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Enhancement of Microgrid Power-Sharing Stability Using Droop Control Power System Stabilizer Based on Genetic Algorithm Optimization

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Abstract

In this study, a novel method is presented to significantly improve stability in isolated microgrids. The approach involves enhancing the conventional droop controller technique by incorporating a power system stabilizer (PSS), which greatly enhances the performance of the controller. Designing an inverter-based autonomous microgrid system poses a challenge in selecting the appropriate gain for the conventional controller, as achieving fast power-sharing requires a high droop gain, but this can compromise system stability. To address this dilemma, a tradeoff is necessary in the design of the conventional droop controller. This paper tackles this challenge by developing a PSS specifically designed for inverter-based microgrids. The gain selection process is achieved through Genetic Algorithm Optimization, ensuring optimal performance. The PSS design is meticulously described step by step, utilizing a standard IEEE system microgrid as the reference model. To validate the effectiveness of the proposed controller, comprehensive time domain simulation analyses are conducted. The results demonstrate the significant improvements achieved in microgrid stability, establishing the efficacy of the developed approach.

Keywords: Droop control, Power-sharing, Power system stabilizer, Genetic algorithm.

I. Introduction

Isolated microgrids have gained significant attention as autonomous power systems that can operate independently from the main grid, providing reliable electricity in remote areas and during emergencies. Effective load sharing among the distributed energy resources (DERs) within these microgrids is crucial for optimal utilization of available resources and maintaining system stability. However, load sharing in isolated microgrids presents unique challenges due to the dynamic nature of renewable energy sources, intermittent load variations, and the absence of centralized control [1]. Traditional control mechanisms, such as droop control and frequency-based control, often struggle to achieve accurate and efficient load sharing in these complex and dynamic environments. As a result, extensive research efforts have been dedicated to developing advanced load sharing strategies and control techniques. Intelligent algorithms, such as optimization algorithms and artificial intelligence-based approaches, have shown promise in enhancing load sharing accuracy, adaptability, and stability in isolated microgrids [2]. These techniques consider the real-time conditions of DERs and loads, allowing for more precise control and coordination among the system components. By addressing the challenges associated with load sharing, research in this area aims to optimize the performance of isolated microgrids, improve energy management, and promote sustainable and resilient power systems.

The droop control approach has emerged as an intriguing technique for regulating load sharing among inverters within an isolated microgrid. This method offers a decentralized control mechanism that allows for autonomous power sharing among interconnected inverters without the need for centralized coordination [3]. In the droop control technique, the output frequency of each inverter is modulated based on the deviation between the actual and desired power sharing ratios. By adjusting the output frequency, the inverters respond to changes in load demand and actively redistribute power accordingly. This decentralized approach promotes system stability and resilience by ensuring a balanced distribution of power among multiple inverters [4-7]. Moreover, the droop control technique is relatively simple to implement, making it an attractive option for load

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sharing in isolated microgrids. Ongoing research focuses on further enhancing the accuracy and efficiency of droop control through advanced algorithms, improved communication protocols, and coordination strategies, ultimately contributing to the optimization of load sharing in isolated microgrid systems [8-10].

The transient behavior of the parallel inverter in an isolated microgrid is of utmost importance due to the absence of an inertial portion within the system. Consequently, the design of the controller plays a critical role in ensuring the stability of the microgrid [11]. Several studies, such as those referenced in [12] and [13], have focused on developing comprehensive small signal models for inverter droop-controlled isolated microgrids. These studies have revealed that the low-frequency modes of the system are predominantly influenced by the parameters of the droop controller. Thus, even minor adjustments to the controller parameters can significantly impact the overall stability of the microgrid. In consideration of stability limits arising from droop control, Reference [14] introduces an energy supervision system for isolated microgrids. Furthermore, numerous investigations have been carried out to incorporate the dynamics of loads into the small signal model, as demonstrated in references [15-18]. Addressing power systems with a high penetration level of power electronics interfaced dispersed generation, Reference [19] examines transient stability, while Reference [20] utilizes structured singular values to analyze the robust stability of a voltage and current control solution for a standalone distributed generation unit. Additionally, [21-24] explore the combined droop and average power approach for load-sharing control in freestanding AC supply mode. Collectively, these studies emphasize the paramount importance of the controller in ensuring the stability of autonomous microgrids. Swift load sharing is crucial to prevent inverter overloading and potential voltage collapse at the terminal points.

Extensive research endeavors have delved into the realm of controller design, aiming to elevate the dynamic performance of microgrids to new heights. In pursuit of heightened transient responsiveness, a groundbreaking modification to the conventional droop controller was introduced in reference [25], incorporating a derivative-integral term. Expanding upon this innovative approach, reference [26] proposed a remarkable three-stage auxiliary controller that harnessed the power of a power system stabilizer (PSS) to unlock even greater performance enhancements. In the pursuit of refining microgrid dynamics while preserving steady-state response, reference [27] developed an adaptive derivative droop control strategy tailored explicitly for this purpose. To fortify microgrid stability against the impact of droop factors, reference [28] advocated the inclusion of a feedforward adjustment, bolstering resilience. Furthermore, the quest for optimal control settings for inverters witnessed thorough exploration in references [29] and [30] through the application of diverse optimization methods. In reference [31], an ingenious PSS-based damping controller was unveiled, specifically designed for microgrids equipped with hybrid inverters and synchronous machine-based distributed generators. Despite the progress made by these previous solutions in enhancing microgrid stability, their implementation often encountered challenges due to the demanding nature of tuning parameters.

