# A systematic review on voltage stability analysis in smart and islanded microgrid parallel inverters

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**ABSTRACT**

The development of a smart grid depends on measuring and communication technologies and gathering heterogeneous data from micro grid. This enormous data contains procedures and methods that make it easier to use vast data while also increasing computing complexity and security. Given the maturity of power electronics technology, the penetration of distributed generation in both on- and off-grid environments has advanced in ways that have never been seen. Any complicated power system, like the off-grid parallel inverters, requires a stability study that considers several state variables. The smart grid environment's rising complexity and data explosion necessitate more hardware, which raises costs and necessitates additional physical space. An introduction to the special issue on voltage stability of micro grids with parallel inverters in power systems is presented in this review paper. Self-synchronizing inverters known as parallel inverters do not require a reference from the main grid to synchronize with one another. There are several general analytical techniques and enhanced procedures covered. The similarities, functionality, applications, designs, benefits, drawbacks, and general effectiveness are then contrasted. The significant contribution of this in-depth review is to establish a strong foundation for subsequent research in the area.



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## 1. INTRODUCTION

The community of the power system manages the vast and complex electric power system. The network will continue to be defined by the sharing of various renewable resources [1]. An increase in renewable energy sources (RES)s makes it possible to distribute the world's electrical output more fairly. Due to technological improvements and environmental concerns, the distribution network is becoming more connected to RESs. Micro grids are small-scale local electricity systems that operate inside larger distribution networks. Wind, solar, and hydropower are all RESs that may efficiently supply their respective portions of the world's energy needs. The micro grid technology improves local energy security and offers significant prospects for isolated areas in terms of power supply [2]. By decreasing the need to import energy, this technology makes a significant contribution to ensuring more secure energy. Frequency regulation does not require any additional effort because of the connection between the utility grid and the micro grid for renewable energy. Stability, bidirectional power flows, modelling, low inertia, the impacts of load disturbance, and uncertainty are the micro grid's top problems [3].

A power system's capacity to sustain or recover adequate voltage magnitudes at each of its network buses before and after a disturbance is known as voltage stability. Failure to do so leads to voltage instability, which, if the instability is not addressed, eventually ends in voltage collapse.When all or a section of a power system network encounters exceptionally low voltages, voltage collapse occurs.Voltage instability has been attributed to a variety of variables, such as reactive power mismatch, unanticipated surges in demand, and the loss of power system components like generators, according to published research. The major causes of voltage instability, however, are unanticipated increases in load, the destruction of power system elements, an imbalance among active and reactive power, as well as the failure of on-load tap changing transformers. Network engineers must be aware of how near or how far they are from the voltage stability limit in order to take corrective action to lessen or completely remove the impact of voltage instability for power system networks to operate safely and reliably. As a result, monitoring and assessing voltage stability become significantly more crucial while running and organising the power system. Thus, researchers have demonstrated a keen interest in the prediction of power system behaviour associated with the assessment and monitoring of voltage stability.

Several mechanisms and methods have been used during the past three decades to propose tools and procedures for voltage stability analysis. Analytical methods and optimization techniques are the two primary subcategories of voltage stability analysis. Voltage stability analysis has static and dynamic sub-branches. The aims of the study are to present an overview of the Voltage stability of micro-grids in transmission lines challenges. To demonstrate the uniqueness of static voltage stability evaluations, simulation tests employing the Jacobian methodology, voltage sensitivity method, reactive and active loss sensitivity technique, and energy function approach were contrasted. Unlike static voltage stability analysis approaches, dynamic voltage stability analysis methodologies have not been thoroughly classified. State variables that affect system stability are used in stability analysis. Because the microgrid environment depends mostly on RESs, autonomous power regulation, and localised power generation, it is projected that adopting smart technology would result in exponential data usage. Smart gadgets capture state variables as data. Using isolated or grid-connected operating modes to service distant end loads is easier with a microgrid. Decoupled controllers, such as the instantaneous real/reactive power (PQ) and direct axis/quadrature (DQ) axis controllers, are utilised in the grid-connected operating mode to synchronise renewable energy to the main grid. Synchronisation includes the use of control mechanisms to maintain constant voltage levels and phase angles in parallel inverters. The capacity of a microgrid to operate as an island is enabled by the increasing penetration of RESs in power networks. More processing power is required due to the dynamics of the parallel-connected inverters as well as the multiple system state variables employed in the stability assessment of the islanded microgrid [4], [5].

The proposed systematic literature reviews have three main goals, they are to investigate the need for voltage stability analysis in smart and island microgrids, to investigate voltage stability using real-time and simulation methods, and use of soft computing techniques for feature-reduced stability analysis of parallel inverters. The rest of the text is structured as: i) The technical aspects of the islanded microgrid is explained in section 2; ii) Power-sharing control in islanded microgrids is covered in section 3; iii) Section 4 provides an explanation of parallel inverters and controllers used for voltage stability and analysis is carried out using simulation and experimental methods; iv) Section 5 describes various voltage stability analysis methodologies and implementation tools; v) The most modern soft computing methods are covered in section 6; and vi) Section 7 discusses the overall conclusion of the review paper.

