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Review

A Review on Mode Transition Strategies between Grid-Connected and Standalone Operation of Voltage Source Inverters-Based Microgrids

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Abstract: Microgrids technologies are seen as a cost effective and reliable solution to handle numerous challenges, mainly related to climate change and power demand increase. This is mainly due to their potential for integrating available on-site renewable energy sources and their flexibility and scalability. The particularity of microgrids is related to their capacity to operate in synchronization with the main grid or in islanded mode to secure the power supply of nearby end-users after a grid failure thanks to storage solutions and an intelligent control system. The most critical operating case occurs when a sudden transition from grid-connected (GC) to stand-alone operation (SA) happens. During the transition, the system experiences abrupt changes that can result in a malfunction of the control system and a possible failure of the power system. The transition issue attracted considerable attention from researchers. Indeed, many research works are proposed to address this issue by proposing detection and transition techniques that ensure a smooth transition at the islanding time. Although there are several approaches to dealing with this issue, a categorization of the proposed methods in the literature and their differences is useful to assist engineers and researchers working on this topic. Thus, this study proposes a comprehensive review to summarize these approaches and point out their advantages and limitations.

Keywords: microgrids; distributed generation systems; voltage source inverters; islanding; mode transition control; seamless transition; grid-connected; stand-alone



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1. Introduction

The operation of the electrical power system is experiencing considerable mutations due to increasing energy demand, electricity market liberalization, fossil fuel scarcity, and the environmental impact of conventional generation methods. Consequently, the conventional electrical power system is not able to meet the balance between energy demand and production and face the aforementioned challenges [1]. Moreover, the mastery and evolution of technologies related to the exploitation of different energy sources and renewable energy sources in particular are pushing ahead the development of new power system paradigms [2]. To face these challenges, a competitive solution consists of producing energy based on the integration of more Distributed Generation (DG). These power challenges are transmuting the conventional electrical power generation concept and introducing an incipient trend coming mainly from the interconnection of distributed generation resources and the electric distribution system [1–4].

Benefits of a coupled DG-electric distribution system include:

- Reduced greenhouse gas emissions;
- Better energy system efficiency;

- Increased system reliability;
- Reduced congestion in distribution and transmission on the traditional power system;
- Services provision, such as voltage support and demand response;
- Increased integration of micro-generation systems along with the existing power generation schemes;
- Bidirectional power flow that offers more energy utilization flexibility.

As the characteristics of DG units are different, connecting them to a distribution system requires the use of power electronic interfaces. These interfaces allow the user to control the instantaneous injection of power. Thus, high-power quality can be achieved through an appropriate control system [5–9].

In order to intensify DG integration into the grid, the development of the microgrid (MG) concept is of interest, as it can integrate multiple interconnected DG types, storage systems, and loads. The microgrid concept is introduced as a promising solution to remedy many technical challenges and benefit from the potential of DGs, notably renewable energy resources [7,10–15]. Currently, the MG concept has numerous definitions; one universal definition considers MGs as a platform for incorporating various DG resources with minimum disturbances to the main utility grid or to local loads. It is also seen as a small-scale demonstrator for Smart Grid development [7,16]. It is expected that new functionalities related to grid technologies and modern electric applications will open other horizons for the development of MG systems, such as the development of MG clusters and Smart Grid applications [10,11].

Figure 1 illustrates the basic architecture of a typical grid interactive AC MG. The use of DG units and MGs offers several benefits linked mainly to environmental and techno-economic aspects [14]. In addition, it improves reliability and power supply security, especially for isolated areas [13–15,17,18]. Therefore, these new paradigms are rapidly developing along with the technological development of power electronics interfaces and power generation systems. Thanks to these developments, the exploitation of renewable energy sources and storage systems becomes easier within the framework of DGs and MGs.

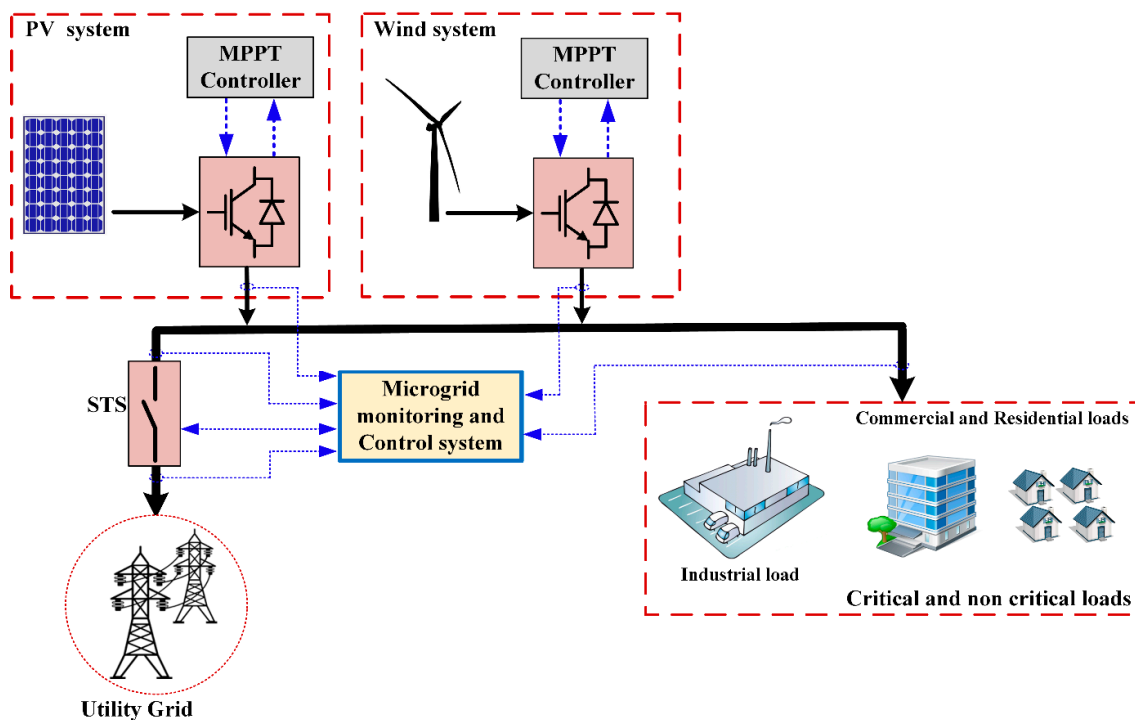


Figure 1. Typical architecture of grid interactive microgrid.

Microgrids can operate in Grid-Connected “GC” or Stand-Along “SA” mode. Thus, MGs should be able to operate in mode transition between GC and SA. In other words,

MGs should be controlled to provide GC and SA functions and to ensure smooth mode transition [8,9,16,19–25].

In the GC mode, the amplitude and frequency of the output inverter voltage are fixed by the main grid. Under fault conditions, DG units and local loads are isolated from the rest of the grid and need to operate in SA mode. In islanded MG, i.e., SA mode, the inverter control system is responsible for regulating the voltage characteristics (frequency and amplitude) [26–29]. Nevertheless, between GC and SA, there is a short period of time where the bus voltage is neither regulated by the inverter controller nor fixed by the main grid, which may result in a decrease in power quality and load malfunction [8,9,22,23,26]. This situation may result in abrupt changes in system state variables, which can affect the whole system [22,30].

Hence, increasing electric supply resilience is a major challenge that arises especially for MG applications, which accelerates the development of advanced control and protection mechanisms. This issue presents a potential new research horizon for many research and development program directions [31–36].

Thus, the goal for MG systems is to be able to function in complement with the utility grid and thus function in GC and SA modes and achieve smooth mode transition. This enthusiasm is reflected in a significant number of studies to remedy the widespread concern about mode transition topics (i.e., relieve the undesirable transient effect). Indeed, the problems experienced during the transition phase mainly concern frequency and voltage disruptions [25]:

- An abrupt variation at the frequency level easily drives disturbances into the output angle of the DG inverter, which is contributing to the destabilization of the total MG system;
- An abrupt variation at the voltage or current level leads to system destruction, notably at the local critical load.

In the literature, various control strategies have been proposed in order to handle mode transition [3,4,16,24]. Developed control strategies aim to guarantee a seamless disconnection or connection between all connected DG units and the utility [8,9,22–24]. By reviewing some papers in this field, we observed that these strategies can be classified into five families depending on their control mechanisms [37–59]. The main motivation of this work is to give an overview of the existing control strategies that focus on mode transition. These control strategies are classified and thoroughly discussed, with a focus on their advantages and/or disadvantages.

This paper reviews different control strategies that deal with mode transition in DG and MG applications. Section 2 presents the typical configuration of MGs and describes the essentials of the hierarchical control strategy used in these applications. Section 3 focuses on the tertiary control layer and performs a review of the modes of operation of MG. Section 4 highlights a detailed outline for each transition control strategy and proposes the classification of these control methods. Section 5 clarifies viewpoints for the near future to be addressed by researchers. Finally, Section 6 underlines the main conclusions reached in this review.

2. Methodology and Scope

The review article presented in this manuscript highlights literature pertaining to the islanding function in microgrids. The islanding function is recognized as one of the key advantages offered by microgrids. The graphic paper is represented in Figure 2.