The literature on the enhancement of microgrid power-sharing stability through algorithms optimization techniques has witnessed significant advancements in recent years. Numerous research studies have focused on investigating the gains achieved by integrating optimization algorithms into microgrid control strategies. These studies aim to assess the effectiveness of various optimization techniques in improving power-sharing stability within microgrid systems. Reference [32] presents a small-signal dynamic model and employs a genetic algorithm to optimize key control parameters in inverter-based microgrids, thereby enhancing their dynamic performance. Reference [33] enhances the droop control strategy by incorporating a frequency correction segment and a fuzzy self-adaptive PID controller. This addition improves frequency stability and reduces voltage fluctuations within the microgrid. Reference [34] introduces a novel control method that utilizes a genetic optimization algorithm to achieve more efficient power distribution among different power generating units in the microgrid.

In the quest for achieving optimal load-sharing, it has been established that substantial angle droop gains play a pivotal role, especially in challenging system conditions. However, it is crucial to strike a balance as high droop gains can have a detrimental impact on the overall stability of the system. To address this challenge, innovative PSS-based controllers have been developed to stabilize the primary droop control loop, offering additional dampening capabilities for low-frequency oscillations. Notably, the proposed technique presents a unique approach by focusing solely on modifying the power controller to achieve the desired dampening effect. This technique exhibits remarkable versatility and adaptability, capable of being designed and implemented in any inverter microgrid configuration, be it radial or mesh. The decoupling of active and reactive loops is a key consideration, simplifying the analysis process for researchers and engineers. Moreover, the introduced genetic algorithm-based optimization techniques in the proposed approach stand out from traditional PSS methods, which have often resulted in unsatisfactory performance. By leveraging the advantages of genetics algorithms, the proposed technique optimizes the PSS gains, eliminating the need for time-consuming optimization of multiple parameters. The optimization process primarily revolves around accurately calculating the phase lag delay induced by the output filter.

II. Conventional Droop Control for Power-Sharing

Figure 1 shows the single-line diagram of the standard IEEE 9 bus system. It is a widely used power system test case that serves as a benchmark for analyzing and studying various aspects of power systems. The system consists of nine buses, three generators, three loads, and multiple transmission lines. The buses are interconnected through transmission lines, forming a network. The system includes a slack bus (Bus 1) that represents the main generator and is typically set as the reference bus. The slack bus has a fixed voltage magnitude and phase angle. There are also generator buses (Buses 2, 3, and 4) where generators are connected, and load buses (Buses 5, 6, and 7) where loads are connected. These buses have both active and reactive power generation/consumption.

The IEEE 9 bus system, when combined with renewable distributed generation (DG) units, provides a realistic framework for studying the integration of renewable energy sources into power systems. In this modified configuration, the traditional generator buses in the IEEE 9 bus system are replaced with renewable DG units, such as wind turbines or solar panels. The DG units are connected to the respective buses, reflecting their physical presence and power injection into the system. This modification allows for the investigation of various aspects related to the integration of renewable energy, such as power output variability, grid stability, and power flow control. By examining the behavior of the modified IEEE 9 bus system with renewable DG units, valuable insights can be gained into the challenges and opportunities associated with renewable energy integration. This analysis helps in developing strategies to optimize power generation, improve system stability, and enhance the overall reliability and sustainability of the power grid.

