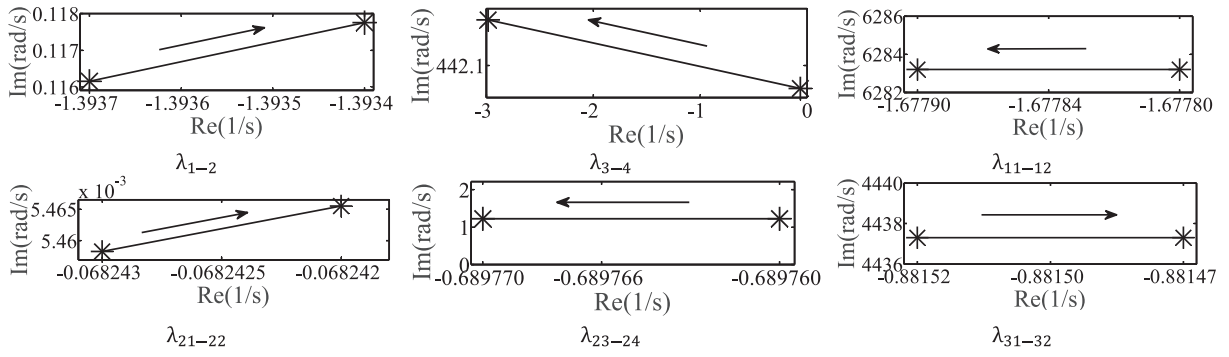


Fig. 20. Root loci of the MG eigenvalues when the solar irradiance increases from 0.0 to 1000 (W/m²) (case 3).

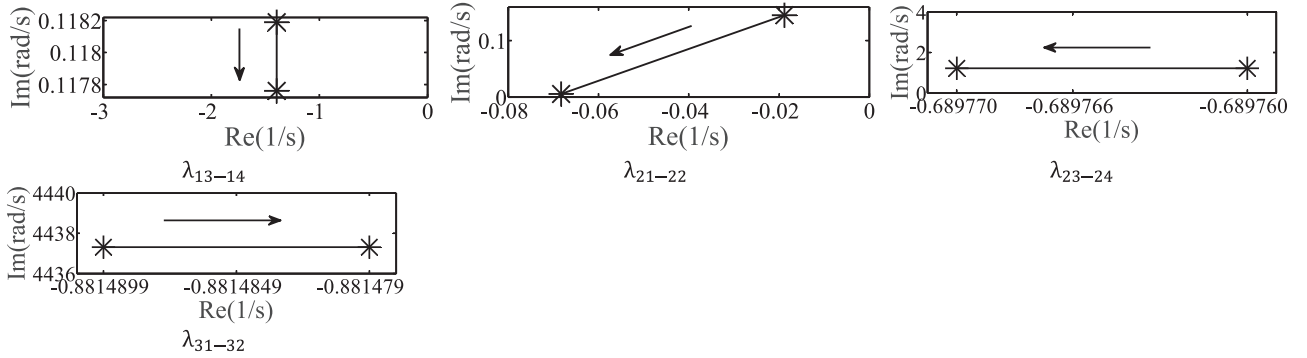


Fig. 21. Root loci of the MG eigenvalues when i_{fcref} of the SOFC is increased from 0.0 to 40 (A) (case 4).

been depicted in this section. Importantly, only the eigenvalues affected by these changes have been illustrated, whereas stationary eigenvalues have not been visualized. Fig. 19 illustrates the root loci of the MG eigenvalues when the maximum vertical speed of the wave, u_m , is incremented from 0.0 to 1.4 (m/s) while maintaining the PV irradiance, i_{fcref} , and output power of SG at 1000 (W/m²), 40 (A), and 148 (kW). This is known as case 2.

It should be noted that the wave force acts on the AWS of the WPGS. It is clear that the augmentation of the u_m from 0.0 to 1.4 induces leftward movement of eigenvalues λ_{5-6} , λ_{9-10} , λ_{11-12} , λ_{13-14} , and λ_{21-22} thereby enhancing the damping characteristics of these modes.

Conversely, eigenvalues λ_{1-2} , λ_{7-8} , λ_{17-18} , λ_{19-20} , and λ_{31-32} exhibit rightward movement as the u_m increases, indicating a deterioration in the damping characteristics of these modes. Nevertheless, Fig. 19 clearly depicts that the presented root loci of the system eigenvalues reside on the left-hand side of the imaginary axis, signifying that the analyzed MG is still dynamically stable amidst wide-ranging changes in the vertical speed of the wave.

Fig. 20 illustrates the root loci of the MG eigenvalues as the solar irradiance of the PV array varies from 0.0 to 1000 (W/m²) while u_m and i_{fcref} are fixed at 1.4 (m/s) and 40 (A), respectively. The plots exclusively illustrate the root loci alterations resulting from increased solar irradiance. The eigenvalue analysis in Fig. 20 reveals that the increase in PV irradiance results in the movement of eigenvalues λ_{3-4} , λ_{11-12} , and λ_{23-24} from the right-hand side to the left-hand side of the complex plane, signifying an enhancement in the damping of these modes.

Conversely, eigenvalues λ_{1-2} , λ_{21-22} , and λ_{31-32} shift towards the right-hand side of the complex plane as PV irradiance rises. The most significant displacement is observed in the root loci of the dominant eigenvalues λ_{3-4} , which is initially located near the imaginary axis at zero PV irradiance and swiftly shifts towards the left-hand side of the complex plane with increasing PV irradiance.

The observed displacement indicates an improvement in the MG's dynamic stability. The dominant pole, representing the system's

slowest-decaying mode, migrates to the left half-plane. Consequently, this shows reflects enhanced dynamic characteristics. This allows the rapid dissipation of perturbations and thereby improving the dynamic stability of the system [75].

The results demonstrate that increased PV irradiance positively impacts the MG's dynamic behavior. The dominant eigenvalues shifting to the left indicate increased damping and overall dynamic stability, meaning that higher PV penetration reduces the MG's sensitivity to disturbances.

Fig. 21 represents the root loci of the studied MG eigenvalues as i_{fcref} of the SOFC varies from 0.0 to 40 (A), while u_m , the PV irradiance and the output power of SG are fixed at 1.4 (m/s), 1000 (W/m²), and 148 (kW), respectively. This is known as case 4. It can be seen from Fig. 21 that the augmentation of the i_{fcref} from 0.0 to 40 (A) induces leftward movement of eigenvalues, λ_{21-22} and λ_{23-24} thereby enhancing the damping torque of these modes. Besides, an increase in the i_{fcref} results in a decrease in the oscillation frequency of the λ_{13-14} , as it moves closer to the real axis, thereby enhancing system damping. On the other hand, the eigenvalue λ_{31-32} shifts towards the imaginary axis as i_{fcref} rises, indicating a deterioration in the damping characteristics of these modes.

As a result, it can be inferred that the rise in i_{fcref} leads to an increase in the output power of the SOFC, which subsequently enhances the damping characteristics of the analyzed MG, improving its overall stability and dynamic performance.

Case 1: Constant inputs

In this section, the output power of the DERs is assumed to be constant. Consequently, solar irradiance is considered as a noise input at approximately 1000 (W/m²), WPGS's input is supposed to be 1.4 (m/s), and the SOFC input is set at 40 (A). The SG output is also taken as 148 (kW), and the load consumption is assumed to be 30 (kW). The simulation results for the aforementioned operating conditions are presented in Fig. 22.