## 2. TECHNICAL ASPECTS OF ISLANDED MICROGRID

In the deregulated environment made possible by the entry of numerous distribution companies (DISCOMS), distributed generation (DG) systems are feasible. Rural electrification will be made possible by this liberalization. According to previous research [6], DG installations at the moment are actually in some ways a return to the early days of electrification. DG is not a novel concept for the power industries. After some time, a new technology has evolved. The emergence of DG is one of the most important recent changes in the energy sector. The cost of wind and solar generating is continuing to decline, according to the Frankfurt School-UNEP Collaborating Centre's study, "Global trends in renewable energy investment 2015" [7]. Cost reductions, government incentives, and growing popularity in replacing fossil fuel sources of energy are driving the rapid growth of the global market for DG. According to a recent Navigant Research analysis titled "Global DG Installation Forecasting 2014-2023," the global installed capacity of DG is predicted to increase from 87.3 GW in 2014 to 165.5 GW in 2023 [8]. From $97 billion in 2014 to even more than $182 billion in 2023, it is expected that global DG income will rise. To deliver electricity to key locations, a microgrid is made up of DGs, energy storage devices (ESDs), and local loads. The primary goal of micro grid (MG) is to maintain the system reliable in the face of multiple network outages. In the literature, there are several definitions [9] and functional classification methods [10] for MGs. A microgrid, according to the MG Exchange Group of the US Department of Energy, is a system concept comprised of several yet coordinated loads and generating units, as well as grid islanding. It also serves as a controlled structure to the main grid despite remaining constrained by well defined electrical boundaries. A MG can connect to and disengage from the electric grid, allowing it to function in both grid-tied and independent modes [11].

When operating in grid-connected mode, a physical switch is affected, connecting the microgrid to the utility grid. Since there is no grid support in island mode, microgrid management is substantially more challenging. The host utility grid imposes the microgrid voltage. However, a microgrid's power flow is bidirectional, and when it is linked to the external grid, this may switch electricity to maintain a steady supply in the surrounding microgrid. When in islanded mode, the microgrid's power source must be able to supply the required load. An essential and potent micro grid running in island mode would represent the interconnected phase. Depending on the distribution system, the microgrid could be an AC and a DC power system, or a hybrid system, with each having advantages and disadvantages depending on how it is utilized. There have been numerous studies on the benefits and drawbacks of both DC and AC microgrids. The efficiency of RESs is affected by a variety of variables that shift throughout time. As a result, the performance of the microgrid, which is dependent on how these resources are used, is also affected. A microgrid offers a more practical and dependable approach to generate power and consume less nonrenewable energy while simultaneously enhancing the stability, reliability, high quality, and security of conventional distribution networks. However, connecting microgrids to the main network might pose a variety of technical and financial difficulties.

Grid-connected micro grids have several disadvantages, including voltage collapse, significant investment, poor power quality, and substantial transmission loss. MGs employ a variety of primary mover technologies, including photovoltaic or PV, fuel cells, windmills, and internal combustion engines (ICE) [12]. Voltage source inverters and suitable controllers are required for solar power systems, fuel cell technology, energy storage systems, and wind technologies to enable flexible operation. From the viewpoint of the customer, a microgrid is a grid system that offers dependable, independent, and high-quality electricity. The construction of a reliable frequency and voltage controlling microgrid system requires the coordination of several micropower kinds. It is feasible to classify the research based on the tree diagram in Figure 1, which analyses microgrid control. The control strategies must consider all system time scales. Primary, secondary, and tertiary microgrid control levels are of three tiers, where the control method without communication indicates an independent operation of a micro grid and with communications indicates coordination of a microgrid and host network. In the modern power grids, hierarchical management is widely used to control voltage, frequency, and maintain power balance.

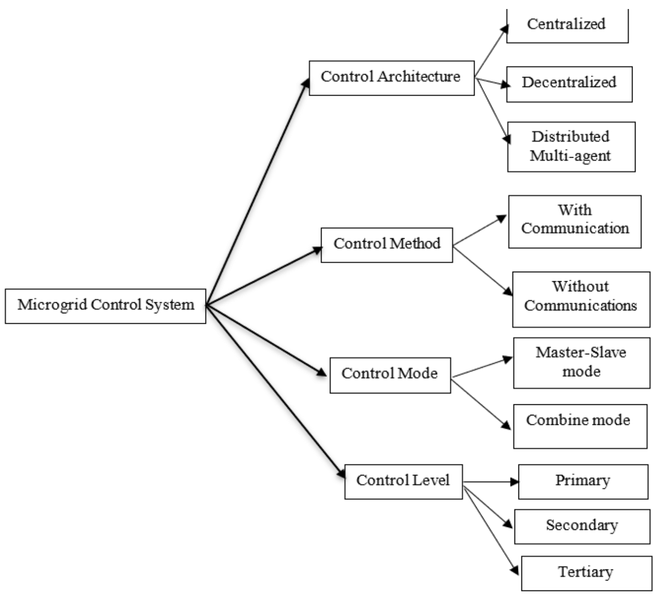


Figure 1. Control of microgrid [12]

By comprehending the important points in this section Table 1 discusses the important topics and key points from the literature. This section discusses about the deregulated environment background, and the idea about the global DG market and the capacity and revenue growth. Definition of micro grid and various classification of micro grid is discussed. Different types of micro grids and operation modes are detailed. Variables affecting micro grid efficiency, challenges, control strategies and customer perspective of micro grid is detailed in this section.