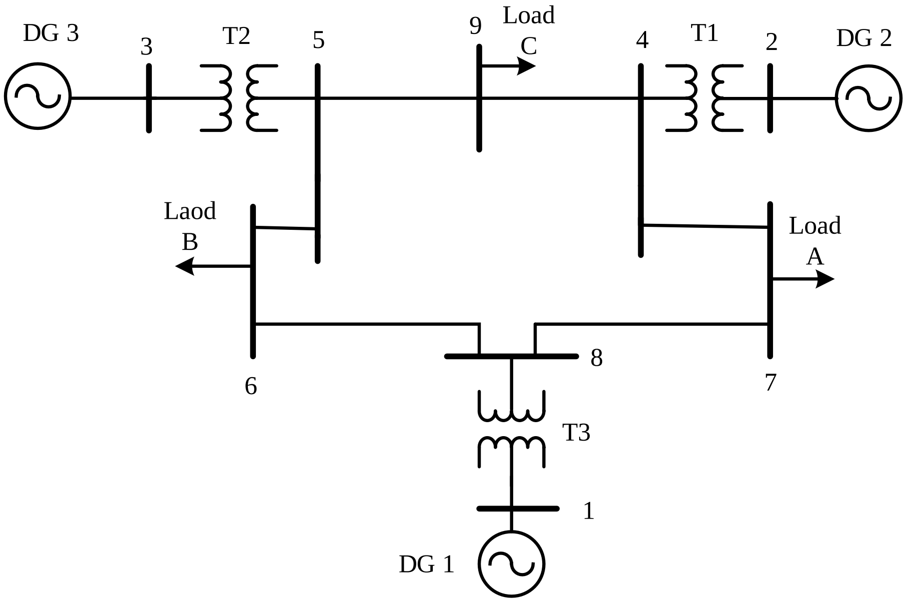


Figure 1. The single-line diagram of the standard IEEE 9 bus system

1. *Droop Controller*

The concept of droop control is based on the principle of voltage and frequency droop, where the power output of each DG is inversely proportional to its frequency or voltage deviation from the nominal value. This means that as the load increases, the frequency or voltage of each DG decreases, leading to an automatic increase in their power output to maintain balance within the system. Conversely, as the load decreases, the frequency or voltage increases, causing the power output of each DG to decrease. Droop control ensures a fair and stable power sharing arrangement among the DGs, promoting efficient utilization of distributed energy resources in the microgrid as shown in figure 2. The instantaneous power at the inverter's output is:

$$\tilde{P} = v_{od}i_{od} + v_{oq}i_{oq} \qquad (1)$$

$$\tilde{q} = -v_{od}i_{od} + v_{oq}i_{oq}. \qquad (2)$$

To extract the fundamental components P and Q from instantaneous powers, a low-pass filter is employed. This filter incorporates a cutoff frequency ω_c, which allows only the desired frequency components to pass through. By applying the low-pass filter, the fundamental components P and Q can be isolated from the instantaneous powers.

$$P = \frac{\omega_c}{S+\omega_c}\tilde{P} \qquad (3)$$

$$Q = \frac{\omega_c}{S+\omega_c}\tilde{q}. \qquad (4)$$

To determine the updated operating frequency and output voltage, the droop gain relations (refer to Fig. 2) are utilized. These relations incorporate an intelligent droop coefficient m_p, which represents the *f-P* drooping behavior, and a droop coefficient n_q, which represents the V-Q droop behavior. With these coefficients, the new frequency and voltage values can be calculated using the following equations:

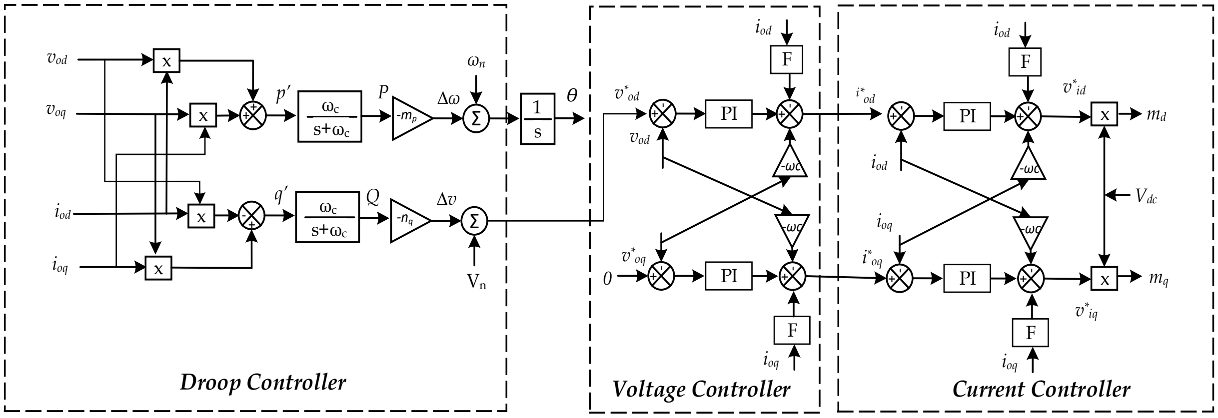


Figure 2. Cascaded control technique for the inverter

$$\omega = \omega_n - m_pP \qquad (5)$$

$$v^*_{od} = V_n - n_qQ, v^*_{oq} = 0, \qquad (6)$$

Where; ω_n represents the nominal frequency, V_n signifies the nominal voltage, ω denotes the new operating frequency, v^*_{od} corresponds to the reference voltage along the d-axis, and v^*_{oq} represents the reference voltage along the q-axis.

The equations used to calculate the droop coefficients, m_p and n_q, are as follows:

$$m_p = \frac{\omega_{max} - \omega_{min}}{P_{max}} \tag{7}$$

$$n_p = \frac{V_{max} - V_{min}}{Q_{max}}, \tag{8}$$

In the islanded mode, the selection of m_p and n_q is crucial. These coefficients are chosen in such a way that the change in load is distributed among the parallel inverters according to their respective ratings.

2) Voltage and Current Controller

The voltage control loop, depicted in Figure 2, plays a crucial role in maintaining bus voltage stability. On the other hand, the current loop serves to safeguard the insulated-gate bipolar transistors (IGBTs) from over-currents. To generate the reference current voltage, a proportional-integral (PI) regulator has been developed. This PI controller follows standard practices and incorporates decoupled and feedforward control loops. The dynamics of the voltage controllers can be expressed as follows:

$$i_d^* = K_{pv}(v_{od}^* - v_{od}) + K_{iv}\int(v_{od}^* - v_{od})dt - \omega^* C_f v_{oq} + F i_{od} \text{ and} \tag{9}$$

$$i_q^* = K_{pv}\left(v_{oq}^* - v_{oq}\right) + K_{iv}\int\left(v_{oq}^* - v_{oq}\right)dt - \omega^* C_f v_{od} + F i_{oq}, \tag{10}$$

where K_{pv} represents the proportional gain, K_{iv} signifies the integral gain, C_f denotes the capacitance of the filter, and F represents the feedforward gain.