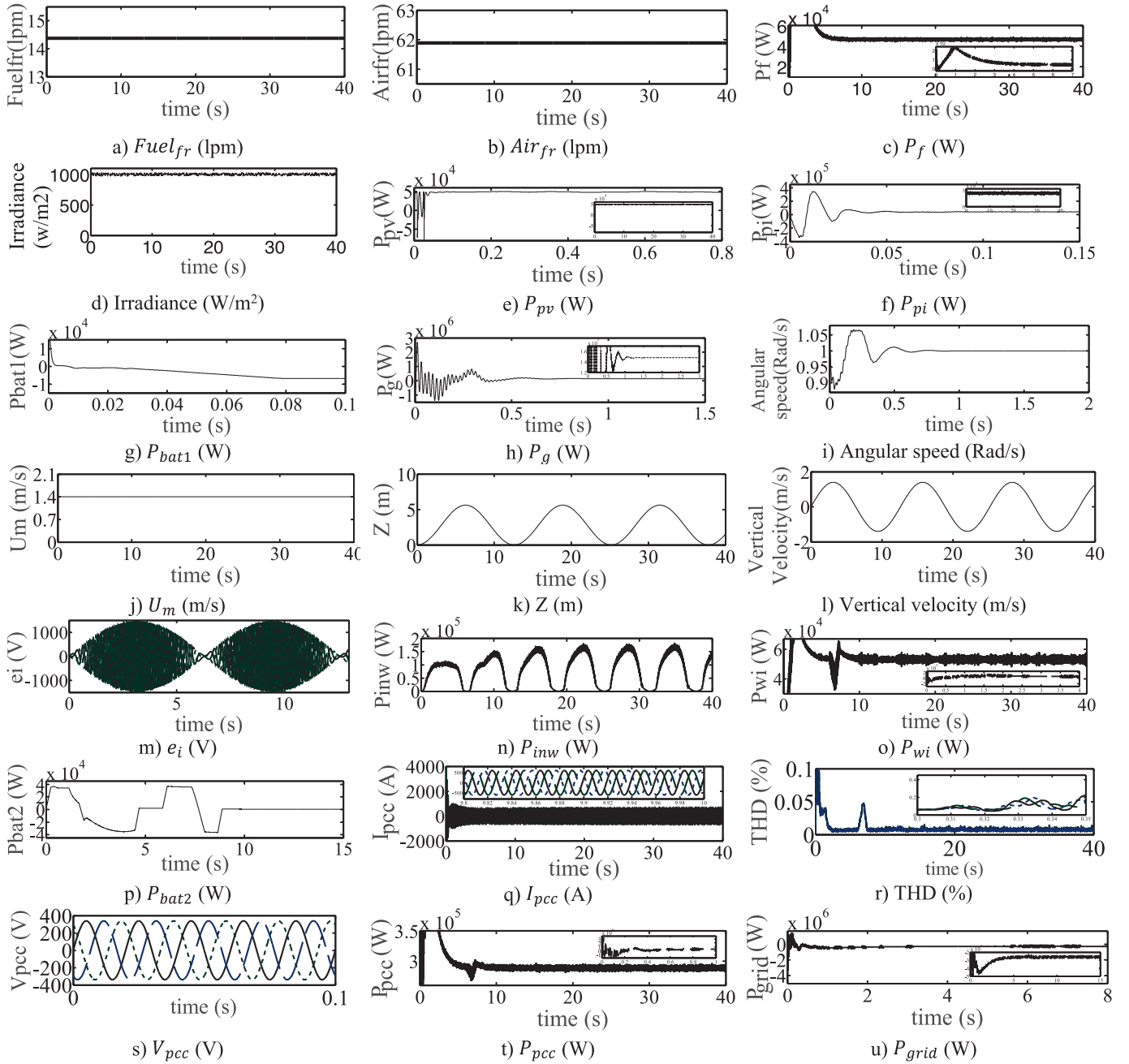


Fig. 22. Dynamic responses of the studied MG in case 1.

According to Fig. 22(a) and (b), $Fuel_{fr}$ and Air_{fr} have been obtained as constant values of 3.2 (liters per minute (lpm)) and 9.17 (lpm), respectively. As a result, the output power of the SOFC (Fig. 22(c)) at B' point was obtained at 47 (kW). Taking into account constant solar irradiance (Fig. 22(d)) and employing the MPPT technique, the output power of the PV (P_{pv} , Fig. 22(e)) and the power (P_{pi} , Fig. 22(f)) of A' point (Fig. 2) have been calculated to be 49 (kW) and 43 (kW), respectively. As illustrated in Fig. 22(g), the power absorbed or delivered by BESS 1 (P_{bat1}), which is integrated with the PV system, represents the battery's charging or discharging states. Analyzing the BESS output power indicates that the controller regulates the charging and discharging operations to maintain a stable DC-link voltage.

In addition, following multiple oscillations, the output power of the SG (P_g , Fig. 22(h)) and its angular speed (Fig. 22(i)) reach stable values of 148 (kW) and 1 (per-unit), respectively. Fig. 22(k) and 22(l) illustrate the displacement and velocity of the AWS buoy, which have been

derived based on u_m (Fig. 22(j)). Subsequently, the induced electromotive force for each phase (e_i , Fig. 22(m)), the output power of the linear generator (P_{inw}) and the output power of WPGS's BESS (P_{bat2}) have been shown in Fig. 22(n) to (p).

As shown in Fig. 22(n), the system's power output increases from zero after a certain period as the buoy's position changes. The power (P_{wi}) of C' point (Fig. 2), the power of the PCC bus (P_{pcc}), and the power injected into the grid (P_{grid}) have been represented in Fig. 22(o), (t) and (u), respectively. These outputs are stabilized and reach their final values after a specific period.

Fig. 22(q) to 22(s) sequentially display the PCC current (I_{pcc}), its THD, and the PCC voltage (V_{pcc}). According to the IEEE Standard 519-2014, the harmonic content of the current must be less than 5%. Fig. 22(r) indicates that the current harmonics are within the acceptable range, below 5%. From Fig. 22(s), the RMS line-to-line voltage of the PCC (V_{pcc-LL}) is 415 V. Fig. 22(t) and 22(u) display the PCC power (P_{pcc})

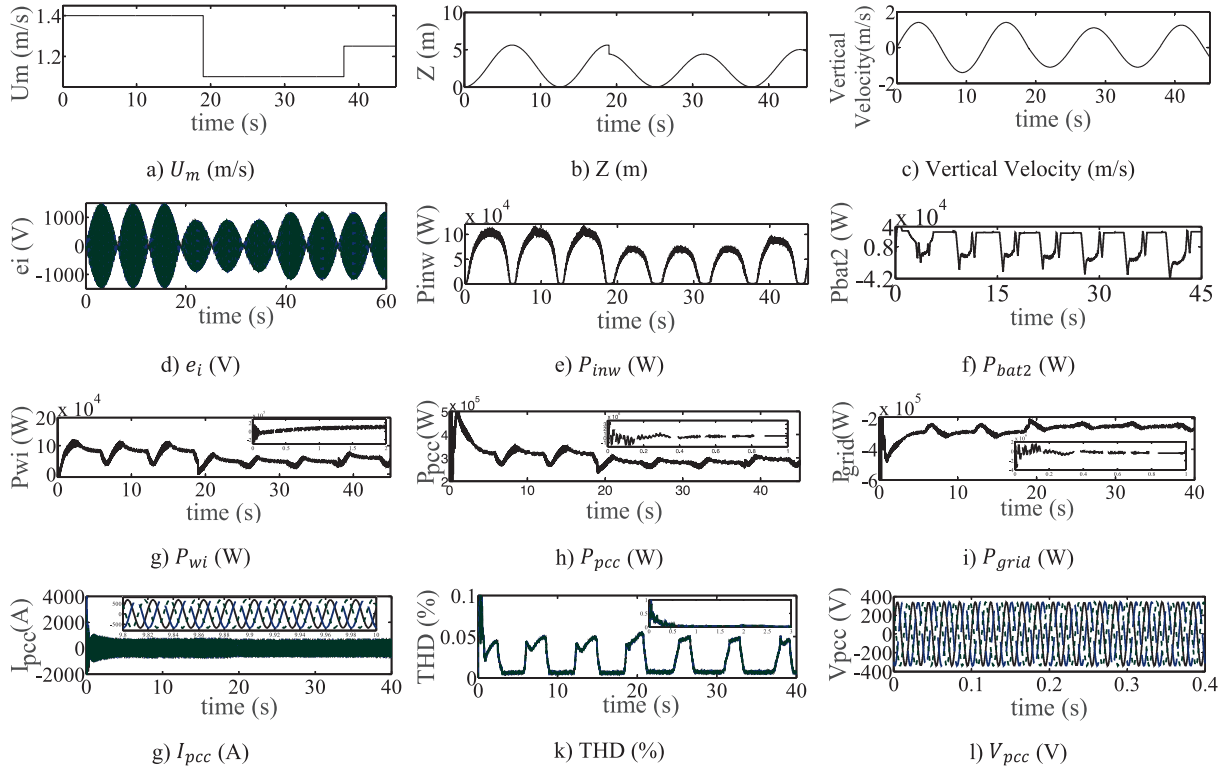


Fig. 23. Dynamic responses of the studied MG under the variations of the U_m acting on the AWS of the WPGS (case 2).

and the grid's received power (P_{grid}), both of which reach a steady, final value after a brief period. The PCC power is obtained from the sum of the output power of the DERs.

Case 2: Variations of the maximum vertical speed of wave (u_m)

In this section, the wave force applied to the AWS of the WPGS undergoes fluctuations, as illustrated in Fig. 23(a), while the output power of the PV, SOFC, and SG are held constant at 49 (kW), 50 (kW), and 148 (kW), respectively. The wave's maximum vertical velocity, considered input to the WPGS, is defined as a step function. The defined input

changes at 19 and 38 s, as shown in Fig. 23(a). Initially possessing the peak amplitude of u_m is 1.4 (m/s), subsequently, u_m decreases to 1.1 (m/s) at $t = 19$ (s), followed by a step increase to 1.25 (m/s) at $t = 38$ (s). Fig. 23(b) to (l) depict the dynamic responses of the investigated MG to the u_m variations. Fig. 23(b) and (c) illustrate the displacement and velocity of the AWS buoy, which have been derived based on u_m . As evident from the figures, both quantities have exhibited proportional variations corresponding to changes in the input.

Subsequently, the induced electromotive force for each phase (e_i), the output power of the linear generator (P_{inw}) and the output power of WPGS's BESS (P_{bat2}) have been shown in Fig. 23(d) to 2(f), while the

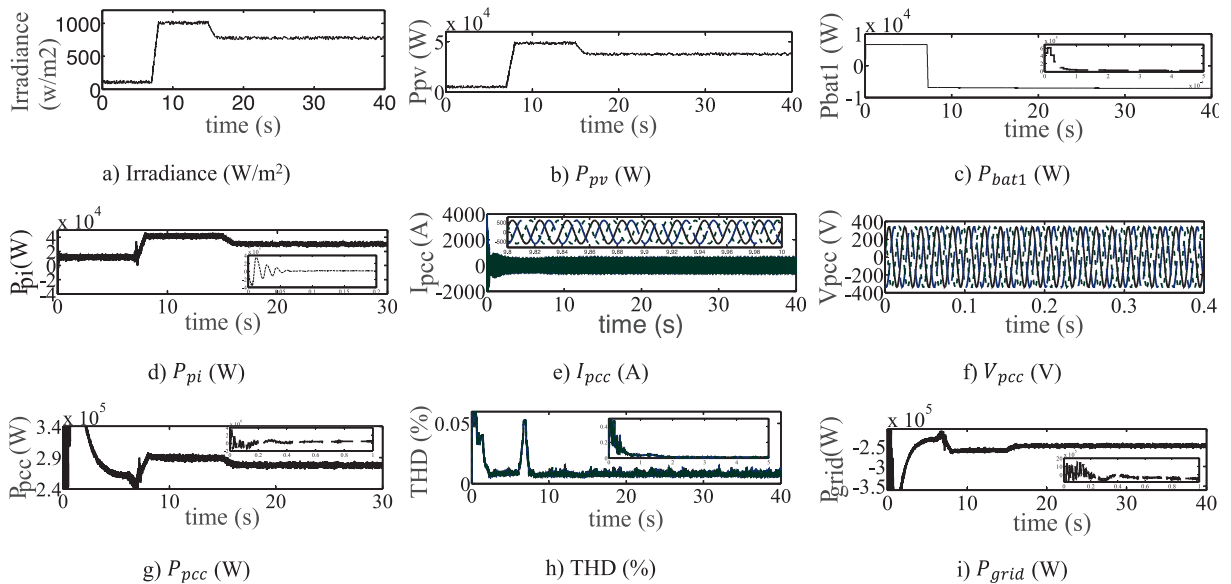


Fig. 24. Dynamic responses of the studied MG under the solar irradiance variations (case 3).