Initially, a pilot study was carried out to understand the basic concepts of microgrid frameworks. Typical MG functions and components with detailed descriptions of hierarchical controls are provided (Figures 3 and 4). This is followed by an overview of the many MG demonstrators deployed all over. An overview of the existing MG systems is proposed in Table 1, providing various details such as geographical location, type of loads, types of generation sources used, the existence of energy storage systems, and the operation modes of the targeted MG. Before delving into the islanding function, specifically focusing on

the detection and management of unplanned islanding. Therefore, as shown in Figure 4, the focus of the review highlighted in this manuscript was to emphasize more on the microgrid operation modes GC and SA and the transition between those operation modes. Following this, a set of keywords relating to islanding conditions, such as the concept, types, islanding detection methods (IDM), and relevant standards, were identified. This rigorous review sheds light on islanding conditions, particularly the challenges associated with unintentional islanding and their quantitative risks, including material damage and economic losses. This systematic review process began with a pilot study, which allowed the authors to gain a preliminary understanding of the progress made in the field of islanding detection standards and methods in MGs. Therefore, the analysis encompassed the control system evaluation for all microgrid operation modes, facilitating a comparison of strategies employed in the smooth transition process. The review of the control transition structure uncovers distinct physical divisions and compares the strategies employed in the microgrid concept. Upon reviewing the control transition structure, it becomes evident that there is a clear physical division and a comparison of strategies employed in the MG concept. The transition control approaches can be broadly classified into five types in Table 5 and Figure 10, Figure 11, Figure 12, Figure 13 and Figure 14: unified control, switch process, feedforward control, droop control, and dispatching unit.

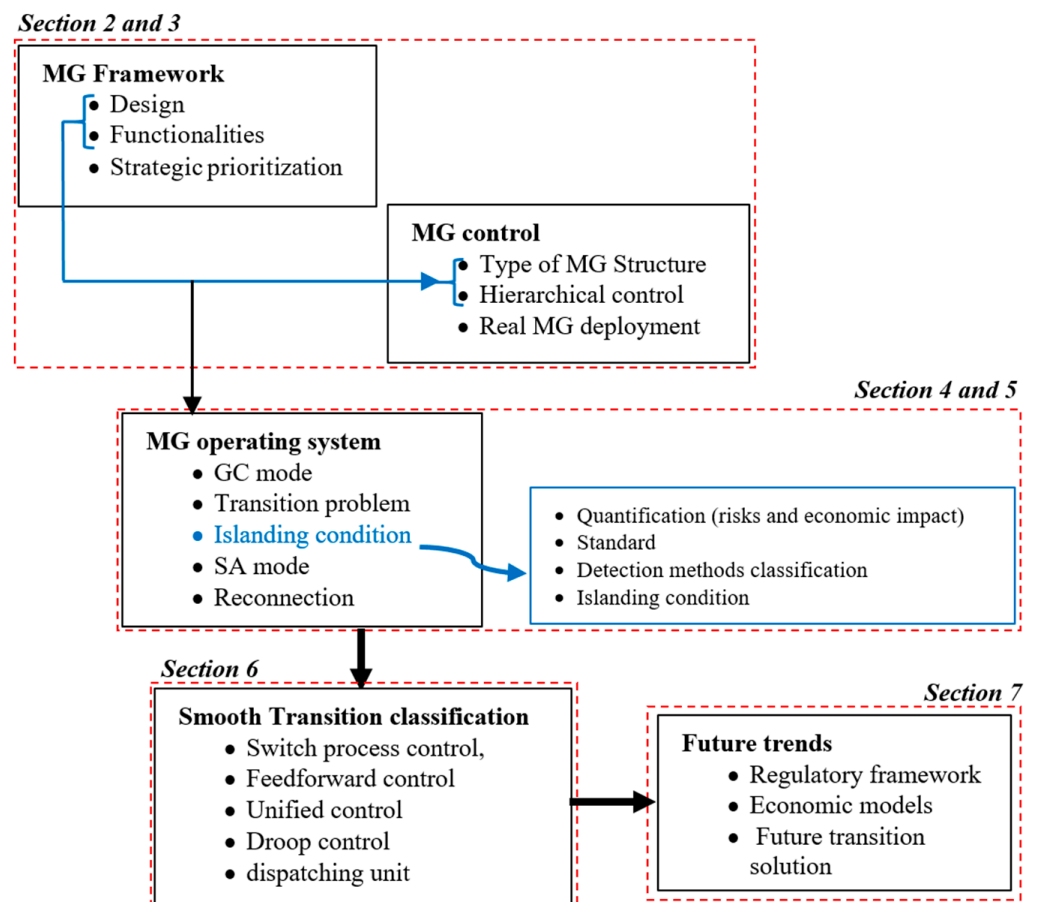


Figure 2. Graphical representation in the review in this paper.

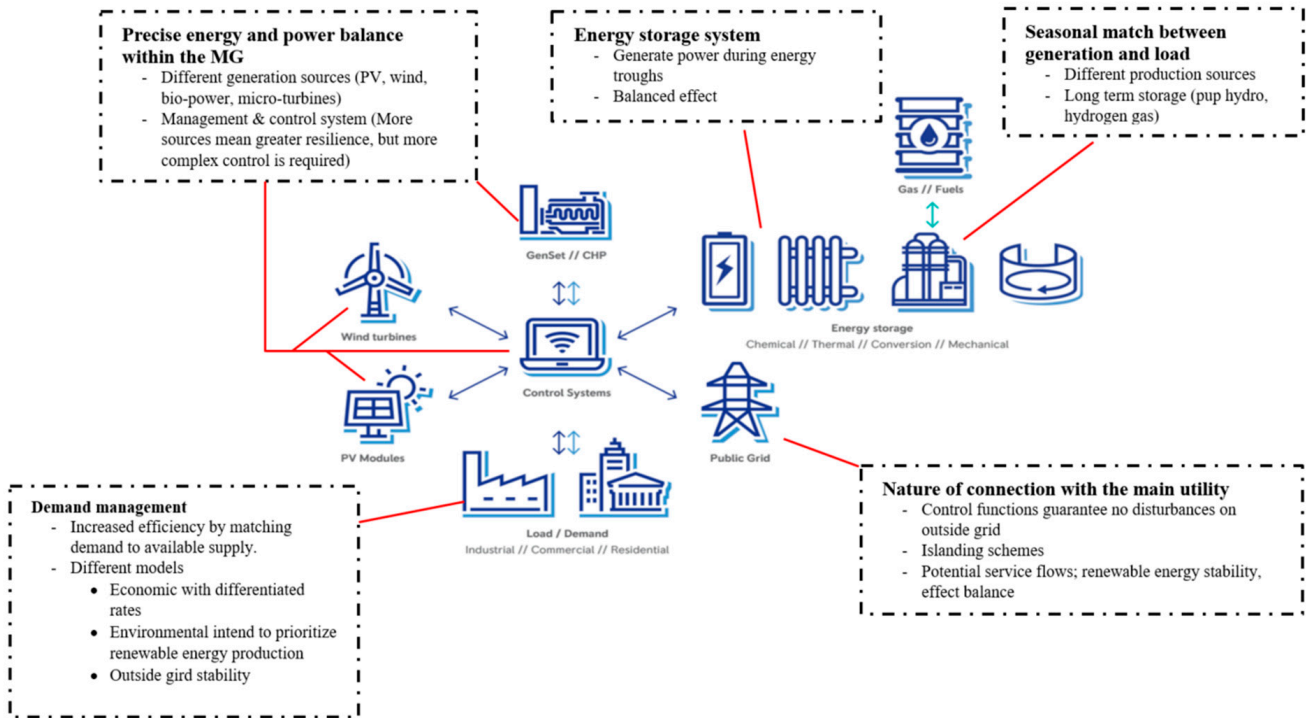


Figure 3. MG conceptual design with the main functionalities.

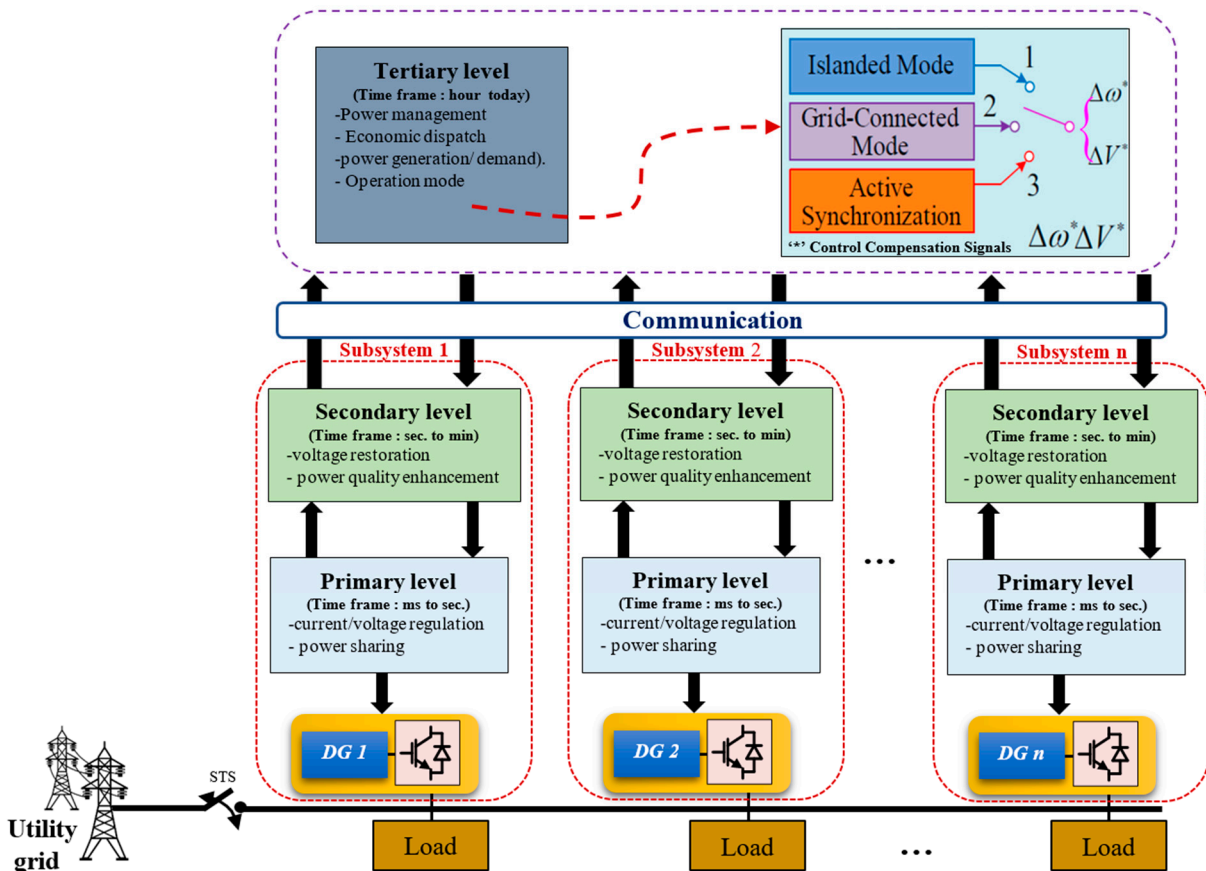


Figure 4. A hierarchical control structure for a microgrid.