Table 1. Technical aspects of microgrid – a summary

| Topic | Key points |
|---|---|
| Background | In a deregulated environment facilitated by various DISCOMS, the feasibility of DG systems emerges, allowing for rural electrification. DG installations harken back to early electrification days and represent a significant evolution in the energy sector. The decreasing costs of wind and solar generation, coupled with government incentives, are driving the global DG market's rapid growth [6], [7]. |
| Global DG market | The global installed capacity of DG is predicted to increase from 87.3 GW in 2014 to 165.5 GW in 2023, with projected revenue growth from $97 billion in 2014 to over $182 billion in 2023 [8]. |
| Microgrid definition and classification | A microgrid comprises DGs, ESDs, and local loads, aiming to maintain system reliability during network outages. Definitions and functional classifications vary in the literature [9], [10]. The MG Exchange Group defines a microgrid as a coordinated system with multiple loads and generating units, capable of grid islanding [11]. A microgrid can operate in grid-tied and independent modes by connecting to/disconnecting from the electric grid [11]. |
| Microgrid operation modes | Microgrid operation involves grid-connected and island modes. The physical switch connects the microgrid to the utility grid in grid-connected mode, while island mode, with no grid support, poses greater management challenges. Power flow is bidirectional, and the microgrid must supply its load when in island mode. The microgrid's power source determines its ability to operate effectively in islanded mode [11]. |
| AC and DC microgrid types | Microgrids can be AC, DC, or hybrid systems, each with advantages and disadvantages. Studies on the benefits and drawbacks of both AC and DC microgrids abound in the literature [11]. |
| Variables affecting microgrid efficiency | The efficiency of RESs is impacted by various variables that change over time. Microgrid performance, reliant on resource utilization, is also affected. Microgrids offer a practical and reliable approach to power generation, emphasizing reduced nonrenewable energy consumption while enhancing the stability, reliability, and security of conventional distribution networks [11]. |
| Challenges in grid-connected microgrids | Connecting microgrids to the main network poses technical and financial challenges, including voltage collapse, significant investment, poor power quality, and substantial transmission loss [11]. |
| Primary mover technologies in microgrids | Microgrids employ various primary mover technologies, including PV, fuel cells, windmills, and ICE [12]. Voltage source inverters and suitable controllers are necessary for solar power systems, fuel cell technology, energy storage systems, and wind technologies to enable flexible operation [12]. |
| Customer perspective on microgrids | From the customer's perspective, a microgrid is a reliable, independent, and high-quality electricity grid system. |
| Microgrid control strategies | Microgrid control involves hierarchical management, considering primary, secondary, and tertiary control methods. The coordination of microgrid and host network is crucial [11]. The research can be classified based on the tree diagram in Figure 1, which analyzes microgrid control. Control strategies must address all system time scales, and the three tiers (independent microgrid operation and coordination with the host network) require specialized approaches [11]. |
| Challenges in hierarchical microgrid control | Challenges in hierarchical microgrid control include maintaining power balance, controlling voltage and frequency, and ensuring the reliability of the microgrid system [11]. |

## 3. SYNCHRONISATION AND POWER SHARING CONTROL IN ISLANDED MICROGRIDS

A microgrid makes it simpler to serve distant end loads utilizing isolated or grid-connected operating modes. Decoupling controllers, including the instantaneous active/reactive power as well as direct axis/quadrature axis controller, are employed in the grid-connected mode of operation to synchronize renewable energy to the primary grid [13]. Synchronization controlled technique is applied to maintain parallel inverters operating at the same voltage level and phase angles. The potential for an islanded operation mode for a microgrid is promised by the increasing penetration of renewable energy in a power system. The stability of the islanded operation mode is examined using a complex model with several state variables. This research proposes a unique modeling approach and a stability analysis process for weak power networks with substantial penetration of power electronics converters. Every network architecture may be modeled using the modeling technique, which also incorporates small-signal state-space models for each network element, such as power lines, loads, power converters, and their control algorithms, in order to model the entire network. Comparing the suggested linearized model's reaction against the non-linear model's response served to validate it. The created small-signal model was then employed in the stability analysis based on the frequency response of singular values to determine the important network and control parameters of the weak grid in the presence of disturbances. Lastly, the original non-linear network model was used to verify the presence of the detected resonance modes.

Load frequency controllers (LFCs) and systems for energy management in microgrid settings employ soft computing techniques. The importance of load frequency management (LFM) has increased in contemporary power networks because of changing demand and generation characteristics. Moreover, the integration of renewable source (RS)s into power systems increases the difficulty of the LFM operation. In order to manage the power mismatch of the specific power system, the idea of secondary frequency control, or LFM, objective is introduced to single and multi-area power systems. For single and multi-area systems, this helps to control the system frequency, and for multi-area systems, it helps to plan the tie-line power exchange. Load frequency controllers are a new technology that is used to regulate and lessen system frequency variation. Yet, clever soft computing techniques that take into consideration many controllers are used to ensure efficient power management [13].

A study by Rasheduzzaman *et al*. [14] is a representation of a droop controller that synchronizes with the parallel inverter architecture used in the Microgrid's islanded mode of operation. When a microgrid is operating in its islanded mode, a portion of the dispersed network is electrically cut off from the main grid, with loads being sustained by local sources. These distributed energy resources (DERs) are often power electronic-based, which makes the entire system hard to evaluate. It suggests using a microgrid system with two DER-functioning inverters. The DQ reference frame is used in the design of the inverter controllers. In order to reflect the system dynamics, nonlinear equations are developed. For the purpose of creating a state-space model of the microgrid, these equations are linearized around steady-state operating points. The mathematical model is derived from an averaged model, which yields a simpler set of equations. The linearized model is used to conduct an eigenvalue analysis to assess the system's small-signal stability. The suggested microgrid system, which consists of two DERs with inverter technology, passive loads, as well as a distribution line, is simulated. To examine the system's dynamics under load perturbation, an experimental test bed is created. To ensure the mathematical model's correctness, simulation, and hardware experiment results are compared to those anticipated by the model.

Parallel inverters with standalone AC supply systems [15] are analyzed for small signal stability. Both voltage and frequency droop is developed to analyze the small signal stability of the system. The root locus method is used to analyze the small signal stability of the system. A study by Alenius *et al*. [16] described how an impedance-based stability criterion is used to verify the stability of many parallel inverters linked to the grid. Utility-scale wind and solar electricity generation are often wired in parallel three-phase inverters to the electrical grid. The harmonic resonance brought on by interactions between the grid and inverters is one of the key problems with such grid-connected systems. The impedance-based stability criteria have been a widely used technique for the study of these systems. The complexity of the system and the difficulties in getting the necessary impedance measurements, however, may reduce the accuracy of the impedance-based technique in systems with many parallel inverters. The combination of parallel inverters and the stability study of such grid-connected systems are covered in this work. The maximum number of paralleled inverters that may be used without the system becoming unstable is defined using a straightforward approach that is based on impedance measurements. Power hardware-in-the-loop setup experimental findings from newly produced at DNV GL Flexible Power Grid Lab.