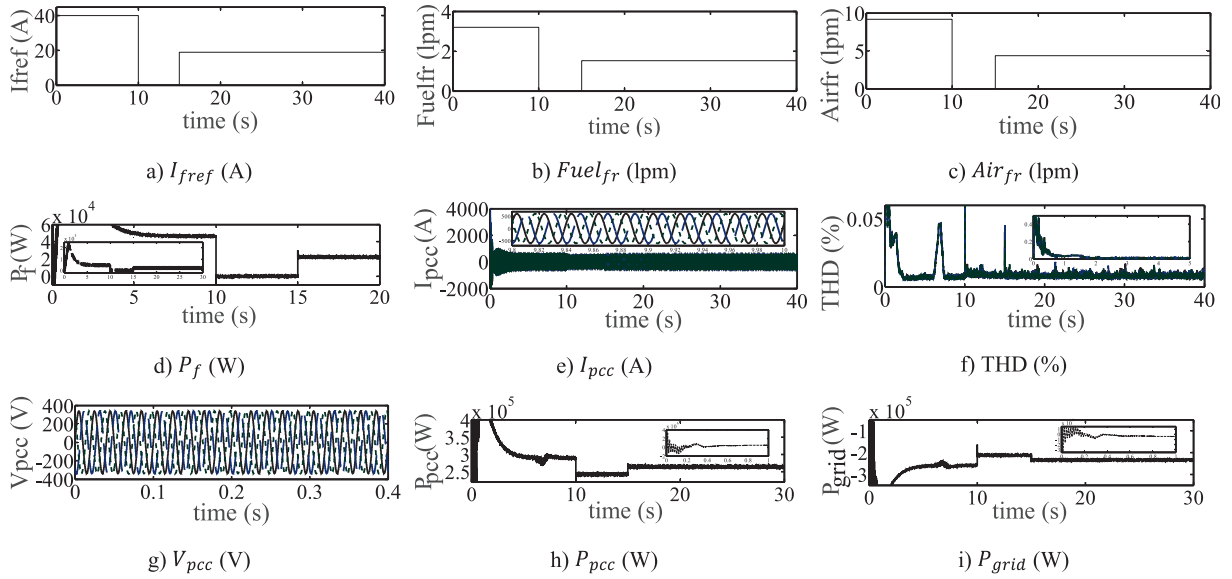


Fig. 25. Dynamic responses of the studied MG under the variations of the input reference current of the SOFC (case 4).

output power of WPGSs (P_{wi}), the power of the PCC bus (P_{pcc}), and the power injected into the grid (P_{grid}) have been represented in Fig. 23(g) to (i). These short-term power levels keep shifting over time due to variations in the u_m . To reduce variations in the DC-link voltage and maintain it at the reference value of 600 (V), a BESS is utilized, which is charged and discharged through the controller shown in Fig. 13. When the DC-link voltage falls below the reference value of 600 (V), the BESS discharges. In contrast, it charges when the voltage exceeds 600 (V). Additionally, the extent of the BESS's charging and discharging operations is constrained within a specific range. As illustrated in Fig. 23(f), the BESS output power alternates between positive and negative values at different times.

This indicates that charging and discharging operations have been conducted to mitigate DC-link voltage fluctuations. The PCC current, its THD, and the phase-to-ground PCC voltage are shown in Fig. 23(g) to (i), respectively. As shown in Fig. 23, when the output power of the WPGS changes, the PCC current level also varies. As indicated in Fig. 23(k), the current THD in the PCC remains below 5% in all defined operating conditions for the WPGS. Additionally, the RMS V_{pcc-LL} is 415 V. These responses reveal that the power fluctuations resulting from wave variations can be efficiently prevented from transferring to the power grid.

Case 3: Variations of PV irradiance

In this section, variations in solar irradiance affecting the PV array are depicted in Fig. 24(a), while the output power of the WPGS, SOFC,

and SG are kept constant at 53 (kW), 50 (kW), and 148 (kW), respectively. The solar irradiance is presumed to ascend from its initial value of 100 (W/m^2) to the peak level of 1000 (W/m^2) at $t = 8$ (s) and subsequently decline gradually back to 800 (W/m^2) at $t = 16$ (s). The fluctuations in solar irradiance are also presumed to include high-frequency variations attributable to the rapid changes in local meteorological conditions. Fig. 24(b), (c), and (d) illustrate how the PV array, the BESS, and the power at point B, respectively, respond to different levels of solar irradiance. These figures demonstrate that changes in irradiance affect the system's response and, consequently, its dynamic behavior. Fig. 24(c) also illustrates the battery's charging and discharging processes in detail. Fig. 24(f) displays the voltage at the PCC and proves its steady behavior under various PV operating points. The power at the PCC and the overall grid power performance, covering both received and absorbed power, has shifted due to variations in solar irradiance, as shown in Fig. 24(g), (c). The current at the PCC (Fig. 24(e)) varies according to changes in solar irradiance. Additionally, under all level solar irradiance conditions, the THD of the PCC current (Fig. 24(h)) remains below 5%.

Case 4: Variations of SOFC input reference current

This section explores the effects of the SOFC power deviation on the MG performance. The SOFC power is altered by implementing multi-step changes in the SOFC's reference input current. The step change in the input current applied to the SOFC is illustrated in Fig. 25(a).

Accordingly, it decreases from 40 (A) to 0.0 at $t = 10$ (s) and

Table 3
Correlation between U_m and P2P power fluctuations with and without of BESS integration.

1	V_{DCW} (V)					P_{wi} (kW)				
	Time Interval (s)	U_m (m/s)	P2P Without BESS (V)	P2P With BESS (V)	Reduction (%)	Time Interval (s)	U_m (m/s)	P2P Without BESS (W)	P2P With BESS (W)	Reduction (%)
	10–16	1.4	319.42	304.25	4.74	10.2–16.2	1.4	96.933	88.095	9.11
	22.5–28.5	1.1	207.86	195.02	6.17	22.6–28.6	1.1	78.429	46.993	40.08
	47.5–53.5	1.2	331.73	241.30	27.26	41.8–47.8	1.2	99.822	58.874	41.02
2	P_L (W)					P_{grid} (kW)				
	Time Interval (s)	U_m (m/s)	P2P Without BESS (W)	P2P With BESS (W)	Reduction (%)	Time Interval (s)	U_m (m/s)	P2P Without BESS (W)	P2P With BESS (W)	Reduction (%)
	6.6–13	1.4	0.05099	0.04984	2.2548	6.6–13	1.4	98.336	91.589	6.86
	25.6–32	1.1	0.04331	0.02917	32.65	25.8–32	1.1	81.626	51.822	36.51
	44.5–51	1.2	0.05236	0.03307	36.84	44.7–51	1.2	102.877	61.820	39.90