The voltage across the filter inductor can be determined using a conventional PI current controller. The dynamics of this controller can be expressed as follows:

$$v_d^* = K_{pi}(i_d^* - i_d) + K_{ii}\int(i_d^* - i_d)dt - \omega^* L_f i_q + v_{od} \text{ and} \tag{11}$$

$$v_q^* = K_{pi}\left(i_q^* - i_q\right) + K_{ii}\int\left(i_q^* - i_q\right)dt - \omega^* L_f i_d + v_{oq}, \tag{12}$$

where K_{pi} and K_{ii} are the proportional and integral gains, respectively.

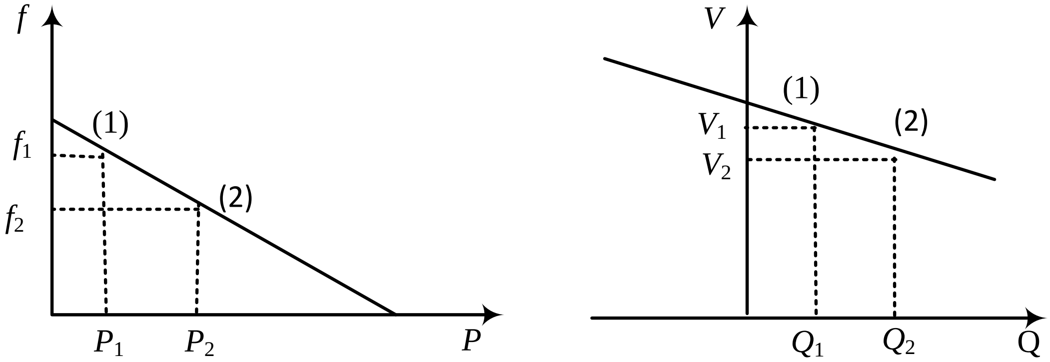


Figure 3. Power versus frequency droop and voltage versus reactive power droop

In the realm of droop coefficient values, the operation and concept of power-sharing within a microgrid delve deeper into the angular frequency difference among the outputs of the inverters. The power-sharing dynamics between sources fluctuate until a new frequency value is defined, as depicted by Equation 3. Figure 3 illustrates the correlation between the power change (P) and the frequency change (f), where there exists a linear relationship. Equation 5 demonstrates that an increase in the term $m_p P$ leads to a significant drop in frequency, prompting the nearest inverter to increase its power and share the load. However, due to the time delay caused by the filter, the frequency change is not instant and may result in oscillations. To counteract this, the coefficient m_p can be increased, urging the inverter to respond swiftly. Nevertheless, caution must be exercised when increasing m_p as it can impact the stability of the system. Thus, a tradeoff emerges between rapid power-sharing and maintaining system stability in the conventional technique.

III. The Proposed PSS for the Microgrid System

In the realm of the isolated microgrid, the response to load fluctuations encounters a slight delay owing to the sluggishness of the low-frequency filter. To address this issue, it becomes necessary to incorporate a lead compensator that can counterbalance this delay. While the notion of a compensator is a commonly accepted practice in synchronous-based systems, we are applying it within the context of an inverter-based system. To illustrate this, we can refer to Figure 4, which presents a block diagram of our proposed power system stabilizer. This stabilizer consists of a gain block and an integral lead compensator transfer function. By combining the output of the power system stabilizer with the original frequency deviation signal, we are able to offset the time delay caused by the low-pass filter. The design process for the compensator hinges on the angle deviation at a higher m_p, taking into account the delay introduced by the low-pass filter, which is represented by the angle θ. The lead compensator can then be calculated using the following formula:

$$-\theta + \angle\frac{sT_1+1}{sT_2+1} = 0. \qquad (13)$$

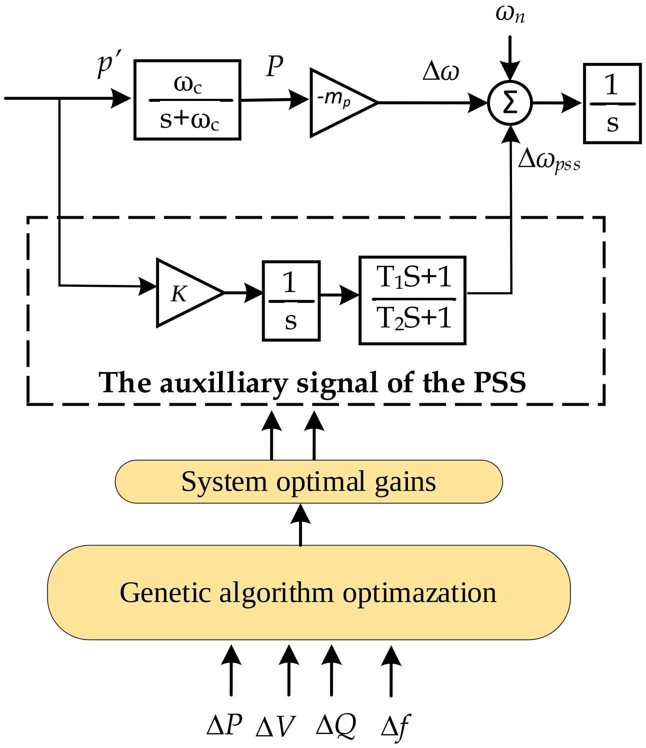


Figure 4. The proposed PSS signal.