Impedance-based stability study employing offshore long cable parallel inverters is introduced in [17]. This research presents the stability analysis of a multiple offshore parallel long-cable-connected inverters (MOPLI) system. It is demonstrated that the MOPLI system consists of so many different inverters and extensive connections, hence determining its stability is really difficult. Moreover, even though there are several impedance-based stability criteria for parallel inverters, the majority of them are found on two false premises, the first is that is all inverters are identical, and the second is that cable effects may be disregarded. Nevertheless, the actual MOPLI system does not support these two hypotheses. This study initially recreates the models of the inverters and lengthy cables one at a time in order to address the challenge. A broad and succinct three-step impedance-based stability criteria has been given for the MOPLI system based on the revised models. The suggested criterion is not only straightforward and workable but also completely takes into consideration the variations in inverters and the effects of wires. Due to the requirement for source load sub-system analysis, research on impedance-based and eigenvalue-based small signal stability analysis applications is confined to the few states stated in [18].

The above-mentioned research looks at enhanced impedance-based controllers for parallel inverters regulated both by PQ-based impedance and droop controller-based approaches. The impedance approach is used by double closed-loop controlled parallel inverters to analyze stability. Droop controllers are the most used synchronization approach when islanded microgrids are also considered. As a summary of this section, a table that comprehends key points on the literature survey is given in Table 2 (see Appendix).

## 4. PARALLEL INVERTERS AND CONTROLLERS

A microgrid's parallel inverters can be managed in a variety of ways, including master/slave, current sharing, droop control, virtual synchronous machine (VSM)-based and virtual oscillator control. The downside of both the microgrid and existing sharing systems is the requirement for communication networks. As a result, the system now contains a single point of failure. The VSM control approach out performs a traditional droop controller in a variety of ways. Nevertheless, most of the VSM-based research published in the literature focuses on the system's active power and frequency characteristics. The isolated AC MG's reactive power varies due to the characteristics of the inductive load. Droop control, a crucial technique for the parallel functioning of inverters, is also well-explained in [19]-[22].

A study by Majumder *et al*. [19] examines the issue of adequate load sharing in a self-sufficient microgrid. Under weak system settings, high gain angle droop control guarantees correct load distribution. Nonetheless, it has a detrimental effect on stability. This disagreement is demonstrated using time-domain simulations, eigenvalue analysis, and frequency-domain modelling. It is suggested to add an additional loop to each DG converter's traditional droop control in order to stabilize the system while employing high angle droop gains. Local power measurement and modulation of each converter's d-axis voltage reference serve as the foundation for control loops. The challenge of coordinated design of supplemental control loops for each DG is stated as an evolutionary problem that has to be solved. It is demonstrated that the supplemental droop control loop stabilizes the system under various operating situations while guaranteeing adequate load sharing.

A study by Barklund *et al*. [20] offers an energy management system (EMS) for a standalone droop-controlled microgrid that regulates the output power of the generators to reduce fuel consumption and guarantee stable operation. Frequency-droop increases have been demonstrated to have a considerable impact on stability in these microgrids in the past. In order to determine the relationship between these factors and stability margins, small-signal methods are combined with qualitative analysis. This enables their selection to guarantee stability. The EMS then implements optimized generator outputs in real time by modifying the droop characteristics within this restriction. A microgrid the size of a laboratory confirms the EMS function through experimental results.

A study by Mohamed and El-Saadany [21] addresses the DG units in microgrids that use paralleled inverter technology and have low-frequency relative stability issues. It can be demonstrated using the small-signal dynamics of a microgrid that when the required power of each inverter increases, the low-frequency modes of the power-sharing dynamics drift to new places, significantly affecting their relative stability until they finally give instability. This work presents an adaptive decentralized droop controller of paralleled inverter-based DG units to maintain power-sharing stability. The static droop characteristics and an adaptive transient droop function serve as the foundation for the suggested power-sharing technique. The suggested droop controller produces a 2-two-degree-of-freedom or DOF tunable controller as opposed to the 1-DOF tunable controller produced by current droop controllers. The power-sharing controller's oscillatory modes can then be dampened by altering the dynamic performance of the power-sharing mechanism without changing the static droop gain. The transient droop gains are adaptively planned using small-signal analysis of the power-sharing mechanism along the loading trajectory of each DG unit to produce the appropriate transient and steady-state response while accounting for the power modes immigration under various loading situations. As the filtered active and reactive powers are used as indices in the gain adaption scheme, a steady and smooth power injection performance may be produced under various loading circumstances. The suggested controller's adaptive nature provides active dampening of power oscillations under various operating situations, resulting in a stable and reliable performance of the paralleled inverter system.

An uninterruptible power supply (UPS) that can be rapidly extended to meet the demands of a growing demand is necessary to deliver dependable power under scheduled and unscheduled outages [22]. A system like this should be capable of redundancy and fault tolerance as well. If a control strategy can be developed that enables smaller inverters to function independently while yet sharing the load, these objectives can be achieved by connecting them in parallel. The author has created a control method that enables the parallel operation of two or more single-phase inverter modules without the need of any auxiliary connectors. This method divides the load across separate inverters in proportion to their capacity by using frequency, fundamental voltage, and harmonic voltage droop. Results from simulations are given to support the theory.