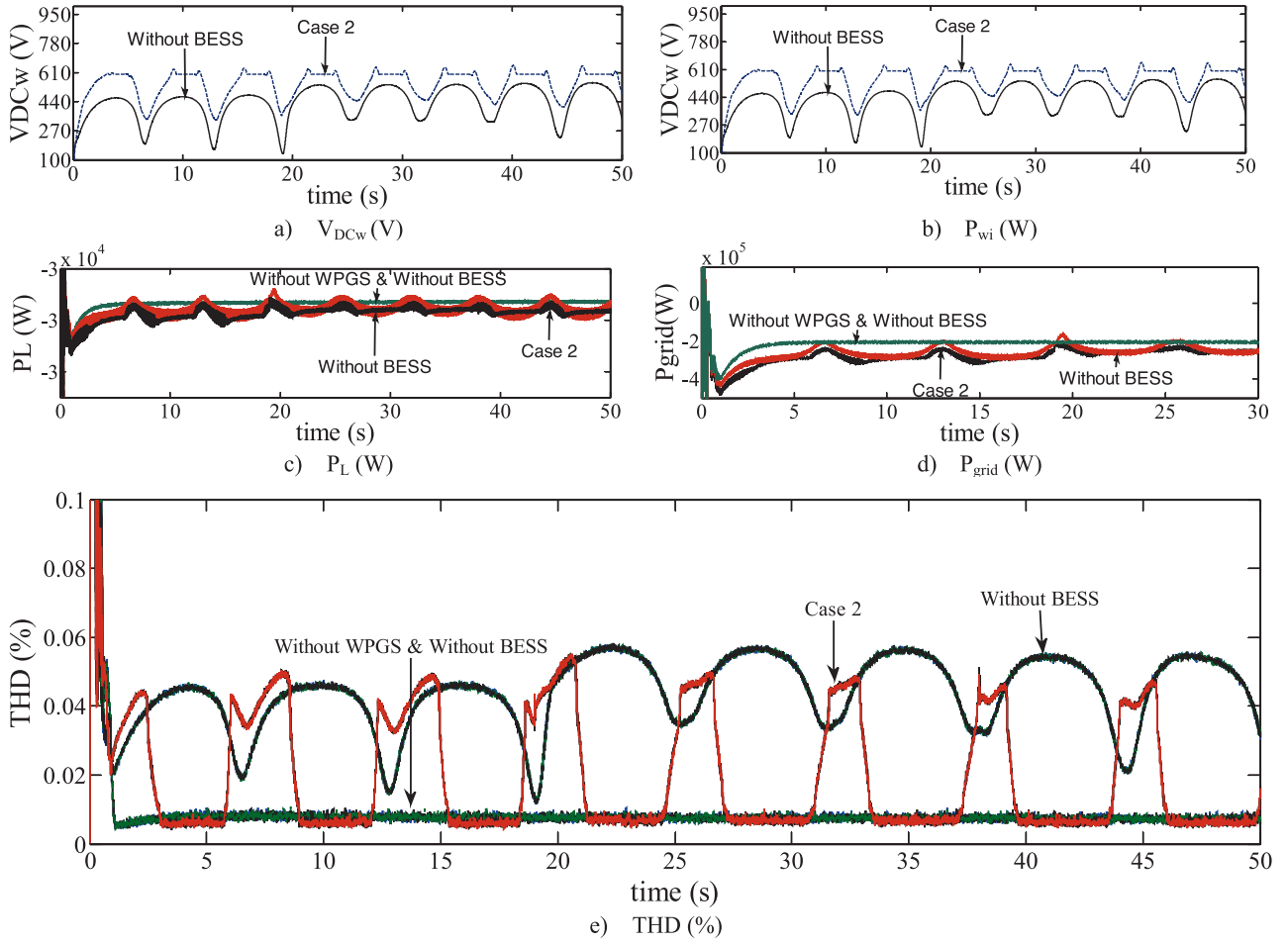


Fig. 26. Dynamic responses of the studied MG under case 5.

subsequently increases from 0.0 to 19 (A) at $t = 15$ (s). The simulation results from applying this input are shown in Fig. 25(b) to (i). As shown in Fig. 25, the parameters $Fuel_{fr}$, Air_{fr} , P_f , I_{pcc} , P_{pcc} and P_{grid} exhibit sequential changes in response to the fluctuations in I_{fref} . The THD for each defined power output of the SOFC is maintained below 5%.

Case 5: Impact of WPGS presence and BESS integration on MG power fluctuations

This scenario evaluates the behavior of the WPGS and the overall MG, both with and without BESS; especially focusing on peak-to-peak (P2P) fluctuations of key parameters such as V_{DCw} , P_{wi} , P_L , and P_{grid} . The P2P and Reductions (%) across different U_m (1.4 m/s, 1.1 m/s, and 1.2 m/s) for the mentioned four key parameters across distinct time intervals are presented in Table 3.

These P2P values, representing the maximum fluctuation range within specified intervals, are compared both with and without BESS integration. It should be noted that the reported Reduction (%) quantifies the relative decrease in P2P amplitude of a given variable after the integration of the BESS, and is expressed as a percentage:

$$\text{Reduction}(\%) = \frac{P2P_{\text{without_BESS}} - P2P_{\text{with_BESS}}}{P2P_{\text{without_BESS}}} \times 100 \quad (70)$$

The P2P values of V_{DCw} during three intervals are presented in Table 3: 10–16 s ($U_m = 1.4$ m/s), 22.5–28.5 s ($U_m = 1.1$ m/s), and 47.5–53.5 s ($U_m = 1.2$ m/s). In the absence of a BESS, the P2P values are 319.42 V, 207.86 V, and 331.73 V, respectively. These values indicate significant fluctuations in wave power generation.

However, with the integration of a BESS, these values decrease to

304.25 V, 195.02 V, and 241.30 V, corresponding to Reductions of 4.74%, 6.17%, and 27.26%, respectively. Therefore, the biggest drop in fluctuations occurs when $U_m = 1.2$ m/s, highlighting the BESS system's real strength in handling those wave patterns. The BESS DC/DC bidirectional converter stabilizes the voltage around 600 V by adjusting V_{DCw} according to the controller described in Section III. A. This Reduction in the DC link voltage helps stabilize fluctuations in grid power.

The parameters P_L , P_{wi} , and P_{grid} were used to examine the sensitivity analysis of the studied MG. P_L was evaluated over specific intervals of 6.6–13 s ($U_m = 1.4$ m/s), 25.66–32 s ($U_m = 1.1$ m/s), and 44.5–51 s ($U_m = 1.2$ m/s). The P2P values of P_L , without the integration of BESS, were measured as 0.050909 W, 0.04331 W, and 0.05236 W, respectively. With the integration of BESS, these values dropped to 0.049484 W, 0.02917 W, and 0.03307 W. Consequently, the corresponding Reductions were achieved as 2.25%, 32.65%, and 36.84%, respectively. While P_{wi} was evaluated during the intervals 10.28–16.28 s ($U_m = 1.4$ m/s), 22.6–28.6 s ($U_m = 1.1$ m/s), and 41.8–47.8 s ($U_m = 1.2$ m/s). The table shows that the P2P values decreased from 96.933 kW, 78.429 kW, and 99.822 kW without the integration of BESS to 88.095 kW, 46.993 kW, and 58.874 kW with the integration of BESS. As a result, the Reduction values were obtained as 9.11%, 40.08%, and 41.02%. P_{grid} was investigated at intervals of 6.6–13 s ($U_m = 1.4$ m/s), 25.83–32 s ($U_m = 1.1$ m/s), and 44.7–51 s ($U_m = 1.2$ m/s). The P2P values decreased from 98.336 kW, 81.626 kW, and 102.877 kW without the integration of BESS to 91.589 kW, 51.822 kW, and 61.82 kW with the integration of BESS. As a result, the Reductions were acquired as 6.86%, 36.51%, and 39.90%.

According to the results mentioned, the impact of BESS on improving

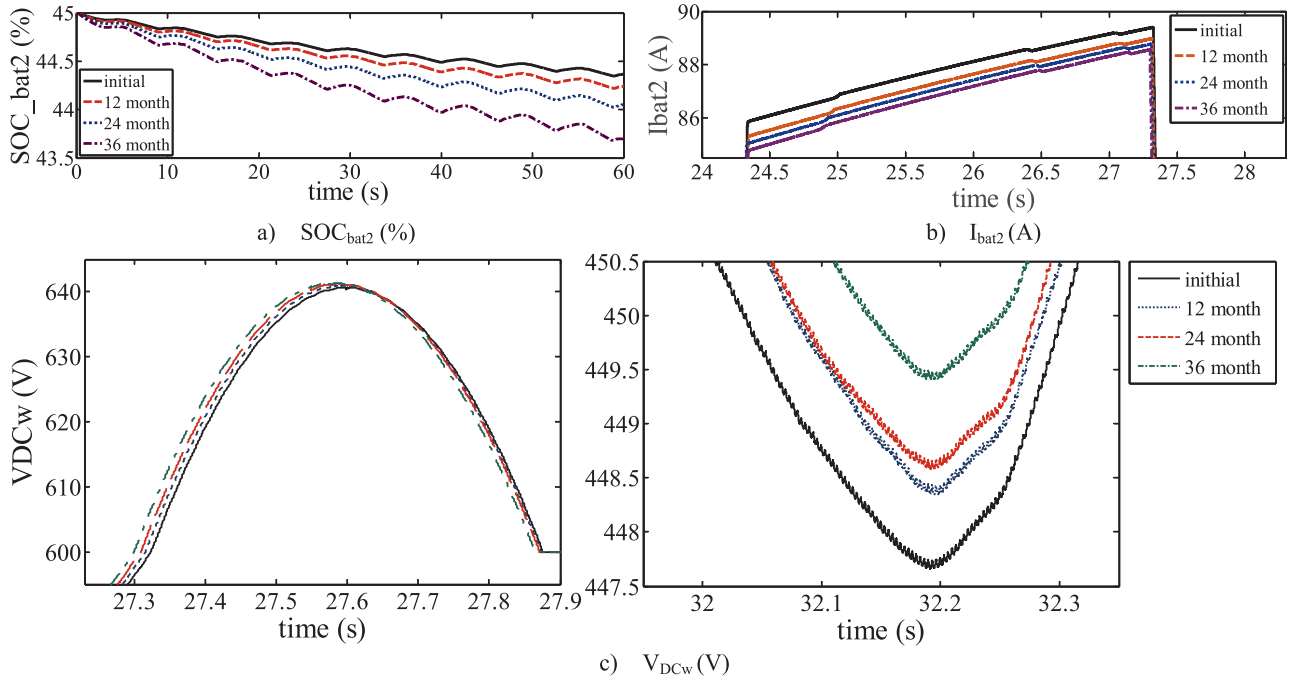


Fig. 27. Dynamic responses of the system under progressive BESS₂ degradation at different lifecycle stages (case 6).

MG performance in $U_m = 1.2$ m/s is greater than at other values; this indicates that BESS effectively smooths power fluctuations under moderate wave conditions by absorbing excess power and compensating for deficits of WPGS. To prove the accuracy of the results presented in Table 3, the time domain simulation of the BESS integration in the studied MG is shown in Fig. 26.