Therefore, to achieve a specified θ, the time constants ((T_1, T_2) is determined through GA optimization. Additionally, the gain K of the PSS in Figure 4 is carefully designed to ensure that the magnitude of the frequency drop ($\Delta\omega = -\, m_p P$) matches the compensator drop $\Delta\omega_{pss}$.

Incorporating an integral controller with the Power System Stabilizer (PSS) offers several benefits for power system stability. It enhances the damping of slow-changing oscillations, improves transient response, increases stability margins, adapts to system changes, and reduces low-frequency oscillations. By continuously adjusting the excitation system based on the integral error signal, the integral controller complements the PSS and provides additional stability and control capabilities. However, it is crucial to design and tune the integral controller carefully to ensure optimal performance and avoid any adverse interactions with other control devices. System-specific analysis and simulations are essential to validate the controller's effectiveness before implementing it in a real-world power system. Overall, the incorporation of an integral controller with the PSS can help maintain a stable and reliable power system operation, especially in the face of various disturbances and changing system conditions.

Incorporating the washing out filter block, in addition to the integral controller, with the Power System Stabilizer (PSS) design provides valuable insights and contributes to its overall performance. The washing out filter attenuates high-frequency components in the input signal, filtering out noise and unwanted oscillations. This filtering improves signal quality, prevents amplification of undesirable signals, and enhances the robustness of the PSS. By focusing on low-frequency oscillations, the PSS becomes more effective in stabilizing the power system. The combination of the washing out filter, integral controller, and PSS offers a comprehensive control approach for damping low-frequency oscillations and ensuring stable system operation. It is important to consider the inclusion of the washing out filter as a standard component in the PSS design to optimize its performance and enhance power system stability.

IV. Genetic algorithm optimization for the proposed gain calculations

The microgrid can be seen as a complex and uncertain dynamic network with nonlinear characteristics. In order to ensure stability and maintain control over the electrical parameters, it becomes imperative to dynamically optimize the droop controller. This optimization process aims to achieve a reasonable distribution of power among the distributed generation (DG) sources. Previous studies in the literatures have explored the minimization of a cost function as the objective for optimizing the droop controller. The most optimal performance goal is obtained by considering the time-weighted absolute error integral. Hence, the design of the cost function can be expressed as follows:

$$J = \sum_{k=K_o}^{K_f} (k - K_o).W.|E(k)| \qquad (14)$$

Where, k represents the simulation time, $K_o and\ K_f$ signifies the start and end times respectively, and W is a weight matrix. Additionally, E(k) refers to the array of absolute error moments, which can be defined as follows:

$$E(k) = [\Delta P(k), \Delta Q(k), \Delta V(k), \Delta f(k)] \qquad (15)$$

In the given context, P(k) and Q(k) represent the errors between the actual values and the active and reactive power, respectively. Similarly, V(k) and f(k) indicate the deviations in voltage and frequency, respectively. The voltage droop scale coefficient, denoted by m_1, m_2, and m_3, is set to 0.06, 0.07, and 0.08 respectively, within the genetic algorithm scheme. Additionally, the frequency droop scale factors, represented by n_1, n_2, and n_3, are all set to 0.05. Using the genetic optimization algorithm, the power is proportionally distributed between each distributed generation (DG) source.

Table I. The test system parameters

Parameter	Notation	Value
Inductance of the filtering element	L_f	1.35 mH
Direct current voltage	V_{dc}	700 V
Capacitance of the filter	C_f	50 µF
Inductance for coupling	L_l	0.35 mH
Reactance of the line	X_{ij}	4.71 Ω
Resistances in the line	R_{ij}	1.03 Ω
Proportional gain of the voltage controller	K_{pv}	0.168
Integral gain of the voltage controller	K_{iv}	189.34
Proportional gain of the current controller	K_{pc}	13.57
Integral gain of the current controller	K_{ic}	1005.3
Gain for feedforward control	F	0.75
Cutoff frequency of the filtering system	ω_c	31.4 rad/sec
Switching frequency	f_{sw}	10 kHz
Inverter power	P_{inv}	4 kw

V. Simulation Results

By using MATLAB/Simulink simulations, where an exciting microgrid system was created. This system had three inverters, each with a voltage of 220 V and a frequency of 50 Hz. These inverters used a special technique called droop control, which ensured that they shared power equally. Interestingly, they were powered by a constant DC source, and we didn't consider their dynamic behavior. What's fascinating about this system is that it worked in a decentralized manner, meaning the inverters didn't need to communicate with each other.

To explore the capabilities of this microgrid system further, we conducted a detailed simulation using the famous IEEE Standard 9-bus system (shown in Figure 1). It compared three control methods: the traditional one and a new one called Power System Stabilizer (PSS) that used Genetic Algorithm (GA) optimization. To optimize the parameters of each Distributed Generation (DG) unit's droop controller, the minimum cost function (Eq. 14) is employed, aiming for optimal outcomes. Throughout the simulation, the focus is solely on the island operation mode, while also accounting for scenarios involving unbalanced loads. By adjusting itself, the droop control parameter can be fine-tuned to achieve the optimal setting in such cases. We introduced changes to the load at two specific times: at $t=1$ *s* and at $t= 2$ s. The results of these simulations were presented in Figures 8 to 11, each illustrating different control techniques.