A study by Diaz *et al*. [23] describes a method based on bifurcation theory to assess the effects of primary reserve scheduling and droops on microgrid stability. The approach is based on rescheduling the droops of chosen generating units that enable frequency (and voltage) control to discover the worst main reserve share or the share that is the closest to instability. In a multi-parameter space with coordinates corresponding to the droop coefficients, the solution which consists of a measurement of the distance to instability in a certain direction is discovered. An isolated microgrid with 69 buses and 11 generating units is used to examine the suggested strategy.

The examination of a few situations demonstrates how the distances and normal vectors offer important insight into the proper scheduling from the perspective of stability, offering guidance on how the primary reserve ought to be more reliably scheduled. There are still some cases when external communication techniques are required for load sharing and restoring the microgrid's voltage and frequency [24]. The control approach for a flexible microgrid is discussed in this research. The microgrid described here is made up of numerous paralleled line-interactive UPS systems. The droop method is the foundation of the control strategy, which prevents crucial connections between UPS units. As a result, a flexible microgrid that can function in islanded or grid-connected mode is developed. The system stability is examined using a small-signal analysis, which provides guidelines for designing the primary control parameters. Results from simulations and experiments are shown, demonstrating the viability of the suggested controller.

It is feasible to produce an incredibly precise equal distribution of linear and nonlinear loads, as has been thoroughly studied [25]. The topic of this study is the design of the output impedance of UPS inverters with the capacity to link in parallel. The P/Q droop approach is the foundation for the power-sharing control loops, which eliminate the need for any communication between modules. As the precision of the power-sharing in these systems is heavily dependent on the output impedance of the inverter, innovative control loops are developed to ensure both stable output impedance and adequate power balancing. Results from simulations and experiments using a parallel-connected UPS system that shares linear and nonlinear loads are given. A control technique for the equal power sharing of two paralleled three-phase power converters including harmonic correction is proposed in [26].

The equitable sharing of linear and nonlinear loads in three-phase power converters linked in parallel without communication between the converters is made possible by a new control mechanism introduced in this research. The challenge that results from connecting two converters with harmonic correction in parallel is the main topic of this study. The outcomes demonstrate that the suggested idea is capable of equitably distributing both linear and nonlinear loads. For islanding parallel inverters in an ac-distributed system, a novel wireless load-sharing controller is presented in [27]. This study investigates the parallel-connected inverters' resistive output impedance in an island microgrid. The control loops are designed and assessed while taking into consideration the unique characteristics of a low-voltage microgrid, where the line impedance is primarily resistive and the distance between the inverters makes it challenging for them to communicate with one another during control operations. Two 6-kVA inverters linked in parallel have produced experimental results that demonstrate the benefits of the suggested wireless control [28], presented an alternative control mechanism that reduced the virtual flux rather than the load voltage, and distributed power uniformly.

There were numerous control schemes for proportional power distribution [29]-[32] suggest an upgraded control method that measures the reactive power control error by injecting small actual power disturbances, which are activated by the low-bandwidth synchronization signals from the central controller, in order to increase the accuracy of reactive power sharing. The traditional reactive power droop control is simultaneously supplemented with a delayed integration term for the reduction of reactive power-sharing errors. Using frequency droop management, the proposed compensation approach accomplishes precise reactive power sharing at a steady state, much as genuine power sharing. Results from simulations and experiments support the viability of the suggested approach.

A study by Farhadi and Mohammed [33] examines the harmonic analysis and real-time operation of isolated and non-isolated DC microgrids. A current-voltage management strategy based on the master-slave control idea is suggested in order to effectively manage the energy and prevent the ac grid power pulsation. Based on various power-sharing patterns, several operating modes were established. Both galvanically isolated and non-isolated DC grid systems underwent the experimental test. The outcomes demonstrate that the suggested energy management algorithm effectively distributes power and regulates voltage. Also, the isolation of the DC microgrid has a substantial impact on the harmonic content of the current depending on the power-sharing pattern.

A study by Guzmán *et al*. [34] describes a unique control technique that enables load sharing across an ac microgrid's power sources without the need for a central controller or inter-voltage-source inverter (VSI) communication; instead, just local output current and voltage are measured for the control technique. The suggested VSI controllers are based on the voltage/power estimation, frequency-locked loop, and variable frequency adaptive linear neuron for the VSI system synchronization. The validity of the claim was verified by experimental findings employing field-programmable gate array devices for the implementation of each VSI control in the microgrid test bench.

The use of secondary control in a microgrid with drooping primary voltage is examined in [35]. The secondary control, in contrast to the primary controller, is communication-based and runs at a slower rate than the voltage-based primary control. The secondary controller controls the power exchange between the microgrid and utility network, the voltage at pilot sites in the microgrid, or the voltage at the point of common connection. On the basis of an optimization method, such as for losses, power quality, and economic income, the set points for secondary control may be established. The microgrid secondary controller modifies the DG units' power set points in accordance with these set points.

To run a single-phase DC/AC converter in both grid-connected (GC) and stand-alone (SA) modes, the universal integrated synchronization and control (UISC) is developed [36]. This system offers smooth transitions between both modes without requiring any changes to the control structure. To demonstrate the effectiveness of the suggested controller in a single-phase scenario, this study offers the derivations, stability analysis, and numerical results. Also included is a mathematical study of the similarities and differences between the UISC and several related approaches.

The current feedback signal and power angle of VSIs are used in the suggested [37] control strategy, which is based on the droop control method. This technique is typically used to reduce transient circulation current and provide good active and reactive power sharing. This novel droop for voltage and frequency is used in this study to significantly increase transient responsiveness. The suggested controller is validated by the simulation results that are presented. The voltage difference between the grid voltage and the reference ac voltage sources was used to determine the active and reactive currents.