Table 1. MG implementation around the world.

Project Name Ref.	Situation	Organization	MG Type	Load Application	DGs	Control	Storage System	Operation
Santa Rita Jail [60–62]	Dublin, California	CERTS, RDSI	AC	University	PV, diesel, fuel cell	Decentralized	Lion battery	GC with seamless Islanding
Borrego Springs [61]	Sand Diego county California	RDSI, ARRA	AC	Residential, commercial and industrial	Diesel, PV	Decentralized	Lion battery Three feeders, batteries, and home storage units	Manuel islanding
The Navy Yard [60]	Philadelphia	AM	AC	Residential	Gas/diesel turbines, PV and fuel cell	Decentralized	Community solar and energy storage	GC
US Fort Collins [63]	Fort Collins, Colorado	FordZED, RDSI	Hybrid	Residential	PV, CHP, micro turbines, fuel cells, diesel	Decentralized	Thermal Storage	GC/SA
Illinois Institute of Technologies [64,65]	Chicago, Illinois	Perfect Power initiative, RDSI	AC	Residential	Gas turbines, PV, wind, diesel	Decentralized	Follow battery	GC/SA
Colonias [66,67]	Texas	State Energy Conservation Office (SECO), Texas Engineering Experiment Station, Xtreme Power	AC	-	Pv, wind, diesel	Centralized	No	GC
University of Miami Testbed [68]	Florida,	University of Miami	DC	University, residential	PV, fuel cell	Decentralized	battery	GC/SA

Table 1. Cont.

	Project Name Ref.	Situation	Organization	MG Type	Load Application	DGs	Control	Storage System	Operation
EU	Benchmark Low Voltage [69]	Athens, Greece	Microgrids Project	AC	Residential	PV, wind, fuel cell	Centralized and decentralized	Battery Flywheel	GC with seamless transient
	Samsø Island [70]	Samsø Island, Denmark	Government and citizens	AC	Residential, pumping	Wind and thermal PV	Centralized Model Predictive Control	Battery	GC/SA
	Ílhavo Municipal Swimming-Pool [71]	Lisbon, Portugal	More Microgrids Project and EDP Distribuição	AC	Residential, pumping and power circuit	Microturbine Diesel generator	Centralized, dual control	No	GC/SA With transition
	Labein Experimental Center [72]	Derio, Spain	More Microgrids Project	Hybrid	University	PV, wind, diesel and microturbine,	Centralized, PQ control	Battery, Super Capacitor Flywheel	GC
	Demotec [73]	Kassel, Germany	ISET and University of Kassel Institute for electrical energy technology	AC	Residential, Commercial Industrial	PV, wind, diesel, CHP	Centralized Master slave control	Battery	GC/SA With transition
	University of Seville [74]	Spain	University of Seville HybLab	DC	Residential, motor	PV, fuel cell	Decentralized	Battery	SA
	Utsira Wind [75]	Norway	StatoilHydro and Enercon	AC	Residential	wind	Centralized	Hydrogen storage	GC
	Power Matching City [73–76]	Groningen, Netherlands	KEMA	AC	Residential	PV, micro-CHP, wind	Centralized	EVs	GC
	Horizon [77]	Manchester, England	H2Ope	AC	-	CHP, wind, PV	Centralized	-	-
Gazi University [78]	Ankara, Turkey	Gazi University	AC	University	PV, wind, diesel	Centralized	Battery	SA	

Table 1. Cont.

	Project Name Ref.	Situation	Organization	MG Type	Load Application	DGs	Control	Storage System	Operation
Asia	Kyoto Eco Energy [79]	Japan	NEDO	AC	Residential	PV, wind, fuel cell, bigas	Centralized	Battery	GC
	Fukuoka [80]	Japan	Smart Energy Laboratory	DC	Home	Wind, PV	-	Battery	SA
	FC-CHP-based Plant Osaka [81]	Japan	-	AC	Hot water supply	Fuel-cell-combined heat and power (FC-CHP)	Centralized	Battery	GC
	Akagi [82]	Japan	NEDO	AC	Commercial/industrial	Diesel	Centralized	No	GC
	INER Testbed [83]	Taiwan	Institute of Nuclear Energy Research	AC	Motor	PV, wind, diesel, gas turbine	Decentralized	Battery	GC
	Subax [84]	China	-	AC	Residential	PV, wind, diesel, gas	Decentralized	Battery	SA
	HFUT Microgrid [85]	China	Lab-in Hefei University of Technology	AC	Static, load	PV, wind, fuel cell, hydro, gas	Centralized	Battery	GC/SA with seamless operation
	Singapore Pulau ubin [86]	Singapore	-	AC	Domestic application	PV, diesel	Decentralized	Battery	GC
	Jeju Island [87]	South Korea	Korea Smart Grid Association and Korea Electro technology Research Institute	AC	-	PV, Wind, fuel cell, Diesel	-	Battery	GC
	Qatar climate conditions [88]	Doha Qatar	Qatar Foundation	Hybrid	Residential/commercial	PV	Decentralized	Lithium-ion battery storage system	GC

Table 1. Cont.

	Project Name Ref.	Situation	Organization	MG Type	Load Application	DGs	Control	Storage System	Operation
Africa	Lucingweni [89]	South Africa	Nersa	Hybrid	Residential	PV, wind, diesel	Decentralized	Battery	SA
	Solar power projects [90]	South Africa	SAG institutions	AC	Rural urban	PV and CPV	-	-	GC
	Optimum isolated hybrid microgrid [91]	Fez, Morocco	-	Hybrid	Residential Rural area	PV, wind, diesel	Centralized	Battery	SA
	Manar microgrid Project [92]	Tunisia	CROM and DSR	AC	Building (Five apartments)	PV	Centralized	Lithium-ion Battery and supercapacitor	GC
	Smart microgrid in sub-Saharan Africa [93]	Nigeria	-	Hybrid	Rural electrification	PV, diesel generator	Centralized	Battery	SA
Australia	Coral Bay [94]	Western	-	AC	Residential/ commercial	Wind, diesel generator	Centralized	Lithium battery	SA
	CSIRO Energy Center [95]	Newcastle	-	AC	Residential (domestic loads)	Wind, PV	-	Battery	GC
	QUT Microgrid [96]	Queensland	-	DC	University applications	Fuel cell, PV,	Decentralized	Battery	SA
	Flinders island microgrid [97]	Flinders	-	AC	Residential Commercial Industrial	Wind, solar and diesel generator	Centralized	Battery	SA

Therefore, the analysis encompasses the control system evaluation for all microgrid operation modes, facilitating a comparison of strategies employed in the smooth transition process. The review of the control transition structure uncovers distinct physical divisions and compares the strategies employed in the microgrid concept. Upon reviewing the control transition structure, it becomes evident that there is a clear physical division and a comparison of strategies employed in the MG concept. The transition control approaches can be broadly classified into five types in Table 5 and Figures 10–14: unified control, switch process, feedforward control, droop control, and dispatching unit. One of the main objectives of the review article is to highlight the use of control approaches to address the transition problem in MGs. The study examines future trends regarding the transition process in microgrids.

3. Microgrid Frameworks

This section conducts a thorough literature review on the conceptual and operational aspects related to MGs. Figure 3 presents the typical functions and components of MGs. In addition, in order to achieve high levels of robustness, resilience, and reliability throughout all operational states and transitions, different control and management strategies need to be implemented. The theoretical field of sustainable transitions has grown rapidly in recent years [95,98–103], and various disciplines such as economics, sociology, economic geography, and engineering are committed to the development of new grid paradigms. In this sense, there are many MG demonstrators deployed all over. An overview of the existing MG systems is proposed in Table 1. Different information in relation to the geographical situation, type of loads, types of generation sources used, the existence of energy storage systems, and the operation modes of the targeted MG are listed in this table. As mentioned in Table 1, some energy development organizations realized their own MG projects, such as CERTS in the US [104], NEDO in New Mexico in collaboration with Japan [105], and MG projects in Europe as simulation and demonstration platforms [77].

The microgrid market in South America is experiencing rapid growth as well. According to a research report released by Triton Market Research, the Latin American microgrid market is projected to achieve a compounded annual growth rate of 10.61% between 2022 and 2028 [106]. This explains the existence of various laboratories and test systems dedicated to microgrids in South America. In [107], a concise portrayal of each microgrids general information, characteristics, and components. Additionally, it incorporates a discourse on the progress made in distributed generation within the Latin American region (in Brazil, Ecuador, Argentina, Mexico, Chile, Peru, etc.).

Currently, multiple demonstration and pilot projects are actively integrating renewable energy sources into isolated microgrid systems. These initiatives, discussed in [108], specifically focus on incorporating renewable energy resources into microgrids that serve remote communities in Canada. For instance, ongoing initiatives in Northern Ontario, such as Deer Lake and Fort Severn, involve the deployment of photovoltaic (PV) and hybrid systems to decrease reliance on diesel fuel. Additionally, the remote mine located in Diavik, Northwest Territories, has implemented a wind farm to reduce fuel consumption, whereas the Northwest Territories Power Corporation has installed a solar and battery system in Colville Lake. Additionally, research was conducted on the utilization of ocean energy. However, in 2020, Canada launched the Ocean Energy Smart Grid Integration Project, with the aim of integrating ocean energy into isolated microgrids on remote islands. The Pacific Regional Institute for Marine Energy Discovery at the University of Victoria received a grant of USD 730,000 to develop a microgrid powered by wave energy for Nootka Island [109].