This figure compares three distinct configurations: (i) the MG without the WPGS and without the BESS; (ii) the MG with WPGS but without BESS; and (iii) Case 2 (see Section IV. D), which integrates both WPGS and BESS. Fig. 26 presents a comparison of V_{DCw} in two cases: one without BESS integration and the other case 2 (see section IV. D). It is clear that integrating the BESS in Case 2, the V_{DCw} P2P is reduced and stabilizes it around the reference value of 600 V. According to Fig. 26 (a)–(d), integrating a BESS into the studied MG reduces P2P fluctuations of both the DC link voltage and overall power oscillations, thereby

enhancing the stability of the MG. Furthermore, Fig. 26(c)–(d) shows that in the absence of WPGS the power absorbed by both the grid and the load is more stable. The THD of the current at the PCC remains below 5% across all configurations, as shown in Fig. 26(e). As illustrated in the figure, in the absence of the WPGS, the THD remains constant. Furthermore, when the WPGS is connected to the MG, the THD increases proportionally with the output power of the WPGS. It should be noted that the THD of the current in case 2 is lower than that of the other configurations during several intervals. Collectively, Fig. 26 validates the data presented in Table 3 and demonstrates the BESS's role in reducing P2P DC link voltage and power fluctuations in the studied MG under wave operating conditions. Furthermore, the more significant Reductions in V_{DCw} , P_{w1} , and P_{grid} at $U_m = 1.2$ m/s indicate improved dynamic stability and overall performance in Case 2.

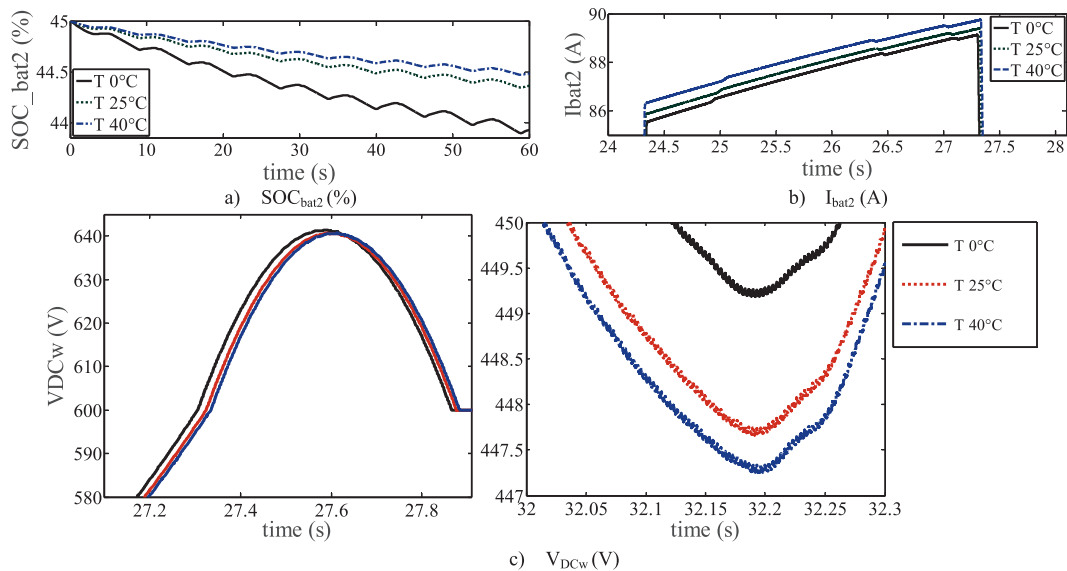


Fig. 28. Dynamic responses of the WPGS under the Temperature BESS₂ variations (case 6).

Table 4
Temperature-dependent BESS electrical and capacity parameters.

Year	Total loss (%)	Capacity [Ah]	Maximum capacity [Ah]	Internal resistance [Ω]
0 (initial)	0	100	104.1667	0.03400
1	17.2085	82.7915	86.24119	0.04277
2	34.4169	65.5830	68.31571	0.05155
3	51.6254	48.3746	50.39024	0.06032

Table 5
Evolution of BESS degradation parameters over a three-year operating period.

Ambient temp ($^{\circ}\text{C}$)	Rated capacity [Ah]	Maximum Capacity [A]	Internal resistance [Ω]	Fully charged voltage [V]
0	58.25	60.68	0.03825	361.6974
25	100	104.1667	0.03400	370.1974
40	125.05	130.26	0.03145	375.2974

Case 6: analysis of temperature and degradation effects on system performance

In this scenario, the individual effects of ambient temperature and long-term battery degradation on the MG's performance were investigated on the system configuration introduced in Case 2.

To assess long-term reliability, the effects of battery aging were studied by modeling the resultant performance degradation—specifically, capacity fade and increased internal resistance—over 12, 24, and 36-month horizons, with the outcomes presented in Fig. 27. The system was also evaluated under three temperature conditions (0°C , 25°C , and 40°C), as detailed in Fig. 28.

Key performance indicators, including SOC_{bat2} , I_{bat2} , and V_{DCw} were monitored throughout these tests. The formulation and implementation of the temperature and degradation models follow the methods established in [76–79]. Temperature-dependent BESS parameters were modeled using the capacity expression reported in the literature, which explicitly accounts for both ambient temperature and discharge rate [76]. Terminal-voltage behavior (open-circuit voltage together with the internal-resistance term) was represented following the CIEMAT/CIEMAT-derived system model commonly used for PV and storage simulation [77].

Irreversible degradation was incorporated using an Ah-throughput (cycle-aging) framework and by comparing alternative lifetime models recommended for lead-acid systems [78]; calendar-type aging and the temperature acceleration of aging were treated with Arrhenius/ Q10-style scaling as discussed in the literature on accelerated temperature testing [79]. Parameter choices and sensitivity bounds were selected to match the methodologies and orders of magnitude reported in the cited works.

Table 4 provides a three-year degradation projection, combining calendar and cycle aging effects. Cumulative loss is reported as both a fraction and a percentage, with annual values given for Capacity, Maximum Capacity, and Internal Resistance. The model reveals a progressive decline in both available and maximum capacity, alongside a corresponding increase in internal resistance over time. This trend indicates a reduction in energy storage capability and greater voltage sag under load.

Table 5 presents the temperature-dependent parameters for a lead-acid BESS, used as direct inputs for a dynamic BESS model under three ambient conditions (0°C , 25°C , and 40°C). These parameters are Rated Capacity (Ah), Maximum Capacity (Ah), Internal Resistance (Ohms), and Fully Charged Voltage (V). The data show that lower ambient temperatures reduce the usable rated capacity and increase internal resistance. For instance, at 0°C , the BESS delivers significantly fewer ampere-hours and exhibits higher resistance than at 25°C . In

contrast, a higher ambient temperature of 40°C increases the instantaneous usable capacity and slightly raises the open-circuit voltage. While this improves short-term energy delivery, it can also accelerate long-term aging.

Together, these tables serve two main purposes. First, they present a clear, reproducible example of how capacity fade and resistance growth evolve with aging. This facilitates year-by-year sensitivity analysis and supports studies on controller derating strategies. Second, they offer temperature-adjusted parameter sets for immediate use in system simulations.

Fig. 27 illustrates the system response under progressive BESS degradation at four lifecycle snapshots (Initial, 12 months, 24 months and 36 months). As shown in Fig. 27(a), SOC_{bat2} trajectories become progressively steeper with aging: for the same power profile the SOC_{bat2} decline per unit time increases as usable capacity diminishes, so later snapshots reach lower SOC values faster and approach protection cut-offs earlier. Fig. 27(b) indicates that the effective BESS current drawn during discharge is reduced after extended ageing (36 months) compared with the Initial case; this reduction can result from either the diminished available capacity/OCV and increased internal impedance of the aged cells or from intentional controller/BMS derating and current-limiting policies applied to protect the degraded BESS. Finally, Fig. 27(c) shows that the DC-link voltage excursions are smaller in the 36-month case: although aging increases internal resistance (which alone tends to increase voltage sag), the net power supplied by the battery is lower (reduced or enforced current limits), so the instantaneous power mismatch seen by the DC-link capacitor and converter is reduced and exhibits smaller transient deviations. In summary, under the modeled degradation the system manifests (i) steeper SOC decay, (ii) lower BESS current magnitudes, and (iii) reduced DC-link voltage fluctuation at 36 months compared with the Initial case — a behavior that reflects the combined influence of reduced source capability and lifecycle-aware control actions and that has important implications for controller tuning, derating strategies and protection settings. Fig. 28 illustrates the dynamic response of the energy storage system under three ambient temperature conditions (0°C , 25°C , and 40°C), focusing on (a) SOC_{bat2} , (b) I_{bat2} , and (c) V_{DCw} . As shown in Fig. 28(a), the SOC_{bat2} decreases more rapidly at 0°C compared to 25°C and 40°C , reflecting the reduced effective capacity and higher internal resistance of the BESS at low temperature, which limits usable energy and accelerates apparent SOC_{bat2} depletion. At the nominal temperature of 25°C , the SOC_{bat2} trajectory exhibits the most stable and linear behavior, corresponding to rated battery performance. At 40°C , a slower SOC_{bat2} decay is observed due to the increased effective capacity and improved electrochemical kinetics; however, this short-term benefit is typically associated with accelerated long-term degradation. Fig. 28(b) shows that at lower temperature (0°C) higher BESS current magnitudes are required to maintain the same power exchange, owing to increased internal resistance and voltage drop, while at 25°C the current profile remains smoother and closer to the nominal operating point. At 40°C , reduced resistance allows lower current for the same power demand, resulting in reduced current ripple. Finally, Fig. 28(c) presents the DC-link voltage behavior under the same three ambient temperatures. Because the DC-link in the test configuration is directly connected to the BESS, the BESS's terminal voltage and internal impedance constitute the effective source stiffness for the DC bus. During discharge, elevated internal resistance and lower terminal voltage at low ambient temperature produce a larger instantaneous power deficit that the DC-link capacitance and converter control must absorb, resulting in deeper and more frequent downward excursions of V_{DCw} at 0°C . Conversely, at 40°C the higher terminal voltage, lower internal resistance and greater effective capacity reduce the power mismatch during discharge and thus the amplitude of V_{DCw} transients, yielding the most stable DC-link profile. During charging events the sign of the instantaneous power mismatch is reversed: at low temperature the same high impedance can cause larger overshoots or corrective control actions (upward excursions) as the