A study by Liu *et al*. [38] proposed a technique for identifying active and reactive currents based on the computation of active and reactive power. Nevertheless, for these two methods, the actual inverter output resistance over reactance ratio is necessary. The active and reactive currents were identified using the amplitude, phase angle, and power angle of the load current, as described by [39]. A quick summary of various literature in this section is given in Table 3.

Table 3. Parallel inverters and controllers – a summary

| Topic | Key points |
|---|---|
| Droop control in microgrids | These papers explore aspects of droop control in microgrids, focusing on issues such as load sharing, stability, and power management [19]-[21]. The paper [19] discusses high gain angle droop control for load sharing under weak system settings. Study of [20] introduces an EMS for a standalone droop-controlled microgrid. Study of [21] addresses low-frequency relative stability issues in DG units using adaptive decentralized droop control. |
| Wireless load sharing in microgrids | These papers investigate novel approaches to load sharing without the need for wired communication [27], [28]. The paper [27] presents a wireless load-sharing controller for parallel inverters in an AC-distributed system. The study of [28] proposes an alternative control mechanism focusing on reducing virtual flux for uniform power distribution. |
| Reactive power compensation | This set of papers introduces control strategies for precise reactive power sharing [29]-[32]. The study of [29] suggests an upgraded control method with reactive power compensation, while [30] explores improved control for proportional power distribution. The paper [31] discusses reactive power droop control supplemented with a delayed integration term. The research of [32] focuses on compensating reactive power-sharing errors using frequency droop management. |
| DC microgrid operation and management | These papers concentrate on the operation and management of DC microgrids [33], [34]. The article [33] discusses a current voltage management strategy for isolated and non-isolated DC microgrids. The study [34] proposes a control technique for load sharing in AC microgrids, emphasizing VSI controllers and synchronization methods |
| Secondary control in microgrids | The study of [35] explores secondary control in microgrids, focusing on communication-based control methods that operate at a slower rate than primary voltage-based control. The secondary controller adjusts power set-points for DG units based on optimization methods. |
| Synchronization and control for converters | These papers [36], [37] address synchronization and control for converters in microgrids. [36] introduces the UISC for single-phase DC/AC converters. [37] presents a droop control method with improved transient response, using the current feedback signal and power angle of VSIs. |
| Identification of active and reactive currents | This paper proposes a technique for identifying active and reactive currents based on the computation of active and reactive power, contributing to enhanced control strategies [38]. |

## 5. STABILITY ANALYSIS IN MICROGRIDS

In the context of stability analysis for autonomous microgrids combining RESs with diesel generators, [40] explores the use of droop control. Specifically, the study addresses scenarios where a RES intentionally reduces its output due to issues, causing the diesel generator to become desynchronized. However, the recovery post-fault requires all reactive power to be produced using renewable energy. The study establishes d-q frame impedance models for both PQ-controlled and droop-controlled inverters. The microgrid's island mode is analyzed akin to a double closed-loop system due to the differing output characteristics of these control methods. The open-loop transfer function of the parallel system is derived, and the system's impedance model is formulated. This proposed impedance model is then used to assess the stability of parallel systems operating in island microgrid mode through the generalized Nyquist criterion (GNC). Simulation and experimental results validate the analysis.

As discussed in [13], a novel modeling approach and stability analysis method are proposed for weak power networks with significant penetration of power electronics converters. This approach includes small-signal state-space models for various network elements such as power lines, loads, power converters, and their control algorithms, allowing for comprehensive network modeling. The suggested linearized model is compared to the nonlinear model's response for validation. The created small-signal model is employed in stability analysis based on the frequency response of singular values to determine key network and control parameters in the presence of disturbances. Finally, the original nonlinear model is used to verify the presence of detected resonant modes.

In contrast to conventional stability analyses, a study by Zhang *et al*. [17] considers the unique characteristics of cables and inverters. Impedance-based and eigenvalue-based small-signal stability analyses are restricted by limited observability at specific states due to the need for source load subsystem analysis. Eigen analysis, as shown in [18], can predict harmonic oscillations in voltage source converters (VSC), while [41] introduces unsupervised feature selection in the context of machine learning and data mining. This technique combines maximum margin criteria (MMC) with a sparsity-based model, enhancing feature selection by considering both class margin and feature correlation. K-means integration is suggested to improve data separability in an unsupervised scenario. Reducing dimensionality for computationally efficient computations, as noted in [42], is a common challenge. Methods such as principal component analysis (PCA) aim to address this. A robust 1-norm maximization-based PCA is proposed to manage high-dimensional data and outliers effectively. The study introduces a non-greedy optimization approach that consistently yields better outcomes than the greedy method, as evidenced by real-world dataset experiments [43].

Additionally, the study in [44] uses a novel technique called the probabilistic neural network (PNN) to evaluate the transient stability of a power system. Feature extraction and selection are applied to reduce the data set and enhance classification accuracy. PCA is utilized to identify key features by analyzing correlations between different aspects. The New England 39 bus system is studied using transient stability assessment based on neighborhood rough set and discernibility matrix. These studies demonstrate a wide range of techniques and approaches used in stability analysis for microgrids, considering the complexities of various control methods, modeling strategies, dimensionality reduction, and feature selection to ensure the reliability and stability of power systems. The summary of this section is tabulated in Table 4.