Taking into account a country's own needs, strategies, priorities, and assets that can be different from one region to another, different MG concepts can be developed. As a result, advancements in these technologies depend on the specificities, priorities, and potential of each country. Therefore, the majority of the MGs developed have at least one of the following aims:

- ✓ Provide an appropriate remedy for delivering electricity to remote areas where it is difficult to connect rural communities, which is the case in many developing countries and isolated areas. Some cases can be found in Africa (Lucingweni, Diakha Medina), Asia (India, Vietnam, Nepal, Koh Jik, Sri-Lanka), and Europe (Akkan, Macedonia) [77,105,110];
- ✓ For Europeans, the major concern is to develop energy communities in terms of renewable energy integration rates, i.e., integrating as much renewable energy on a large scale [99]. To achieve this, several EU countries have ambitious goals to decarbonize their energy systems (reduce gas emissions by 80–95% compared with 1990 by 2050). To achieve these goals, new policies and directions have been made to increase renewable energy production (mostly solar and wind energy) [100]. For example, in Feldheim, Germany, the power supply is 100% renewable [95]. To achieve a transition to 100% renewable energy by 2050, in Denmark, appropriate energy policies have been made to improve the energy efficiency of the residential sector [101]. In addition, numerous research programs focused on MGs' development have been launched within EU research frameworks, such as the DISPOWER project or the MORE MICROGRIDS project, in order to develop advanced control schemes (decentralized and centralized control) and communication protocols. In this direction, many universities and technological institutes have also developed their own MG to carry out experiments while they are self-producers (Manchester, Aalborg, Fraunhofer, Chalmers, Illinois) [102].
- ✓ The security of supply remains a major concern in the US in case of war or disaster [65]. The US Department of Defense focuses on the deployment of MGs in hot spots. The Navigant research predicts that the annual MGs implementation spending by the US Department of Defense is expected to exceed USD 1 billion annually by 2026 [65,111]. In this sense, many communities in the US have ambitious targets for the transition toward more renewable energy production, mainly from solar and wind energy. In this context, some initiating projects have been launched within US research frameworks, e.g., Sandia National Laboratories and the University of Buffalo have applied the social burden of power outages method in two projects to date [112].

4. Microgrid Control

Depending on its application, architecture complexity, scale, and component technologies, a microgrid controller can be structured on different levels with different objectives and timescales [113]. Commonly, three hierarchical levels, described in Figure 4, are defined [113–117]: (i) The primary level deals with the on-line control of the local outputs (voltage, current). It also ensures power sharing in the presence of multiple DG units. This control level is close to the physical system and does not depend on communication facilities. The control dynamics at this layer are around milliseconds. (ii) The secondary level, which requires communication facilities, is mainly dedicated to supervision and power management. It ensures the transfer of information and consignments between the primary and tertiary control levels. The time of operation at this level ranges from milliseconds to minutes. (iii) The tertiary level, as an offline control, is more related to energy planning and grid service provision such as voltage–frequency stabilization and maximizing the economic gains of the microgrids. The dynamics of this last level range from hours to days. Hereafter, additional information on the control levels roles, especially with regard to the management of transient modes (islanding and reconnection to the grid), are given.

- **Primary level control:** based on local measures, primary control performs the local bus voltage stabilization and current control inside the microgrid. Furthermore, power sharing between the DG units based on droop techniques is used to modify the inner loop references. This level confers inertia to the DG units and allows for eliminating circulating currents that are a threat to the materials, such as power electronic devices. To ensure complete microgrid integration, the primary control

should include algorithms to manage islanding events and, therefore, handle the inerrant overcurrent that arises from an accidental transition between the operating modes. The transition management algorithm should ensure a fast reconfiguration of the control references (a few milliseconds) without abrupt discontinuities in the control references in order to achieve a smooth transition.

- **Secondary level control:** This level uses communication facilities to ensure power management between the units and can be classified as centralized or distributed. This stage for handling power-sharing inaccuracies by providing voltage and frequency deviations to the primary control. Moreover, it can incorporate several management functions such as forecasting uncertainties, correcting the power consignments to exploit the intraday market, and ensuring the battery's state of charge management. From an operating mode perspective, this level is mainly associated with the management of microgrid reconnection to the main grid. The synchronization process can take a few minutes. It can also manage load shedding to maintain the power balance between production and consumption inside the microgrids, especially in off-grid operations. Once the utility grid is restored, the active synchronization algorithm will be initiated to reconnect the microgrid to the main grid. Ensuring uninterrupted power supply and minimizing rush currents, the seamless transition strategy from the SA mode to the GC mode holds immense importance. During the active synchronization (AS) process from the IS mode to the GC mode, it is crucial for the point of common coupling (PCC) to synchronize with the utility grid in terms of voltage amplitude, frequency, and phase in order to achieve a smooth transition. Thus, the active synchronization compensation signals $\Delta\omega^*$ and Δv^* are given.
- **Tertiary level control:** This control level is mainly concerned with offline energy scheduling in order to satisfy objectives that are often related to techno-economic efficiency optimization. The optimization is carried out within a long- or medium-term time horizon (a 24 h planning horizon is the most common). The purpose of this optimal planning is to estimate the best set-points, which are transmitted to the operational level (secondary control), to exploit the degrees of freedom used to control the system under study, based on the day-ahead market, storage capacities, demand-side forecasts and flexibility, and all renewable production forecasts. Regarding operation modes, this level is used to prepare large-scale operations such as the preparation of storage elements and/or schedule load shedding to absorb transient disturbances and stabilize voltage frequency and amplitude, particularly during peak consumption times. This level can also be used to prepare the assistance operations as a black-start grid to recover from a blackout and for the planning of maintenance operations.

As a summary of the role of the different stages in operating modes, (i) the tertiary level exploits and plans microgrid capacities to absorb the transient disturbances of the grid and maintain stable frequency and voltage magnitudes. It can also use microgrids to assist the main grid in recovering from a blackout. The secondary level is the link between the tertiary and the primary control and is devoted to the connection and synchronization of microgrids to the main grid. It can also ensure load shedding to maintain power balance inside clusters of microgrids. The primary level ensures securing operation under fast transient modes, such as a non-scheduled islanding.

5. MG Functionality and Operation Modes

Microgrids can operate in two main modes: grid connected and off grid. Microgrids also incorporate additional functionalities for transient mode management between the two main modes, namely, islanding transitions and grid reconnections [118]. The MG operation modes are depicted in Figure 5. In the following, a description of the specificities of the MG operating modes is given.

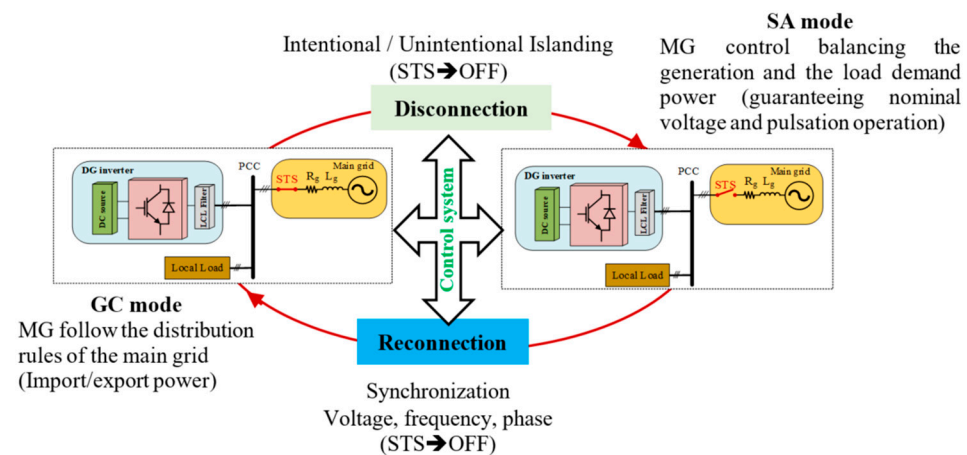


Figure 5. MG functionality and operation modes.

5.1. Transition Problems and Related Issues

A Microgrid transition between the GC and SA modes is a promising alternative, providing greater availability and flexibility. Transition smoothness remains highly challenging, due to the fact that it heavily depends on control strategy and the corresponding parameters [31]. However, a successful transition between grid connected and standalone is a considerable challenge for many researchers because existing methods are still not entirely satisfactory.

Methods of transition prevention have been studied. Figure 6 is a graph of IEEE conferences and journals published in the GC and SA operating modes between 2000 and 2023. From 2006 onwards, it shows that there is increased interest in the transition between microgrid operating modes.

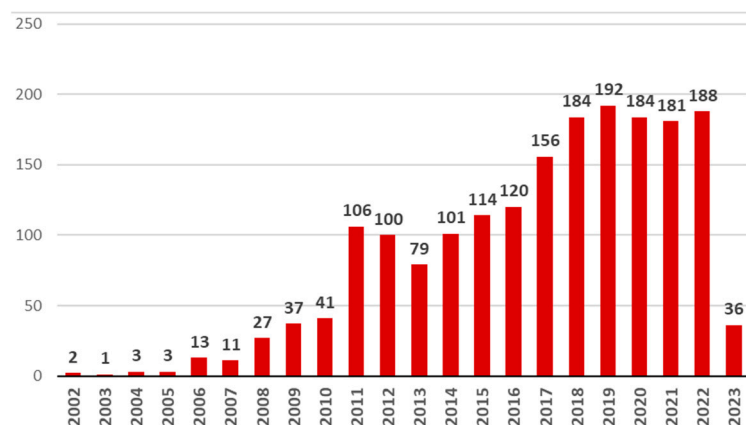


Figure 6. IEEE-published papers on microgrid operating in GC, SA, and their transition modes, 2000–2023.