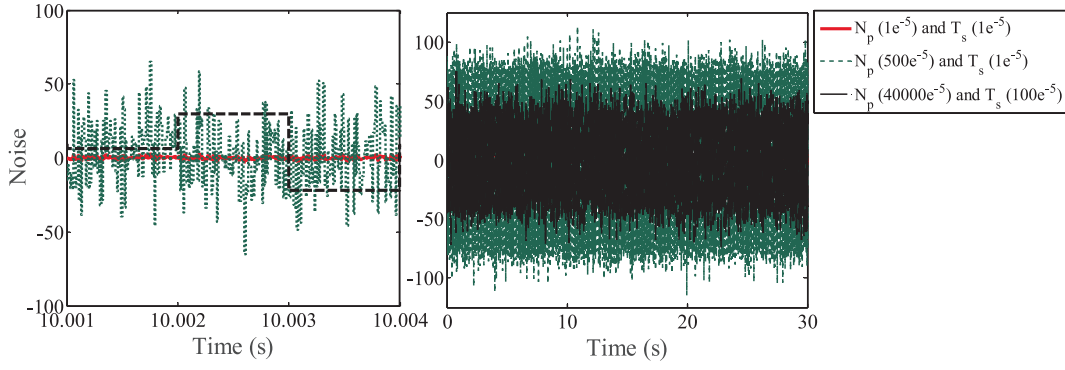


Fig. 29. Implemented sensor noise models for robustness evaluation.

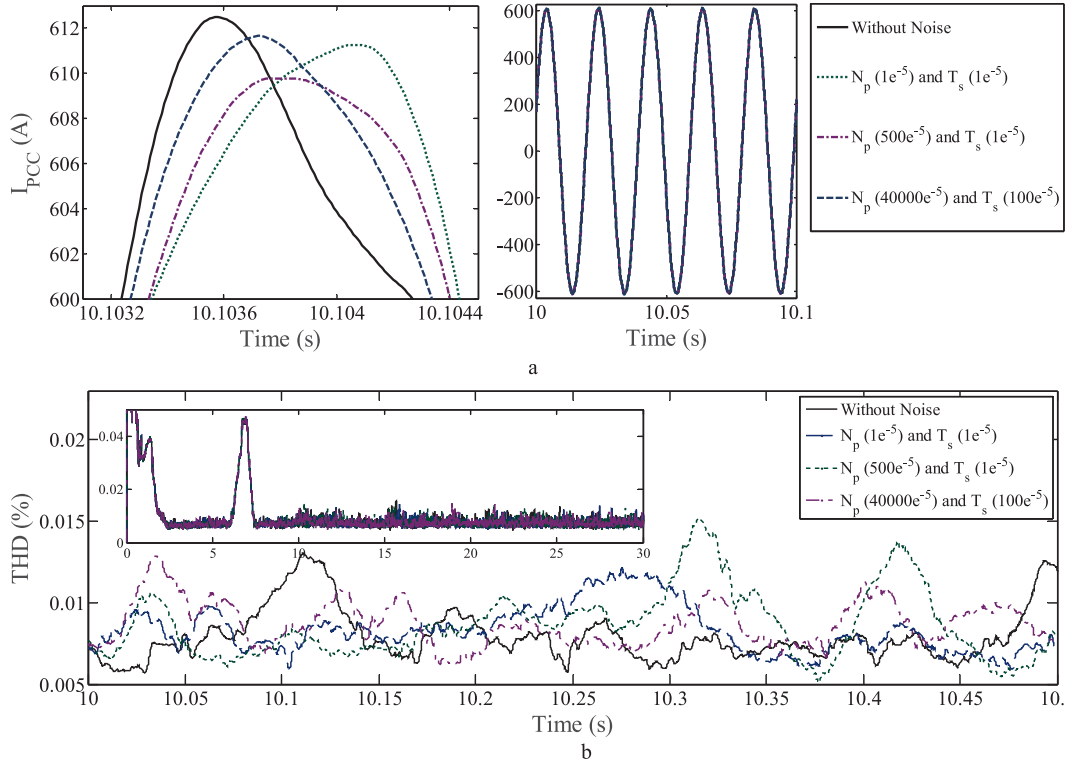


Fig. 30. Impact of sensor noise on grid-injected current: (a) PCC current waveform, and (b) its corresponding THD.

converter injects energy into a relatively stiff but high-impedance source, whereas at elevated temperature the lower impedance mitigates these overshoots and facilitates smoother voltage regulation. In summary, higher ambient temperature produces a stiffer effective DC source and smaller V_{DCw} deviations in both discharge and charge modes, although this short-term operational benefit must be weighed against the accelerated long-term degradation that elevated temperatures induce.

Case 7: stability and robustness validation of the proposed control scheme

In this scenario, the robustness of the proposed controllers under realistic measurement conditions is evaluated by implementing three distinct sensor noise models. The noise is characterized by its power level N_p and effective sampling time T_s , modeling the intensity and bandwidth of the measurement disturbance, respectively. The first model ($N_p = 1 \times 10^{-5}$, $T_s = 1 \times 10^{-5}$ s) represents a high-fidelity sensor with negligible noise. The second model ($N_p = 500 \times 10^{-5}$, $T_s = 1 \times 10^{-5}$ s) simulates a noisier sensor while maintaining a high sampling rate. The

third and most challenging model ($N_p = 40000 \times 10^{-5}$, $T_s = 100 \times 10^{-5}$ s) emulates a low-cost sensor package with significant noise and a slower measurement update, introducing substantial signal corruption and phase lag. The time-domain profiles of these three noise models are presented in Fig. 29.

In the simulation framework, these additive noise signals were injected into the primary voltage and current feedback channels. Each of the three noise scenarios was applied independently and sequentially to the closed-loop systems employing Controllers of (Figs. 12, 14, 16, 18), and V_{grid} . This methodology allows for a direct comparative analysis of each controller's performance degradation and stability margins when subjected to varying degrees of measurement imperfection, from near-ideal to highly adverse sensing conditions. The effectiveness of the proposed control strategies under the influence of sensor noise is further validated by analyzing the quality of the injected current at the PCC. As demonstrated in Fig. 30(a), the waveform of the PCC current remains highly stable, showing only minimal distortion despite the varying levels of measurement noise applied to the feedback loops. This visual stability is quantified through THD analysis in Fig. 30(b), which confirms that for

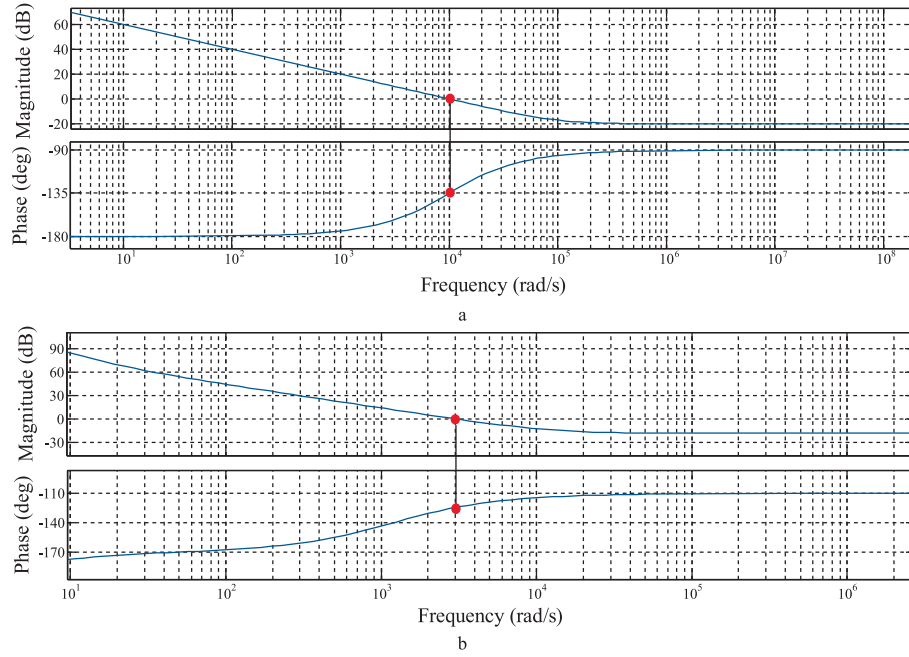


Fig. 31. Bode plots of the (a) PV system's bidirectional BESS converter controller and (b) PV system's VSI controller under nominal conditions.

all controllers and across all three noise scenarios, the current THD is consistently maintained below the 5% threshold. These results critically demonstrate that the proposed controllers successfully reject sensor noise, effectively preserving both dynamic performance and strict power quality standards under realistic, non-ideal measurement conditions.