Table 4. Summary of stability analysis in microgrids

| Topic | Key points |
|---|---|
| Droop control in microgrids | The paper [40] investigates the use of droop control in autonomous microgrids with RESs and diesel generators. Analyzes scenarios where intentional RES output reduction leads to diesel generator desynchronization. Establishes d-q frame impedance models for PQ-controlled and droop-controlled inverters. Applies GNC for stability assessment. |
| Modeling and stability analysis in weak power networks | The study [13] proposes a modeling approach and stability analysis method for weak power networks with significant power electronics converters. Incorporates small-signal state-space models for various network elements. Validates linearized models against nonlinear responses and employs stability analysis with frequency response of singular values. |
| Impedance-based small-signal stability analyses | The articles [17], [18], [41], [17] consider unique cable and inverter characteristics in small-signal stability analysis. [18] Predicts harmonic oscillations in VSC using Eigen analysis. The article [41] introduces unsupervised feature selection combining MMC with sparsity-based models for machine learning and data mining. |
| Dimensionality reduction techniques | The research [42] introduces a robust 1-norm maximization-based PCA to manage high-dimensional data and outliers effectively. Proposes a non-greedy optimization approach yielding better outcomes than the greedy method. |
| Transient stability assessment with probabilistic neural network (PNN) | A study by Wahab *et al.* [44] evaluates the transient stability of a power system using PNN. Applies feature extraction and selection to enhance classification accuracy. Utilizes PCA to identify key features and analyze correlations. Studies the New England 39 bus a system using transient stability assessment based on neighborhood rough set and discernibility matrix. |
| Comprehensive techniques in stability analysis | Multiple studies in the section demonstrate a wide range of techniques in stability analysis, considering complexities of control methods, modeling strategies, dimensionality reduction, and feature selection for ensuring reliability and stability of power systems. |

## 6. SOFT COMPUTING TECHNIQUES

The transient stability assessment (TSA) is a method employed to assess the stability of a power system under various disturbances, encompassing planned short-circuit failures and element outages. This evaluation is crucial to ascertain the system's behavior during transient events. When the system's response to a disturbance is deemed unstable, emergency management procedures are initiated. Traditionally, TSA has relied on time domain simulation, a process that involves numerically solving the system's dynamic equations over a range of time steps. However, this method can be computationally demanding and time-consuming, especially for complex power systems. To address these challenges, researchers have been exploring alternative approaches to speed up the TSA process while maintaining accuracy [45]. One such approach involves the use of advanced analytical methods, such as eigenvalue analysis and impedance-based techniques, to quickly assess the system's transient stability. These methods provide valuable insights into stability margins and the behavior of the system following disturbances without the need for extensive time domain simulations. By combining analytical techniques with intelligent algorithms and machine learning, researchers aim to enhance the efficiency of TSA while ensuring accurate results. These advancements are essential for maintaining the reliability and stability of power systems, particularly as they become more complex and interconnected with the integration of RESs and advanced control strategies.

The field of TSA in power systems has undergone significant advancements to improve its efficiency and accuracy. Researchers have introduced three main strategies aimed at accelerating TSA while maintaining its precision: the energy function methodology proposed by [46], the extended equal area criteria (EEAC), and the integration of artificial intelligence (AI) techniques. The energy function methodology, as outlined in [46], offers a systematic approach to evaluating transient stability. This method focuses on quantifying the energy function of the system and analyzing its trajectory during disturbances to predict stability. Despite its conceptual soundness, implementing this technique in complex systems has proven challenging due to the intricate modeling requirements it demands. Similarly, while the EEAC presents a viable framework for assessing stability by analyzing the area under the transient stability curve, applying it to large and intricate systems poses its own set of difficulties.

In response to these challenges, researchers are increasingly turning to AI methods to expedite TSA, leveraging the growing availability of phasor measurement unit (PMU) data and advancements in computer science. In recent studies, the fusion of AI with PMU data for online TSA has gained traction. This approach treats TSA as a classification problem, and researchers have focused on refining data selection for training, optimizing algorithms, fine-tuning parameters, and constructing ensembles of algorithms.

By utilizing data mining techniques, it becomes possible to analyze time series data and predict transient voltage stability with greater accuracy. One illustrative study, as presented by [47], leverages PMU data and a hybrid support vector machine (SVM) for transient stability assessment. The integration of PMU data enables a more comprehensive understanding of the system's dynamics, while the hybrid SVM model enhances accuracy.

A study [48] introduces an innovative approach that frames online power system transient stability assessment as a two-class classification problem. This novel methodology utilizes the core vector machine (CVM), a data mining algorithm, to analyze large volumes of PMU data. The CVM model is trained and tested offline, and then applied in real-time for online TSA, resulting in reduced time consumption and heightened accuracy compared to conventional SVMs.

In parallel, an intelligent system (IS) [49] has emerged to address the dual demands of rapid response and accurate assessment. By employing ensemble classifiers based on extreme learning machines (ELMs), the IS is capable of classifying system stability post-disturbance. The system also features a self-adaptive decision-making process, dynamically adjusting reaction times to optimize classification accuracy. This adaptability allows emergency controls more time to respond effectively, showcasing the potential to revolutionize transient stability assessment in real-world scenarios. The effectiveness of the IS has been validated through case studies, demonstrating its potential to reshape the landscape of transient stability analysis.

Furthermore, in the context of imbalanced data mining, the work [50] explores the application of cost-sensitive ensemble learning classifiers. These classifiers, integrated with techniques like feature selection and dimension reduction, offer a promising solution for online transient stability assessment. By considering the cost implications of different outcomes, these classifiers aim to optimize both speed and accuracy. The proposed approach outperforms traditional methods, especially evident in complex scenarios such as the 10-machine 39-bus system. In conclusion, the evolution of TSA methodologies underscores the growing role of AI techniques and PMU data in enhancing the efficiency and accuracy of power system stability assessments. These advanced strategies hold the potential to reshape the transient stability analysis landscape, paving the way for more efficient and reliable management of intricate power systems. Table 5 provides an organized overview of different papers, highlighting their key contributions and common themes in advancing the field of transient stability assessment in power systems. Transient stability analysis, ensemble classifiers, and cost sensitivity are different topics that are summarized from the soft computing techniques.