One of the crucial operations for the energy sustainability and load balancing of the microgrid system is the transition issue between the grid-connected mode and the islanding mode. The technical problem underlying this is that the output inverter is supported by the main grid during GC and controlled by the local inverter. However, during the transition between those operation modes, the voltage magnitude and frequency are not supported by the grid nor by the inverter. This operation state, if not strictly monitored, can easily cause a whole MG operation problem, which could result in damage to or the destruction of equipment [4].

Furthermore, a stable transition between those operation modes is a vital concern because it can cause both voltage peaks across the local load and peak currents to the main utility. Therefore, a provision of transparent transient conditions from grid-connected

mode to island mode or vice versa is a necessity [32]. This consideration highlights the performance of the microgrid control system. Another significant issue is strongly linked to a specified modeling of the transition dynamics between both operation modes. This is usually the basis of the interactions between the electrical power distribution and the penetration of all DG inverters. Energy management and load scheduling are issues of prime concern in this regard. In other words, guaranteed uninterruptible power supplies. Thus, two major deficiencies can be summarized from the existing transition method [33,34]:

- A sudden alteration in inverter operating mode, for instance, will cause the inverter to switch from current control to voltage control as soon as islanding failure is present;
- A controller's parameters are chosen based on practice and experience. Otherwise, an efficient and systematic checking method does not exist.

A careful examination of the dynamic transient state behavior of microgrids shows that the real technical challenges can be summarized as [32–35]:

- The sensible load that must always be supplied;
- The sensible load must be protected against any abrupt power variation (mainly voltage frequency).

Accordingly, during the transition period, it is essential for the control system to implement adequate precautions that smooth out undesirable disturbances, such as voltage spikes and rush currents. These precautions aim to prevent excessive voltages and ensure stable operation throughout the entire transition process.

5.2. GC Mode

In normal operation (GC mode), the microgrid is expected to follow the rules of the utility without being involved in the main power supply function. This approach is adopted in the microgrid functioning principle for continuous and stable electric power system operation.

Furthermore, in this operating mode, the microgrid can export its excess power to the main grid or draw power from it. As a result, the microgrid must have the ability to control the fluctuation of active and reactive power flows while monitoring the energy storage state [36,119]. When designing and developing the microgrid control system, several significant issues related to the grid-connected (GC) mode should be considered. These concerns can be summarized as follows [120,121]:

- The system dynamics need to be fixed to a large extent due to the small size of the distribution units;
- Typically, the dynamic response of the control signals is slow whenever there is a variation in the output power;
- To improve system stability, a virtual inertia should be incorporated into the control loops of each power electronic interface;
- The uncontrolled grid-injected power flow: at the PCC, the fluctuation of active and reactive power is sensitive to the utility grid's state [122].

5.3. Islanding Detection

5.3.1. Islanding Detection: Concept

According to IEEE 1547 of 2008, an “island into the electric power system” is defined as “a condition in which a part of the system comprising the DGs system and local load is isolated from the rest of the electric grid under a grid failure or loss at the PCC. Furthermore, this island acts as a local production resource and continues to supply power to local loads” [123]. Islanding can typically be intentional or unintentional (unplanned). Intentional islanding is planned in advance and occurs during maintenance operations. Numerous publications have raised concerns about unplanned islands. In fact, multiple factors could lead to unintentional islanding, including [123–126]:

- A fault on the area electric power system, causing a disconnecting device to open, but the fault is not detected by the PV inverter or by local distributed energy resource protection devices;
- Utility switching of distribution lines and loads; intentional disconnection of the distribution line for utility service or repair;
- Distribution line and load switching by utility services; intentional disconnection of the utility grid for utility service or repair;
- Equipment failure that results in the unintentional opening of a disconnecting device;
- Bad actor with malicious intent;
- Human error;
- An act of nature.

As a general rule, planned islanding does not have negative consequences, as they are anticipated and managed during and after disconnection from the main utility. However, unplanned islanding is caused by an unforeseen disturbance in the system. Incorrect detection of such situations can lead to serious problems. These problems mainly concern safety hazards, power quality, voltage, and frequency stability. They may result in significant risks of damage to utility equipment or customer-connected loads due to transient conditions occurring between the islanding event and the eventual disconnection of the DG inverter from the grid. [125,127].

Moreover, when islanding mode disappears and the DG system needs to reconnect, the inverter is likely to be out of synchronization, which can result in damage to local devices and loads due to the phase difference between the output inverter and the main grid [128].

5.3.2. Quantification of Risk of Islanding

When quantifying the damage caused by an islanding condition, several metrics come into play, including the overall outage duration, loss, and lost energy. These metrics indeed correlate with overall welfare loss. However, there are other factors to consider as well [129–131].

- ✓ The occurrence of a blackout directly results in economic harm. Processes are disrupted, production batches are lost, and manual restarts are required, among other factors. Prolonged islanding, particularly when power is out, poses a special challenge because freezing can cause severe damage to customer property. Furthermore, they endanger critical components of the energy supply system, such as power plants and heating networks. According to the US president's council [130,131], the average annual cost of partial power outages caused by severe weather ranges between USD 18 billion and USD 33 billion. The cost can be much higher in a year with record-breaking storms (in 2008, for example, the year of Hurricane Ike, weather-related outages cost the economy between USD 40 billion and USD 75 billion). Therefore, preparing for the challenges posed by climate change necessitates investment in 21st-century technology that improves grid resilience and reliability. This is why the American Recovery Act allotted USD 4.5 billion for smart grid investments. In [132], a simulation dynamic model in Costa Rica demonstrated that islanding resulted in significant economic losses (USD 92,780/h);
- ✓ The extent of damage escalates significantly when an outage surpasses the backup system's design capacity for critical facilities. Moreover, as backup power depletes, certain components of the power system may gradually become unavailable. For instance, in Germany, approximately 150,000 interruptions lasting more than 3 min are recorded annually for low-voltage (LV) end customers. However, these substantial numbers, however, only marginally increase the System Average Interruption Duration Index by about 2 min per year per end customer at the LV level. The overall duration index is approximately 12–15 min per year, excluding extreme event (resilience-related) outages from these general reliability statistics [130,133].

5.3.3. Islanding Detection: Standardization

As DG's deployment progresses, a higher level of penetration will be achieved, where unintentional islanding could pose a serious risk to the power system's safe and reliable operation. These factors have been highlighted as critical concerns in power research programs, which explain the intense focus on unintentional microgrid islanding in several research projects [134]. Consequently, numerous standards have been developed by many countries for all grid-tied DG inverters [135].

These standards are established by various commissions primarily to enhance safety and quality factors, address islanding issues, and address electromagnetics. The most relevant international organizations in this regard include the IEEE in the United States (Institute of Electrical and Electronics Engineers), the IEC in Switzerland (International Electrotechnical Commission), and the DIN and VDE (DKE) in Germany (German Commission for Electrical, Electronic, and Information Technologies). Figure 7 showcases the widely used standards and their specifications for grid-connected DG systems [135–137].

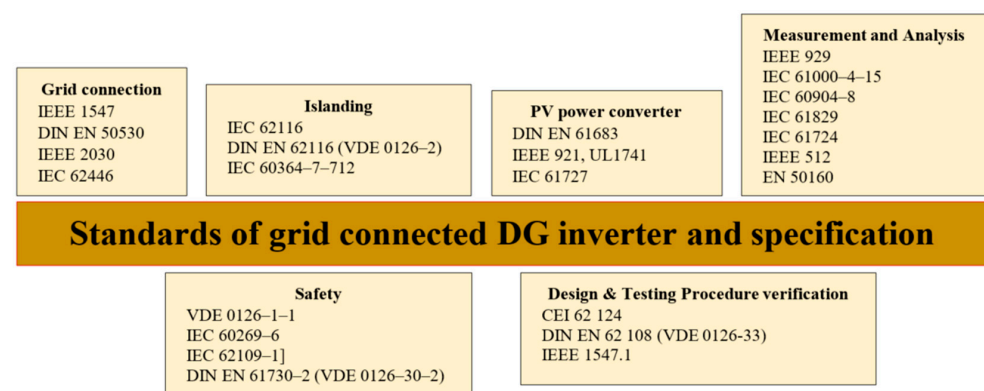


Figure 7. Standards and specification.

All of the standard requirements require detecting islanding conditions as soon as the island indicator takes place and ceases to energize the utility grid. The voltage, frequency, and power quality requirements for disconnection are specified in Tables 2 and 3, respectively. The reconnection standard is outlined in Table 4.

Table 2. Disconnection voltage and frequency standards.

IEEE 1547 Std.		IEC61727 Std.		VDE 0126-1-1 Std.	
Voltage Rang (%)	Clearing Time (s)	Voltage Rang (%)	Clearing Time (s)	Voltage Rang (%)	Clearing Time (s)
V < 50	0.16	V < 50	0.10	110 < V < 110	0.2
50 ≤ V < 88	2	50 ≤ V < 85	2.00		
110 < V < 120	1	110 < V < 135	2.00		
V > 120	0.16	V > 135	0.05		
Frequency rang (Hz)	Clearing time (s)	Frequency rang (Hz)	Clearing time (s)	Frequency rang (Hz)	Clearing time (s)
59.3 < f < 60.5	0.16	$f_{n-1} < f < f_{n+1}$	0.1	57.5 < f < 50.2	0.2

Table 3. Disconnection power quality standard.

IEEE 1547 Std.		IEC61727 Std.		VDE 0126-1-1 Std.	
DC current injection limits					
$I_{DC} < 0.5\%$ of the rated RMS current	0.16	$I_{DC} < 0.5\%$ of the rated RMS current	0.10	$I_{DC} < 1\%$ of the rated RMS current	0.2

Table 3. Cont.

IEEE 1547 Std.		IEC61727 Std.				VDE 0126-1-1 Std.
Voltage Harmonics limits						
Harmonic order	$h < 11$	$11 < h < 17$	$17 < h < 23$	$23 < h < 35$	$35 < h$	Totale Harmonic Distorsion THD (%)
%	4.0	2.0	1.5	0.6	0.3	5.0

Table 4. Reconnection standards.