Figure 5 revealed something interesting. The system with GA showed better performance compared to the traditional method and the unoptimized PSS technique. The PSS without GA performed well in maintaining a steady power-sharing and frequency, but it was slow in adjusting power between the inverters, which caused a prolonged frequency mismatch. As a result, the system heavily relied on a value called mp, making it vulnerable to sudden changes in the load.

In Figure 6, we focused on the reactive power and voltage waveforms of the three inverters. The main goal was to check how well each technique controlled the reactive power in the system. We compared the conventional method, the PSS without GA, and the PSS with GA. By carefully examining the waveforms in Figure 6, we could evaluate the performance of each technique in controlling reactive power. Figure 7 and 8 presents the simulation results for DG2 and the third DG omitted due to the figures number requirements.

The conventional method served as the starting point for comparison. The PSS without GA and the PSS with GA were alternative strategies that used power system stabilizers. Comparing these techniques, we found that the proposed approach with the optimized droop controller using GA showed significant advantages. It had better resilience against variations in droop gain, which is crucial for stable performance. Although slight oscillations were observed in the results, they had minimal impact on the system. In terms of damping, the proposed controller clearly outperformed the others, demonstrating its superior performance.

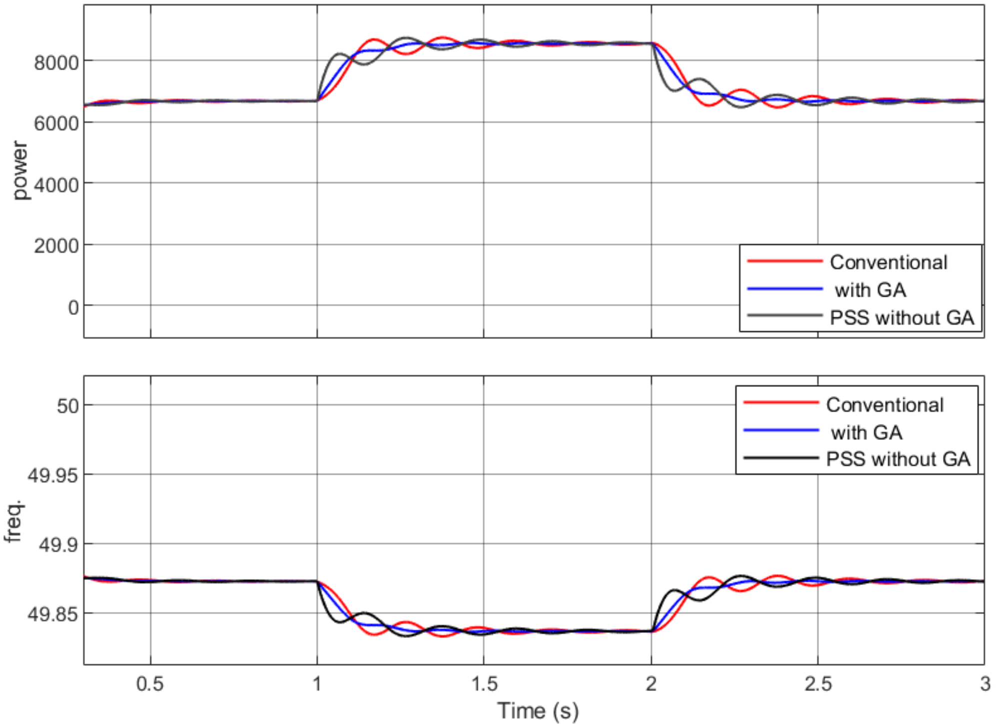


Figure 5. Performance of the different controller techniques DG1.