Table 5. Summary of transient stability assessment in power systems using soft computing techniques

| Topic | Key points |
|---|---|
| Transient stability assessment | The paper [47] leverages PMU data and a hybrid SVM for transient stability assessment. The integration of PMU data enables a comprehensive understanding of the system's dynamics, while the hybrid SVM model enhances accuracy. CVM is used in [48]. |
| Ensemble classifiers | The paper [49] introduces an IS utilizing ensemble classifiers based on ELMs for classifying system stability post-disturbance. Features a self-adaptive decision-making process to optimize classification accuracy, showcasing potential revolutionization of transient stability assessment. |
| Cost sensitivity | The paper [50] explores cost-sensitive ensemble learning classifiers for imbalanced data mining in online transient stability assessment. Integrates techniques like feature selection and dimension reduction, aiming to optimize both speed and accuracy, outperforming traditional methods in complex scenarios. |
| Other topics covered | Integration of AI techniques with PMU data for online TSA. - Challenges in implementing traditional methodologies in complex systems. - Advancements in classifier models for improved accuracy and reduced time consumption in transient stability assessment. - Potential revolutionization of transient stability analysis through adaptive decision-making and cost-sensitive ensemble learning. \| |

## 7. CONCLUSION

The RES has recently been proven to be a competitive alternative to existing power production methods. Power electronic-based converters are the principal interface for connecting RES to the electric grid system. Droop, VSM, open circuit voltage (VOC), and open circuit voltage-particle swarm optimization (VOC-PSO) control algorithms are used in an islanded MG to manage parallel inverters and ensure synchronization and power sharing. No control scheme necessitates communication between inverters. Synchronization necessitates the use of control algorithms to maintain constant voltage levels and phase angles in parallel inverters, enabling a microgrid's islanded mode of operation by increasing the amount of renewable energy penetration in a power system. Because of the large number of system state variables, the islanded microgrid's stability research employs parallel linked inverter dynamics, necessitating more computational power. Several pieces of literature on the self-synchronization of parallel inverters are covered in this overview. A feature-reduced stability analysis is recommended to make the stability analysis of parallel inverters less computationally demanding. Soft computing techniques like TSA a methods employed to assess the stability of a power system. The TSA is accelerated by three main strategies the energy function methodology, the EEAC, and the integration of AI. Large volumes of PMU data are analyzed by utilizing CVM and a data mining algorithm. The benefit of the IS is validated through case studies, illustrating its potential to reshape transient stability. This review paper presents several ideas or collections of knowledge for academics, academicians, users, and technicians interested in investigating power system voltage stability, anticipating, and preventing instability. A tabulated summary of each topic covered in the survey is given for each section.

## APPENDIX

Table 2. Synchronization and power sharing in islanded mode - a summary

| Topic | Key points |
|---|---|
| Microgrid operating modes | A microgrid facilitates serving distant end loads through isolated or grid-connected modes. Decoupling controllers, including active/reactive power and direct axis/quadrature axis controllers, are utilized in the grid-connected mode to synchronize renewable energy with the primary grid [13]. Synchronization control techniques maintain parallel inverters at the same voltage level and phase angles. The increasing penetration of renewable energy promises the potential for islanded operation, with stability assessed using a complex model [13]. |
| Modeling weak power networks | The research proposes a unique modeling approach and stability analysis process for weak power networks with significant penetration of power electronics converters. Various network architectures are modeled using small-signal state-space models for each network element. A linearized model is validated against a non-linear model's response, and stability analysis is conducted based on the frequency response of singular values to determine network and control parameters [13]. |
| Load frequency controllers in microgrids | LFCs and energy management systems in microgrids employ soft computing techniques. The importance of LFM has increased in contemporary power networks, particularly with the integration of RESs. Soft computing techniques are utilized to ensure efficient power management [13]. |
| Droop controller in islanded microgrid | Paper [14] presents a droop controller representation synchronizing with parallel inverter architecture in the microgrid's islanded mode. It utilizes a microgrid system with two DER-functioning inverters, employing the dq reference frame in inverter controller design. Nonlinear equations are linearized around steady-state operating points to create a mathematical model, validated through simulation and hardware experiments under load perturbation [14]. |
| Small-signal stability in LV inverter microgrid | Paper [15] addresses the small-signal stability of LV inverter-based microgrids. It introduces a simplified approach based on dominant inverter coupling impedances relative to interconnecting line impedances in LV distribution networks. Analytical identification of system equilibrium points simplifies the stability analysis, accurately predicting system instability boundaries for resistive interconnecting lines [15]. |
| Impedance-based stability in parallel inverters | Paper [16] describes the use of an impedance-based stability criterion to verify the stability of parallel inverters linked to the grid. It covers the combination of parallel three-phase inverters in utility-scale wind and solar electricity generation. The study defines the maximum number of paralleled inverters for stability, based on impedance measurements, utilizing experimental findings from a power hardware-in-the-loop setup. |
| Stability analysis of MOPLI system | Paper [17] presents the stability analysis of a MOPLI system. The study recreates models for inverters and cables, addressing the challenge of numerous inverters and extensive connections. It introduces a three-step impedance-based stability criteria for MOPLI, considering variations in inverters and cable effects, providing a straightforward and workable criterion [17]. |
| Enhanced impedance-based controllers | Research in [18] focuses on enhanced impedance-based controllers for parallel inverters regulated by PQ-based impedance and droop controller-based approaches. Double closed-loop controlled parallel inverters use the impedance approach for stability analysis. The study highlights the use of droop controllers, particularly in islanded microgrids [18]. |

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