IEEE 1547	IEC61727
$88 < v < 110\%$	$88 < v < 110\%$
and	and
$59.3 < f < 60.5$ (Hz)	$59.3 < f < 60.5$ (Hz)
	Delay standby Delay minimum 3 min.

5.3.4. Islanding Detection Methods (IDM)

The study of Islanding Detection Methods (IDMs) in the field of DG has been presented under different names over the years. These names include islanding detection, non-islanding, anti-islanding (AI), and unintentional islanding [125]. In the literature, several IDMs have been proposed to effectively detect the islanding mode. To evaluate each IDM, some performance indices are utilized, reflecting accuracy, speed, and effectiveness criteria. These indices typically include the Non-Detection Zone (NDZ), Detection Time (DT), and impact on power quality [138,139].

On the other hand, certain studies have highlighted the broad generalization capability of IDMs concerning topology adaptation [132,140,141]. A smart and passive technique for detecting islanding events that can adapt to various conditions including changes in grid topology was proposed in [140]. In [132], a novel approach called the Topology Identification Matrix Method was devised specifically for a microgrid system featuring a dynamic network. In this study, a fault protection strategy based on a multi-agent system was implemented to effectively coordinate the protection measures. In the same vein, a hybrid IDM based on two passive IDMs, namely, rate of change in active power and rate of change in reactive power, was proposed for an 11 kV Malaysian distribution system in [141]. The performance of this IDM was validated in the PSCAD environment for various scenarios, including islanding detection, fault analysis, quality factor evaluation, load fluctuations, DG tripping, grid topology, and non-detection zone (NDZ) range assessment.

Typically, IDMs can be classified into two categories based on the location of detection: local methods at the converter side and remote methods at the grid side [125]. Figure 8 illustrates the IDM groups along with their specific strengths and weaknesses.

- **Remote methods:** these methods rely on communication between the output inverter and grid. Versus local methods, remote techniques demonstrate excellent performance, particularly for multiple inverter systems. They exhibit a negligible NDZ, no impact on power quality, high reliability, and easy implementation. However, these methods require a communication infrastructure and additional peripherals, such as sensors and telecommunication devices on both the utility and DG sides. Consequently, these methods can be quite expensive, especially for small systems;
- **Local detection methods:** these methods primarily rely on continuous monitoring of system parameters at the PCC, including current, voltage, frequency, and harmonics. The concept behind local methods is that islanding mode can be easily detected when these parameters exceed the threshold values specified by standards. Local methods can be further categorized into three types: passive, active, and hybrid. Figure 9 shows the overall flowchart of locale IDMs. Passive, active, and hybrid methods are briefly outlined as follows [125,127,128,135–139].

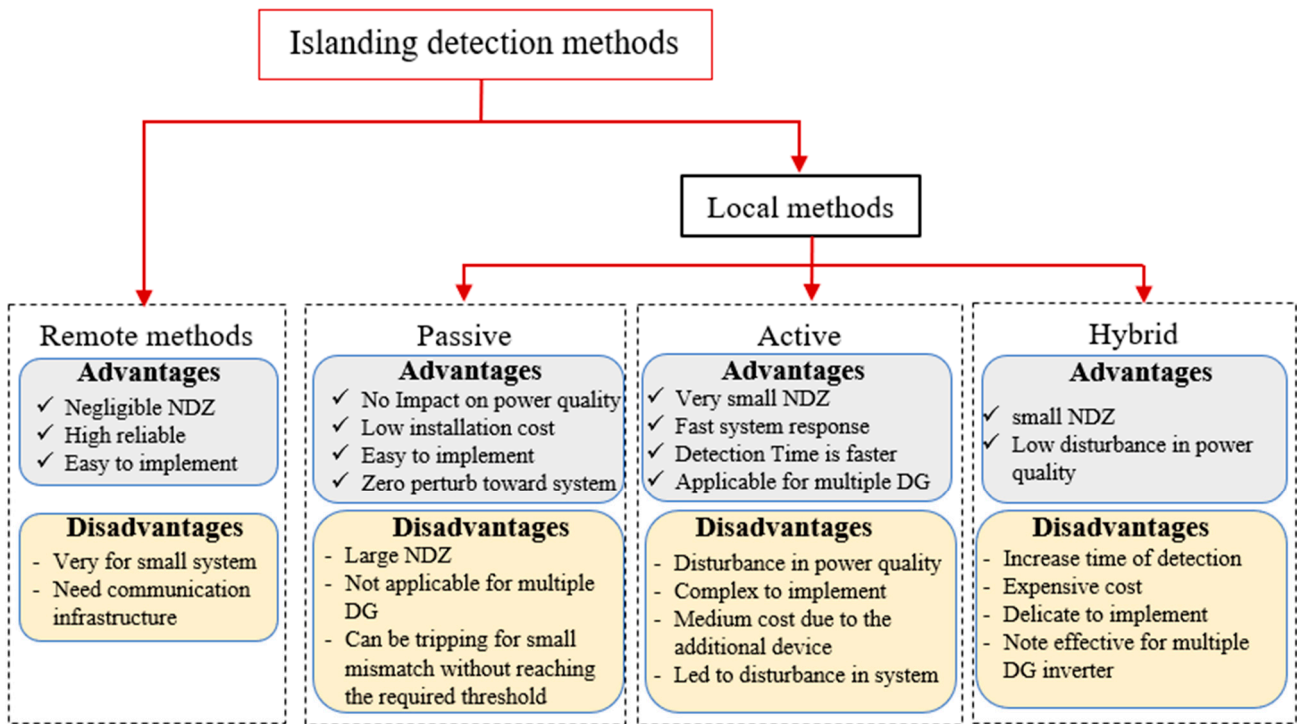


Figure 8. IDM Classification and performances.

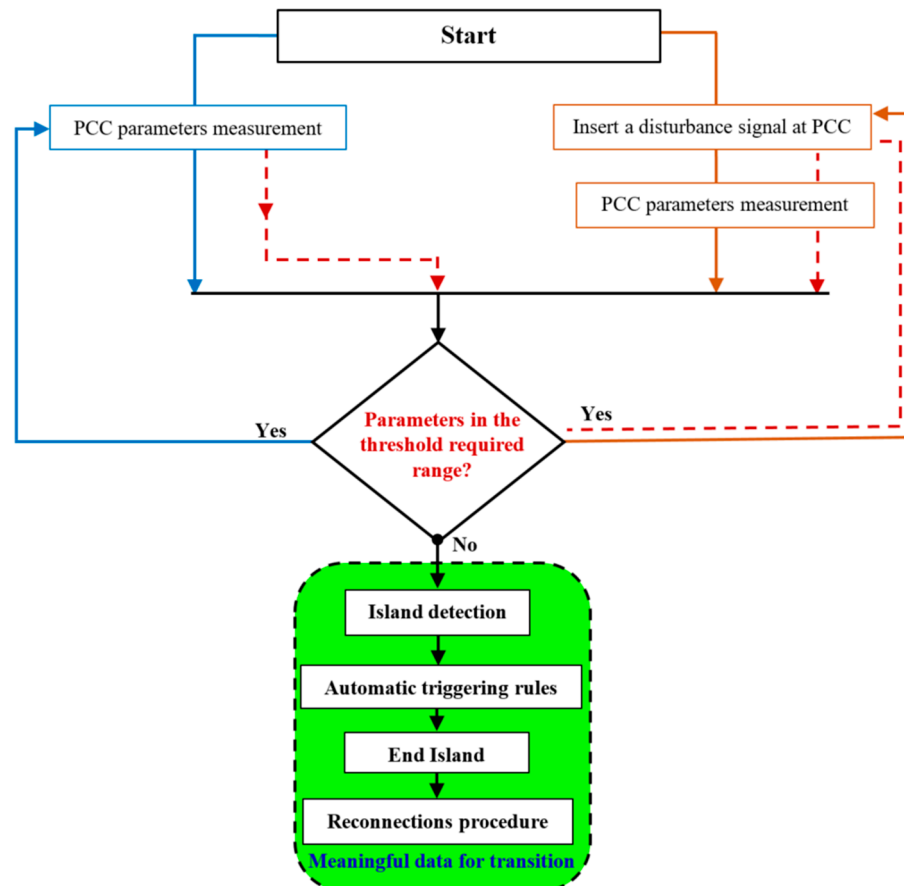


Figure 9. Overall design of IDM: passive, active, and hybrid flowchart.

Passive techniques: These methods were among the first to be developed. They involve the direct measurement and comparison of parameter fluctuations at the Point of Common Coupling (PCC) against the required threshold. Passive methods offer several advantages, such as easy implementation, no degradation in power quality, fast detection time, and low cost. However, their main limitation is the larger Non-Detection Zone (NDZ).

Active methods: These methods are mainly designed to overcome the limitations of passive methods. The concept behind active methods involves perturbing feedback and then observing the response. In active methods, a small disturbance signal is injected into the parameters at the Point of Common Coupling (PCC) to accelerate the system's convergence towards its limits. Essentially, it involves intentionally destabilizing the Distributed Generation (DG) system when islanding occurs. This small disturbance signal becomes significant once the utility is disconnected, indicating an islanding condition. Compared to passive methods, active methods enhance the precision of islanding detection with a very small or even zero Non-Detection Zones (NZDs). However, the implementation complexity of these techniques increases due to the additional circuit used to generate periodic disturbance signals. In addition, introducing periodic disturbance signals into the system can impact power quality and system stability.

Hybrid methods: Hybrid methods have been developed to address the challenges faced by active and passive strategies while retaining their respective advantages. These methods combine active and passive techniques to improve the efficiency of islanding detection. Typically, the active method is implemented only when an islanding condition is suspected by the passive technique. Hybrid methods have proven successful in reducing the Non-Detection Zone (NDZ) while minimizing the degradation in power quality compared to other conventional local techniques. However, it tends to increase with hybrid methods, as they combine the detection times of both active and passive approaches.