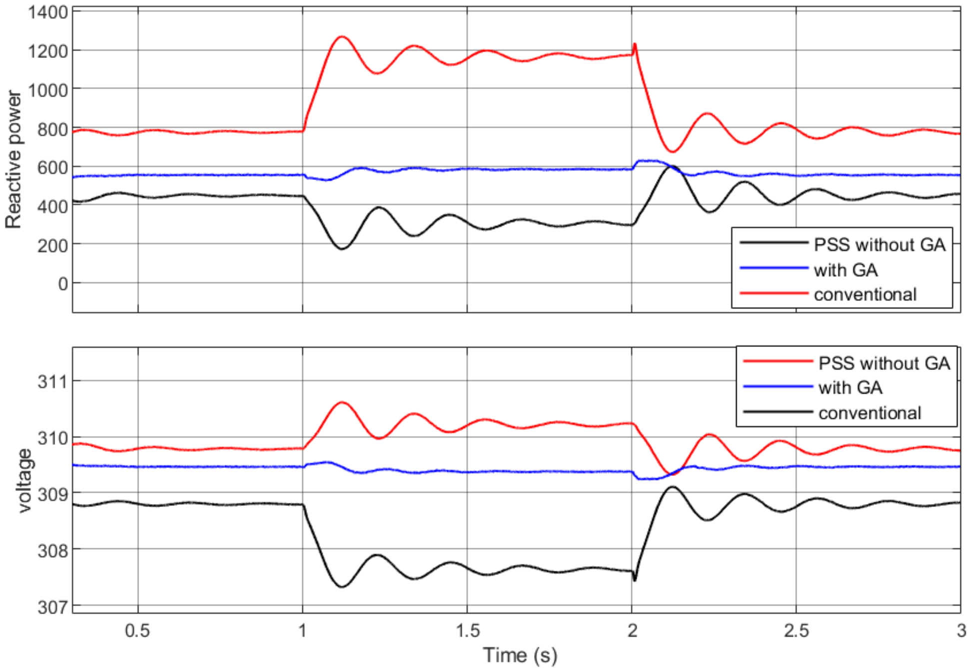


Figure 6. Performance of the different controller techniques DG1.

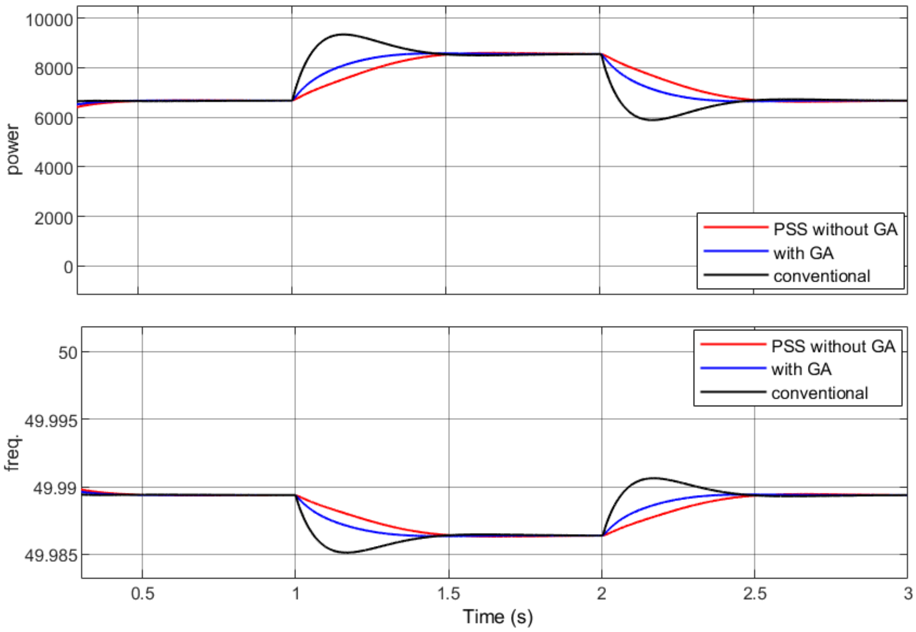


Figure 7. Performance of the different controller techniques DG2.

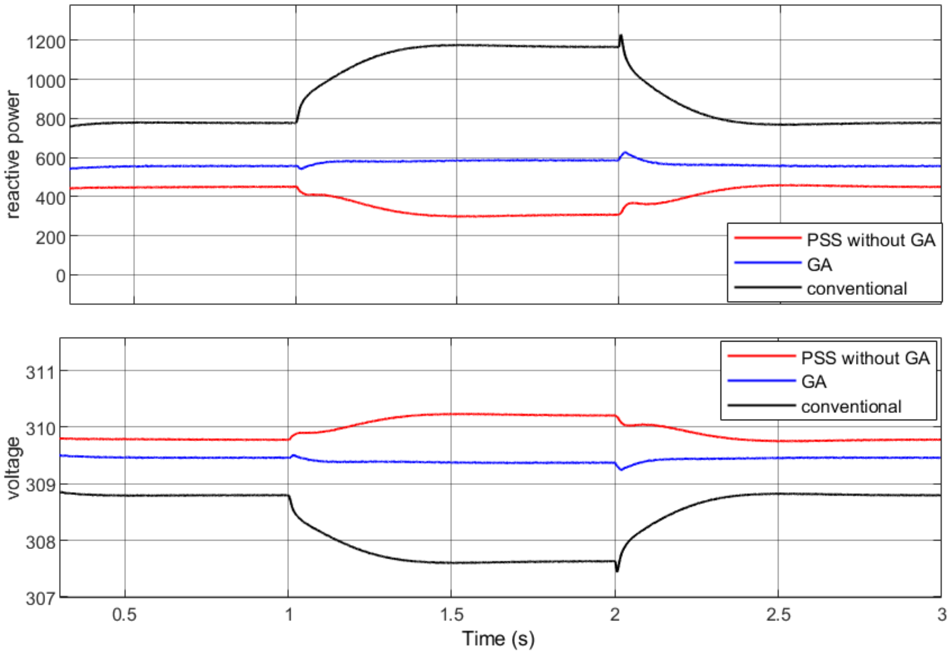
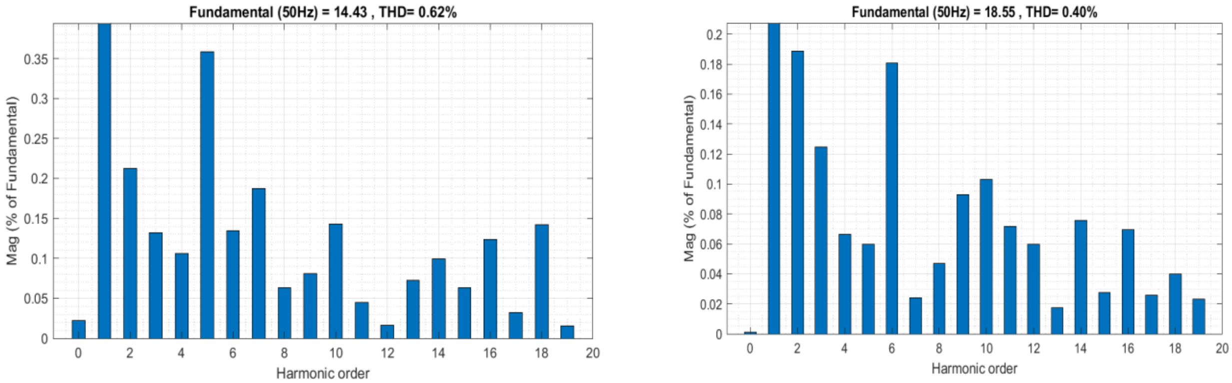