To further demonstrate the inherent stability and robustness of the proposed control scheme, the frequency-domain characteristics of two critical controllers are analyzed under nominal conditions in the absence of sensor noise. Specifically, this analysis focuses on the controllers within the PV system. Fig. 31 presents the Bode plots for (a) the PV system's bidirectional DC/DC converter controller and (b) the PV system's VSI controller. In Fig. 31(a), the controller exhibits a phase margin (PM) of 45° at a crossover frequency of $\approx 1 \times 10^4$ rad/s, indicating a stable, well-damped response suitable for fast power tracking. Fig. 31(b) shows the VSI controller with a phase margin of 58.75° at a crossover frequency of $\approx 3 \times 10^3$ rad/s. The substantial PM in Fig. 31(a) provides a balanced compromise between responsiveness and damping, ensuring reliable performance under typical power variations.

The even larger PM in Fig. 31(b), combined with its lower crossover

frequency, reflects a more conservative and robust design. This design enhances the system's inherent tolerance to phase delays while promoting greater damping to maintain power quality. Collectively, the frequency-domain metrics of these PV system controllers confirm their foundational stability and capacity to preserve closed-loop performance, establishing a solid basis for their effective integration within the overall microgrid control framework.

G. Case 8: computational complexity and scalability analysis

In this scenario, the computational burden of the proposed hierarchical microgrid control system is rigorously evaluated.

The analysis is conducted by simulating 16 distinct operational modes, each with a different configuration of active controllers. The key variable N_{CP} is defined as the number of active controllers within the system, ranging from 0 to 8. The objective is to characterize the growth rate of the computational cost, expressed in Big O notation, as a function of N_{CP} . The simulation environment was configured with a fixed duration ($T_{sim} = 5$ s) and a sample time ($T_s = 10^{-5}$ s). Consequently, the total

Table 6
Simulation-based evaluation of computational time and scalability for a proposed MG.

Mode	WPGS system Controller of		PV system Controller of			FC system Controller of		T_{CPU}
	VSI	Buck/Boost converter	VSI	Buck/boost converter	Boost converter	VSI	Buck converter	
1	×	×	×	×	×	×	×	1.08
2	✓	×	×	×	×	×	×	1.72
3	×	✓	×	×	×	×	×	1.10
4	×	×	✓	×	×	×	×	1.75
5	×	×	×	✓	×	×	×	1.71
6	×	×	×	×	✓	×	×	1.23
7	×	×	×	×	×	✓	×	1.47
8	×	×	×	×	×	×	✓	1.16
9	✓	✓	✓	✓	✓	✓	✓	4.53
10	×	✓	✓	✓	✓	✓	✓	3.89
11	✓	×	✓	✓	✓	✓	✓	4.09
12	✓	✓	×	✓	✓	✓	✓	3.83
13	✓	✓	✓	×	✓	✓	✓	4.06
14	✓	✓	✓	✓	×	✓	✓	4.31
15	✓	✓	✓	✓	✓	×	✓	3.77
16	✓	✓	✓	✓	✓	✓	×	4.01

number of simulation steps per run is constant and given by ($N_{\text{step}} = T_{\text{sim}}/T_s = 500,000$). The measured CPU time T_{CPU} for each configuration therefore directly reflects the aggregate computational load. The baseline cost, corresponding to the system with all controllers disabled (Mode 1, $N_{\text{CP}} = 0$), is ($T_{\text{CPU}} = 1.08$ s). The total CPU time increases systematically as controllers are activated, reaching ($T_{\text{CPU}} = 4.53$ s) when all eight controllers are active (Mode 9, $N_{\text{CP}} = 8$).

Based on the data from the series of simulations under different operational modes (as presented in Table 6), the relationship between T_{CPU} and N_{CP} is derived empirically. The results demonstrate a strongly linear trend as N_{CP} progresses from 0 to 8, modeled as:

$$T_{\text{CPU}} = T_{\text{base}} + k_{\text{CP}} \cdot N_{\text{CP}} \quad (71)$$

where ($T_{\text{base}} \approx 1.08$ s) represents the baseline execution time and k_{CP} denotes the average incremental cost per controller. This linear scaling is substantiated by the data from modes where a single controller is removed from the full set (Modes 10–16), each resulting in a consistent and predictable reduction in T_{CPU} . The empirical evidence conclusively establishes that the system's computational cost scales linearly with the number of active controllers, corresponding to an $O(N_{\text{CP}})$ time complexity.

This finding of linear scalability, $O(N_{\text{CP}})$, is critical for assessing the system's practical viability. It demonstrates that expanding the MG architecture with additional distributed energy resources and their associated controllers will incur a proportional and manageable increase in computational load. This predictable scaling confirms the computational efficiency of the proposed control framework and underscores its suitability for larger-scale MG deployments. All simulations were executed on a workstation with an Intel Core i5 processor operating at 2.67 GHz. It is noted that the absolute T_{CPU} values are hardware-dependent and would be correspondingly lower on processors with higher operational speeds and improved architectural features.

Discussion on the impact of the proposed scheme on reliability

The proposed coordinated control scheme, integrating a dedicated BESS for the AWS-based WPGS within a multi-source hybrid MG, demonstrably enhances overall system reliability through a multifaceted, interconnected approach. In the context of dynamic power systems, reliability is defined as the capability to ensure continuous, stable, and high-quality power delivery to both the grid and local loads, despite the inherent stochasticity of renewable generation and external disturbances. The comprehensive simulation results, spanning eigenvalue analysis, time-domain performance, and robustness testing, provide concrete evidence of this enhancement across several critical dimensions:

1. Enhancement of Dynamic Stability and Damping, Mitigating Instability Risk:

The integration of high-penetration wave energy, characterized by its high peak-to-average power ratio and oscillatory power output, poses a significant threat to system stability by exciting poorly damped electromechanical and converter-driven oscillatory modes.

The dedicated dual-loop BESS controller for the WPGS acts as a fast-acting power buffer. Its adaptive charging and discharging actively decouples the inherent wave power transients from the rest of the MG. This stabilizing effect is quantitatively validated through eigenvalue and root locus analysis (Section IV.A, IV.B). The analyses confirm that the system's dominant oscillatory modes remain stable and exhibit improved damping (evidenced by leftward migration in the s -plane) under simultaneous variations in wave excitation, solar irradiance, and SOFC operating points. A system with enhanced modal damping possesses a fundamentally higher reliability margin, as it can absorb disturbances without the risk of growing oscillations that could trigger protection systems or lead to voltage collapse.

2. Guarantee of power quality and grid code compliance, ensuring operational continuity

Consistently high power quality is a prerequisite for reliable operation, preventing nuisance tripping of protective relays and avoiding equipment degradation. The unified feedforward decoupling control framework applied across all power electronic interfaces (rectifiers and VSIs) ensures precise, independent control of active and reactive power. This maintains stable DC-link voltages and produces a high-fidelity AC output. Time-domain simulation results across all primary operational cases (Cases 1–5) consistently demonstrate that the THD of the current at the PCC is maintained below the 5% limit, achieving full compliance with IEEE Standard 519–2014 (Fig. 22(r), 23(k), 24(h), 25(f)). This strict adherence to grid codes under diverse operating scenarios directly minimizes the risk of disconnection and compatibility issues, thereby bolstering operational reliability.

3. Active mitigation of high-amplitude power fluctuations, reducing component and grid Stress

The pronounced fluctuations inherent to wave energy translate into significant mechanical, thermal, and electrical stress on all system components, from power semiconductors to generator windings, potentially accelerating wear and failure rates. The proposed control scheme delivers a direct and quantifiable mitigation of these fluctuations. As detailed in Case 5 (Table 3), the integration of the WPGS-dedicated BESS achieves a maximum reduction in P2P power fluctuations of 41% for key parameters such as P_{wi} , P_{grid} , and V_{DCw} . The comparative time-domain waveforms (e.g., Fig. 26) visually corroborate this substantial smoothing effect. By attenuating these high-amplitude swings, the control strategy directly reduces dynamic stress across the entire generation and distribution infrastructure, contributing to lower failure rates, extended equipment lifespan, and more predictable power exchange with the main grid—all critical elements of a reliable system.

4. Computational scalability with linear complexity, ensuring practical deployability

The practical reliability of a control system is also contingent upon its computational efficiency and predictable resource scaling. As rigorously evaluated in Case 8, the aggregate computational burden of the proposed hierarchical control scheme exhibits a linear scaling relationship, $O(N_{\text{CP}})$, with the number of active controllers (N_{CP}). This empirical finding, derived from simulations across 16 operational modes (Table 6), confirms that adding or removing control units incurs a proportional and manageable increase in processing time. For a system targeting expansion or modular operation, this linear complexity ($O(N_{\text{CP}})$) is a critical reliability attribute. It ensures that the control framework remains computationally feasible and deterministic in real-time applications, preventing unforeseen latency or overloads that could compromise system stability as the microgrid architecture grows.

5. Robustness under real-world imperfections and aging, ensuring long-term dependability

Reliability extends beyond ideal conditions to encompass performance degradation and measurement inaccuracies over time. The extended case studies (Cases 6 & 7) validate the scheme's robustness against such practical challenges. The system maintains stable operation despite BESS performance degradation over a simulated 36-month period (modeling capacity fade and increased internal resistance) and under significant sensor noise with varying sampling rates (Figs. 27, 28). Furthermore, the controller demonstrates effective performance across a range of ambient temperatures (0 °C to 40 °C), adapting to changes in BESS kinetics and capacity (Fig. 28). This resilience to component aging and measurement noise confirms that the reliability benefits are not

merely theoretical but persist under non-ideal, realistic operating conditions.