5.4. Standalone Mode

In the islanding operation, the whole microgrid will function autonomously (appointed equally SA mode); therefore, it must have enough power capability to provide the total load power demand [142]. Furthermore, a disturbance that requires a feeder to work individually may also happen. This is inaccurate power sharing due to the unbalanced feeder impedances. Usually, local loads are sensitive to any voltage variation. Hence, to achieve a successful standalone operation, the MG scheduling must have enough local generation to meet the demands of the sensitive loads, whereas the sensitive loads will rely on the utility supply [143]. These considerations provide a significant advantage to the microgrid concept, as it offers greater flexibility in dealing with disturbances and emergency conditions. This enhances the system's reliability and ensures the security of local loads.

The IEEE 1547 standard outlines several advantages of using SA operations, as highlighted in points [143,144]. These benefits can be summarized as follows: enhancing reliability for customers, minimizing costs, mitigating overload issues in the electric supply system, resolving power quality problems, and facilitating maintenance operations on power system components without disrupting service to end-users.

However, during the SA operating mode, the microgrid is faced with the imperative task of addressing the following crucial issues:

- ✓ Power balancing between supply and demand;
- ✓ Provide a stable voltage and frequency;
- ✓ Acceptable power quality;
- ✓ Intercommunication between system components.

5.5. Reconnection

After the end of the islanding disturbances, the DG inverter will reconnect to the utility to resume normal operation in the GC mode. During this operational mode, the major challenge is to ensure seamless synchronization with the required standard. Achieving a

smooth reconnection is mainly focused on the efficiency of the synchronization process. Therefore, in the MG control design, important consideration should be given to the synchronization system [145]. Thus, achieving a smooth and successful reconnection evidently means that the adopted synchronization process should be enabled to avoid large “zero” inrush currents during the pre-synchronization process [146,147].

Among those methods is a novel virtual torque (VT) and virtual flux linkage (VFL) synchronizing process that has been designed to enable a reliable seamless reconnection [148]. The proposed method permits a synchronizing torque command to the frequency control loop and minimizes the overshoot inverter output and its counterparts on the AC bus. In [149], a three-phase SRF PLL has been proposed to achieve smooth re-synchronization to the grid without affecting the microgrid voltage during the transition period for a residential microgrid community.

According to the standards listed in Table 4, a microgrid system must meet certain synchronization criteria. In the literature, numerous synchronization algorithms have been investigated as guidelines for grid-connected inverter control [150]. The most popular system is the Phase Locked Loop (PLL) system. It is used to estimate the phase and frequency of the main grid (e.g., extract the phase, amplitude, and frequency of the grid voltage). Various synchronization schemes are typically designed based on PLL systems such as enhanced PLL (EPLL: Enhanced Phase Locked-Loop), PLL with SOGI-PLL, Synchronous Reference Frame-PLL (SRF PLL), and other strategies such as Frequency Locked Loop (FLL) as well as their derivatives (SOGI-FLL, MSOGI-FLL, SOSF-FLL, etc.) [151–153].

To select the appropriate synchronization process, several performance criteria need to be considered, including frequency and phase overshoot, computational complexity, dynamic response under faults, and accurate estimation under system uncertainties (such as unbalanced faults, harmonics, phase jumps, etc.). The performance synchronization techniques are typically evaluated based on the following aspect [37,151–153]:

- ✓ Fast and accurately detect the grid voltage status (e.g., phase, amplitude, and frequency);
- ✓ Robustness against noises, stationary and transient disturbances;
- ✓ The ability to follow the amplitude variations in the network voltage in the event of a voltage drop;
- ✓ Precisely performed where the system frequency varies rapidly due to the grid voltage inertia;
- ✓ High filtering performance in the event of harmonic distortions;
- ✓ The feasibility of hardware and software implementations.

6. Smooth Transition Strategies Classification

For all DGs connected to the utility, the main challenge for the control system is to establish not only a control strategy for the GCs and SAs but also endure the highest transition-related peaks. Thus, the control system must take into account both microgrid operation modes while, at the same time, guaranteeing a smooth transition between them. Therefore, the transition between the control structures for different operating modes was a hindrance for the multi-functional converter in a MG system, owing to the contradiction of input, output, and disturbance in the control diagram [154]. In this context, numerous transition approaches were proposed to alleviate the transition effect [38–58]. By reviewing state-of-the-art literature, we have seen that these strategies can be broadly classified into different categories based on their control structure. The following key subsections provide a detailed overview of each transition control structure. Additionally, Table 5 presents a comprehensive outline of a typical concept and its application, highlighting the feasibility of the main transition schemes.

Table 5. A summary of examples of a smooth transition strategy.

MG Type	Control Technique	Control Variables	Validation		Advantages	Disadvantages	Tran. Groups	Ref./Years
			Sim.	Exp.				
Individual converter case	Voltage controlled (VSI)	Voltage phase and magnitude	✓		<ul style="list-style-type: none"> - Achieve smooth transition between GC and SA. - islanding detection capability without NDZ. - Fault tolerant capability during GC operation. 	<ul style="list-style-type: none"> - Instability issue during SA in reason to reactive power loop. - Instability question can be faced due to lack of coordination with other DG. 	Feedforward	[59] (2019)
	Grid interactive PWM	Load voltage and grid current	✓	✓	<ul style="list-style-type: none"> - Applicable for single-phase, grid-connected DG inverter. - Supply uninterruptible power to local loads under grid failure. - Easy to implement. 	<ul style="list-style-type: none"> - Significant voltage/current spikes during transient state. - An additional cost due to the use of multiples sensors. - System response degrade. 	Switch	[155] (2023)
	PLL-based sequence	Grid voltage and current	✓	✓	<ul style="list-style-type: none"> - Compensate the voltage and current spikes existing in [95]. - Positive and negative capacitor cycles are used. - Keep power level across loads during transition phasor. 	<ul style="list-style-type: none"> - Complex and expensive implementation due to additional circuits/capacitors. 	Switch	[156] (2022)
	Load shedding scheme				<ul style="list-style-type: none"> - Support transition between GC and SA through modified technique. - Load shedding flowchart to attain islanding detection. - Reconnection capability using resynchronization flowchart. - PLL generates the reference phase during SA mode. 	<ul style="list-style-type: none"> - High oscillation in grid current and output voltage during reconnection. - System capacity and reliability reduced due to disconnection of non-critical load. - System response degrades significantly under distorted and unbalanced grid voltage conditions. - Complex implementation of PLL system. 	Feedforward	[157] (2019)
	Self-synchronizing synchronverter	Error and grid angle	✓	✓	<ul style="list-style-type: none"> - Does not require a dedicated synchronization system. - Improve system performance. - Relieve computational burden. 	<ul style="list-style-type: none"> - Does not require a dedicated synchronization system. - System response degrades due to requirement of synchronizing time. - Reactive power disturbance in SA mode. - Requires modification into control system during transition phase. 	Switch	[159] (2019)

Table 5. Cont.

MG Type	Control Technique	Control Variables	Validation		Advantages	Disadvantages	Tran. Groups	Ref./Years
			Sim.	Exp.				
Individual converter case	Virtual torque/virtual flux-based synchronizing technique	Synchronizing virtual flux and torque command	✓		<ul style="list-style-type: none"> - Effective universal synchronization into both phase and voltage magnitude level. - Simple implementation. - Unified synchronizing technique. 	<ul style="list-style-type: none"> - Does not require a dedicated synchronization. - The synchronization controller is highly sensitive to gain value. - The inherent property of synchro-converter causing degradation in system response. 	Unified	[31] (2019)
	Indirect current control	Capacitor voltage and phase angle	✓	✓	<ul style="list-style-type: none"> - Simple implementation. - Unified synchronization technique. - Voltage loop adjusted output current in two operating modes. 	<ul style="list-style-type: none"> - During transient state, grid current can be distorted by a DC offset or a wrong value. 	Unified	[160] (2019)
	SVPWM control Dither synchronization signal	RMS line to line value nominal grid angle	✓	✓	<ul style="list-style-type: none"> - Transitions between operating modes without a controllable switch and with only one set of sensors. - An attractive configuration for inexpensive small systems. 	<ul style="list-style-type: none"> - The peak current exceeds the acceptable level during the transition. - During transient time intervals, the grid angle is affected by some distortion for several cycles. 	Unified	[161] (2022)
	Model Predictive Control (MPC)-based objective function	Active, reactive, and voltage output inverter	✓	✓	<ul style="list-style-type: none"> - Fast response fluctuation due to non-linear controller. - Seamless transition due to use of phase adjustment and grid synchronization procedure. - Synchronization without PLL system. 	<ul style="list-style-type: none"> - System performance affected by mismatches between model fed values and actual values of LC filter. 	Switch	[162] (2017)
	Parallel V/I control for power Uninterruptible Power Supply (UPS)	Current and voltage output inverter	✓		<ul style="list-style-type: none"> - Attain smooth transition. - A power failure detection circuit ensures that the power fed to the local load remains regulated by BESS. 	<ul style="list-style-type: none"> - UPS cannot operate autonomously in parallel with another DG system. - UPS cannot be used for MG applications. 	Droop Switch	[163] (2009)
	Frequency and voltage synchronization flowchart	Capacitor current Grid voltage			<ul style="list-style-type: none"> - Unified controller that regulates used for both operation modes. - Faster response. - Transition without additional switching. 	<ul style="list-style-type: none"> - Unmodified dynamics power control because it is fixed by droop control. - The adopted voltage control strategy is highly sensible to short circuits and grid failure. 	Droop Unified	[164] (2021)

Table 5. Cont.