Figure 8. Performance of the different controller techniques DG2.

In the context of GA-based techniques, a comparison can be made using Figure 9, which illustrates the Total Harmonic Distortion (THD) of the inverter current before the load change. In the first scenario, the THD value is recorded as 0.62, while in the second scenario, the THD value is reduced to 0.4. This comparison highlights the impact of the load change on the quality of the inverter current waveform. The lower THD value in the second scenario indicates a significant improvement in the quality of the inverter current, suggesting better harmonic performance and reduced distortion. This outcome demonstrates the effectiveness of the GA-based techniques in enhancing the overall performance and stability of the system.



(a) The THD of the inverter current before the load change. (b) The THD of the inverter current after the load change.

Figure 9 (b) The THD of the inverter current

Implementing the proposed Power System Stabilizer (PSS) design in real-world microgrid systems involves several practical aspects. Here are some key considerations for its practical implementation:

1. System Analysis and Modeling: Conduct a thorough analysis of the microgrid system, including its components, dynamics, and operating conditions. Develop an accurate system model that captures the behavior of generators, loads, inverters, and other relevant devices. The model should be validated using real-world data and measurements.

2. Control System Integration: Integrate the PSS design into the microgrid's overall control system architecture. Ensure compatibility and coordination with existing control devices, such as supervisory control and data acquisition (SCADA) systems, energy management systems (EMS), and protection systems. Implement appropriate communication protocols to exchange signals and data between the PSS and other control devices.

3. Parameter Tuning and Testing: Conduct parameter tuning for the PSS design to optimize its performance within the microgrid system. Use simulation tools and software to assess the impact of different parameter settings on stability and response. Validate the PSS design through comprehensive testing, including offline simulations and, if possible, field tests on a smaller scale before full-scale implementation.

4. Hardware and Software Implementation: Depending on the microgrid system's architecture, determine the hardware and software platforms required for implementing the PSS design. Select suitable control hardware, such as programmable logic controllers (PLCs) or digital signal processors (DSPs), to execute the control algorithms in real-time. Develop or adapt control software to implement the PSS algorithms and integrate them into the control hardware.

6. Testing and Validation: Before deploying the PSS in the operational microgrid system, conduct rigorous testing and validation. Verify the PSS's performance under various operating conditions, disturbances, and scenarios using simulation tools and hardware-in-the-loop (HIL) testing. Validate the PSS's effectiveness in improving stability and damping low-frequency oscillations.

7. Commissioning and Maintenance: Once deployed, commission the PSS in the microgrid system, ensuring proper functionality and coordination with other control devices. Monitor and maintain the PSS's performance by regularly assessing

its parameters, conducting periodic system stability studies, and updating the PSS design as needed to address changes in the microgrid system or operational requirements.

It's worth noting that the practical implementation of a PSS design in a real-world microgrid system may vary depending on the specific system configuration, available resources, and regulatory requirements. Close collaboration between power system engineers, control system experts, and microgrid operators is essential to ensure a successful and effective implementation of the PSS design.

VI. Conclusions

This paper introduces a novel Power System Stabilizer (PSS) design for a microgrid, utilizing the optimization technique of Genetic Algorithm (GA). The proposed PSS addresses the issue of lag response caused by filter delays in the output of the autonomous microgrid by incorporating a lead compensator. This compensator aims to counteract the delay and improve system performance. Additionally, the proposed technique offers a solution to the design problem associated with conventional droop controller coefficients. Implementing the proposed PSS design is straightforward, involving the addition of a supplementary signal parallel to the droop controller loop. This supplementary signal helps dampen frequency fluctuations resulting from load-sharing among the inverters. By employing this new controller, the microgrid's stability margin is enhanced, both at low and high droop coefficient values, while achieving faster power-sharing. The controller effectively reduces frequency dynamics and steady-state oscillations, without impacting the power-sharing process between the inverters. To validate the effectiveness of the proposed controller, extensive simulations are conducted under various operating scenarios. The results confirm that the PSS-based droop controller scheme significantly contributes to preserving the stability and reliability of the microgrid.

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