6. Frequency-domain stability validation of PV controllers

The inherent stability and robustness of the PV system controllers are quantitatively confirmed through frequency-domain analysis. As presented in Fig. 31 and discussed in Case 7, the bidirectional DC/DC converter controller achieves a phase margin of 45° at a crossover frequency of $\approx 1 \times 10^4$ rad/s, while the VSI controller exhibits a phase margin of 58.75° at $\approx 3 \times 10^3$ rad/s. These ample phase margins indicate well-damped, robustly stable control loops capable of tolerating phase delays and uncertainties. This foundational stability directly supports the system's reliability by ensuring that the PV sub-system can maintain performance under both nominal and perturbed conditions.

7. Enforcement of instantaneous power balance and voltage support, preventing cascading Failures

A core reliability function is the prevention of local disturbances from escalating into system-wide failures. The primary control objective of regulating the DC-link voltage (e.g., at 600 V for the WPGS bus) ensures instantaneous real-power balance within the MG's DC network. As shown in dynamic responses, the BESS seamlessly compensates for power deficits or surpluses from the highly variable WPGS and the PV array. This fast, active power balancing prevents DC voltage collapse or dangerous overvoltage conditions that could force inverters into protective shutdown. This capability is crucial for reliability, as it contains disturbances at their source and prevents local voltage violations from cascading throughout the system. In summary, the proposed scheme enhances reliability as a direct, system-level consequence of its integrated and efficiently scalable design. It actively damps destabilizing oscillations, ensures stringent power quality compliance, physically smooths damaging power swings, scales with predictable linear computational burden, proves robust against sensor errors and component aging, validates its frequency-domain stability margins, and enforces local power balance. Collectively, these features transform the highly variable and challenging wave energy resource from a potential liability for grid stability into a manageable, predictable, and valuable asset within a resilient and scalable hybrid MG architecture.

Study limitations and future work

Despite the comprehensive simulation-based analysis presented in this study, certain limitations must be acknowledged. The findings and validations are derived from detailed high-fidelity nonlinear models. However, hardware-in-the-loop (HIL) testing using platforms like Opal-RT or physical experimental validation of a full-scale prototype was not feasible under the current infrastructural and practical constraints. Consequently, while the simulation results are robust and promising, they represent a necessary first step prior to real-world deployment. Building upon this foundation and to address these limitations, the following pathways are identified as crucial directions for future research:

- (a) **Experimental Validation and Prototyping:** The foremost next step is the experimental validation of the proposed control schemes. This includes HIL testing to verify performance under real-time constraints and converter switching dynamics, and the eventual development of a scaled-down or full physical prototype for field testing under realistic marine and grid conditions.
- (b) **Cybersecurity-Resilient Operation:** The coordinated control framework relies on communication and sensor data. Future work must investigate its vulnerability to cyber-physical attacks (e.g., false data injection, time-delay attacks) and develop

integrated intrusion detection systems (IDS) and attack-resilient control algorithms to ensure operational security and stability.

- (c) **AI-Enhanced Forecasting and Adaptive Control:** To further optimize performance, Machine Learning (ML) techniques offer significant potential. This includes using Reinforcement Learning (RL) for the online, adaptive tuning of controller parameters (e.g., for the BESS), and employing deep learning models (e.g., LSTMs) for accurate short-term forecasting of wave power and solar irradiance. These forecasts can be integrated into a Model Predictive Control (MPC) framework for proactive, optimal energy management.
- (d) **Islanded Operation and Grid Services:** Extending the system's functionality to operate autonomously is critical for resilience. Future research will focus on designing and validating control strategies for stable islanded (off-grid) operation and seamless mode transition between grid-connected and islanded states. This includes developing hierarchical control for local voltage/frequency regulation and robust synchronization controllers for safe grid reconnection.

By pursuing these directions, the research can evolve from a validated simulation model toward an intelligent, secure, and resilient maritime energy platform, ready for practical implementation and capable of providing reliable grid services.

Conclusion

In this paper, a comprehensive dynamic stability analysis and several coordinated controllers are presented for a grid-connected hybrid MG that integrates an AWS-based WPGS with PV, SOFC, SG, and dedicated BESS. A high-fidelity nonlinear model of the studied MG was developed, and a dedicated control structure was implemented for the bidirectional BESS converters. Additionally, a feedforward decoupling scheme for power-electronic interfaces was designed to eliminate cross-coupling and stabilize the DC-link voltage. The effectiveness of the proposed controllers on the dynamic stability of the MG was evaluated through eigenvalue analysis, root loci technique, and time-domain simulations.

Furthermore, the results demonstrate that P2P fluctuations were reduced (up to 41%), the DC-link voltage was maintained at the specified setpoint, and the PCC current THD remained below 5% across all scenarios. Frequency-domain analysis of the PV system controllers further confirmed their inherent stability, with phase margins of 45° at $\approx 1 \times 10^4$ rad/s and 58.75° at $\approx 3 \times 10^3$ rad/s. The control scheme also demonstrated robust performance under realistic conditions, including sensor noise, BESS degradation over a 36-month period, and a range of ambient temperatures (0°C to 40°C). Moreover, comparative analyses confirmed that integrating both a BESS and its dedicated control into the studied MG provides significant damping characteristics and improves power quality. A critical finding from the computational scalability analysis (Case 8) is that the aggregate controller burden scales linearly, $O(N_{CP})$, with the number of active controllers, confirming practical feasibility for system expansion. In summary, the proposed framework enhances system-level reliability by ensuring dynamic stability, guaranteeing power quality, mitigating damaging power swings, and maintaining power balance, all while exhibiting predictable computational scaling and robustness to practical imperfections.

While the validation of the results is based on numerical simulations and is encouraging, several important limitations are not addressed in this paper; for instance, communication delays and converter switching effects. Hence, future work to validate the control schemes in practical measurement, communication, and switching environments will involve both hardware-in-the-loop (HIL) real-time simulation and the development of a physical prototype for field trials. The results of all test cases suggest that the presented control scheme provides an effective and reliable method for integrating an AWS-based wave power generation plant into a hybrid MG in terms of dynamic stability and power quality.

Table 7

Employed system parameters.

53-kW WPGS [43,54]
$\phi = 2.97327$; $N_{ph} = 492$; $C_w = 0.3F$; $M_s = 4$; $W_s = 0.2m$; $\tau = 0.072m$; $RL = 7.5\Omega$; $L_{sw} = 0.115H$; $R_a = 1.5\Omega$; $R_w = R_{w1} = R_{w2} = 0.001\Omega$; $L_w = L_{w1} = L_{w2} = 94.314mH$; $C_{wf} = 53.715\mu F$
49-kW PV Array, dc/dc boost converter and filter [59]
$P_{mp} = 213.15$ W, $V_{mp} = 29$ V, $I_{mp} = 7.35$ A, $N_{cell} = 60$ cells, $V_{oc,n} = 36.3$ V, $I_{sc,n} = 5.96$ A, $R_s = 0.39381\Omega$, $R_{sh} = 313.0553\Omega$, $N_{ms} = 11$, $N_{mp} = 21$, $A = 1.3$, $q = 1.6022 \times 10^{-19}$ C, $k = 1.3806 \times 10^{-23}$ J/K; $C_p = C_{Dcp} = 286.53\mu F$, $L_p = 17.9$ mH; $R_p = R_{p1} = R_{p2} = 0.001\Omega$; $L_p = L_{p1} = L_{p2} = 94.314mH$; $C_{pf} = 53.715\mu F$
50-kW SOFC, dc/dc buck converter and filter [59,71]
To account for the SOFC configuration, two identical SOFC stacks, each rated at 25 kW and 630 V, are connected in parallel and considered as single SOFC unit: $P_{rate} = 25$ kW; $F = 96487C/mol$; $R = 8.314J/(mol\ K)$; $T = 1133$ K; $E_0 = 1.18V$; $N_0 = 900$ cells; $K_r = N_0/4F = 2.3 \times 10^{-3}mol/(s.atm)$; $K_{H_2} = 0.843mol/(s.atm)$; $K_{H_2O} = 0.281mol/(s.atm)$; $K_{O_2} = 2.52mol/(s.atm)$; $\tau_{H_2} = 26.1s$; $\tau_{H_2O} = 78.3s$; $\tau_{O_2} = 2.91s$; $r = 0.126\Omega$; $T_e = 0.8s$; $\tau_f = 5s$; $r_{H_2O} = 1.145$; $PF = 1.0$; $P_{fuel} = 101325Pa$; $P_{air} = 1.2 \times 101325Pa$; $U_{H_2} = 0.8$; $U_{O_2} = 0.3$; $x = \%4$; $y = \%21$; $R_f = R_{f1} = R_{f2} = 0.001\Omega$; $L_f = L_{f1} = L_{f2} = 1$ mH; $C_{ff} = 49.736\ \mu F$; $C_f = 0.0163F$; $C_{Dcf} = 0.1F$; $L_f = 61.5mH$
BESS (Lead-Acid)
$E_0 = 347.74$ V; $R_b = 0.034\Omega$; $k_b = 0.10126$ V/Ah; $A = 23.1329$ V; $B = 9$ Ah; $Q = 100$ Ah; $C_b = 714.29\ \mu F$; $L_b = 807.69$ mH; $C_{Dcb} = 0.0013$ F

Employed MG parameters

The complete employed parameters of the studied MG are listed in Table 7.

CRedit authorship contribution statement

Rebin Mohammad Amini: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Resources, Software, Validation, Visualization, Writing – original draft. **Rasool Kazemzadeh:** Supervision, Writing – review & editing. **Javad Morsali:** Methodology, Supervision, Validation, Visualization, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The paper includes all the required data. The author will make any further data available to applicants upon reasonable request, subject to a per-case check.

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