MG Type	Control Technique	Control Variables	Validation		Advantages	Disadvantages	Tran. Groups	Ref./Years
			Sim.	Exp.				
Multiple converters cases	Linear-integration-method-based on droop characteristic	Nominal active and reactive power	✓	✓	<ul style="list-style-type: none"> - MG operation based on droop control to avoid critical communications (more reliable with less communications). - Seamlessly transfer based on droop characteristic adjustment. 	<ul style="list-style-type: none"> - Attaining synchronization at other than rated load condition leads to power unbalanced. - Slow controller response causing low power quality. - Accurate droop characteristics (V-f) tracking not achieved 	Droop control	[165] (2020)
	Hybrid voltage source inverter with Dispatching Unit (DU)	Output frequency and voltage magnitude	✓	✓	<ul style="list-style-type: none"> - During transient state, dispatch unit provides power drop, guaranteeing a stable transition. - Power fluctuations between inverter are regulated without communication. - Improved power quality. 	<ul style="list-style-type: none"> - Expensive solution due to the additional DU cost. - During transition phase, power losses are compensated only by the DU, which is made under stress operations. - System reliability is low 	Dispatching unit	[53] (2015)
	Active feed-back compensator and droop control	Output inverter voltage, current, and frequency.	✓		<ul style="list-style-type: none"> - Seamless transition is attained by adjusting the droop coefficients. - Unified controllers for both operation modes. - Capability to ride through grid faults. - Can adopted for dispatchable as well as non-dispatchable system. 	<ul style="list-style-type: none"> - Large mismatches notable for low-power systems, due to the small deviation introduced into droop coefficients. - Slow control response, which affects power quality during transient states. 	Droop Unified	[166] (2019)
	Enhanced power flow control using SRF-PLL	Grid voltage and frequency	✓	✓	<ul style="list-style-type: none"> - Seamless mode transition maintained without extra sensors. - Mitigate the impact of grid fluctuation through Feedforward of grid frequency and voltage magnitude during GC mode. - Enhance system stability along with the identical power flow control. - Improves control accuracy by voltage amplitude compensator. 	<ul style="list-style-type: none"> - The system instability is highly sensitive to sudden variations at the voltage phase. - Controller design is critical due feedforward terms. 	Feedforward	[120] (2016)

Table 5. Cont.

MG Type	Control Technique	Control Variables	Validation		Advantages	Disadvantages	Tran. Groups	Ref./Years
			Sim.	Exp.				
Multiple converters cases	Modified linear voltage compensator	Output voltage, current, and current capacitor	✓	✓	<ul style="list-style-type: none"> - Achieve seamless transition. - High capacity to suppress voltage, current, and frequency spikes during transition phase. - Enhanced dynamic performance by adding more damping. - Easy to implement. 	<ul style="list-style-type: none"> - The overall system stability can be affected by the herein feedforward terms. - Design parameters are sensitive. 	Switch	[30] (2019)
	BESS-assisted, modified control	PCC voltage of each node Sudden load current	✓	✓	<ul style="list-style-type: none"> - Smooth disconnection/reconnection without affecting the microgrid voltage during transition period. - System stability is increased due to transient free operation during the local load disturbances occurring. - Compensates for the unbalanced current and harmonic current issues. - Reactive power, harmonics, and unbalanced load currents issues are compensated for by modified power control technique. - High power quality across loads. 	<ul style="list-style-type: none"> - Large capacity of storage system required. - Expensive implementation and maintenance. 	Switch	[149] (2018)
	Windowing factor-based grid synchronizing control	Grid voltage and phase angle	✓	✓	<ul style="list-style-type: none"> - Synchronization without PLL system. - Higher power quality under nonlinear load. - During transition jump, frequency and phase issues are avoided. - Increased system reliability and performance flexibility. 	<ul style="list-style-type: none"> - Difficult implementation because the parameter control design is highly sensitive to value of window factors and gains. 	Switch	[167] (2018)
	Droop control norms (V/f set-points of the MG are agreed)	Real and reactive output power demands.	✓		<ul style="list-style-type: none"> - Unified control and power circuit for GC and SA mode. - Accurate power sharing. - During GC mode current faults are limited due to current limiting introduced into inverter. 	<ul style="list-style-type: none"> - High bandwidth communication with DCs system is required. - System design complex due mainly to large computational burden. 	Droop Unified	[168] (2015)

Table 5. Cont.

MG Type	Control Technique	Control Variables	Validation		Advantages	Disadvantages	Tran. Groups	Ref./Years
			Sim.	Exp.				
Multiple converters cases	Active synchronization using a tertiary mode supervisory control	Active synchronization compensation Signals (voltage amplitude and frequency)	✓		<ul style="list-style-type: none"> - Seamless transition modes are achieved with systematic hierarchical control frame. - Reduced processing burden on the control system. - Provides a cost-effective method for a practical microgrid. 	<ul style="list-style-type: none"> - Complex implementation. - Compromise between system response time and data transfer capacity of the communication channel. - Requires local neighbor-to-neighbor interaction with a sparse distributed communication network. 	Unified	[33] (2018)
	Uninterruptible-Power-Supply-based control	Output inverter: current and voltage	✓	✓	<ul style="list-style-type: none"> - Achieving seamless transfer between GC and SA modes. - Facilitating smooth transition between battery charging and discharging modes due to dc link voltage controller that sets the active power demand. - High power quality across local loads. 	<ul style="list-style-type: none"> - High stress on the uninterruptible power supply unit. - Failure of uninterruptible. - Power supply unit can compromise the MG stability. - Expensive implementation. 	Droop-Switch	[169] (2022)
	Virtual Oscillator Control (VOC)-based grid synchronization	Scaling factor, filter parameters L and C	✓	✓	<ul style="list-style-type: none"> - Unified seamless transition between different modes without the need for changing controllers. - Increased damping response during transition mode. - Achieve superior synchronization and convergence (power sharing accuracy). - Improved power quality through notch filter which suppress harmonic currents. 	<ul style="list-style-type: none"> - Microgrid stability is highly related to VOC controller response, i.e., fast variations in VOC lead to entire MG instability. - Controller design is highly sensitive to gain values. - Design of higher layer controllers is very tedious. 	Droop unified	[170] (2019)

6.1. Strategy Based on Switch Process Scheme

6.1.1. Switch Process in the Control Loop

As its name implies, this schematic control is conceived based on a Static Control Switch (SCS) process positioned at the control system between the two functional modes. Figure 10 depicts the general control structure of the SCS. This global control structure is composed of two cascaded control loops separated locally by the SCS process.

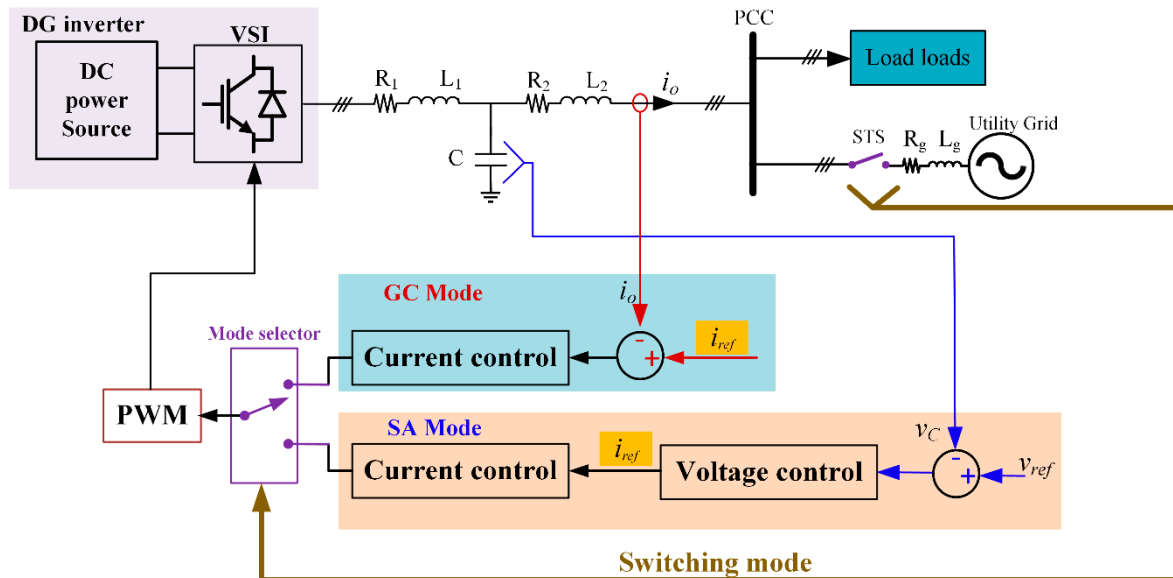


Figure 10. Block diagram of the SCS smooth transition structure.

Indeed, the SCS is assigned to change the mode of control from the current controller to the voltage controller. During the GC mode, the DG inverter is operational as a current source based solely on the current controller loop. As soon as an islanding condition is detected through the adopted AI flowchart, the SCS is actuated to bring about a change in the controller system, which means connecting the cascade voltage loop. Consequently, the inverter functions as a voltage source. This control strategy is considered as a conventional method [38].

The performance of this strategy can be enhanced by accelerating the SCS process. This, in fact, emphasizes that the transition performance is significantly influenced by the performance of the anti-islanding algorithm, particularly its speed and accuracy.

Numerous current studies have been performed to deal with the transition issue based on the SCS process strategy [38–43]. In [38], a smooth transition approach based on SCS was proposed for a three-phase DG inverter application. The controller loops (current and voltage) in this strategy were designed using two PI regulators. This approach was studied experimentally and theoretically for both control modes (GC and SA modes) and during the transition phase. Similar transition strategies were achieved in [39,171,172]. In [39], a switch selector was placed between the GC controller and the SA controller. The proportional resonant controller (PR) was utilized for both controller modes in a single-phase microgrid application. In [171], a power-electronics-based, bidirectional solid state transfer switch (SSTS) was employed for seamless disconnection and reconnection of the DFIG stator in a hybrid microgrid (solar, wind, and battery). A novel Petri recurrent wavelet fuzzy neural network (PetriRWFNN) was proposed in [172] as a replacement to the conventional PI controller to achieve seamless switching and grid reconnection responses in the microgrid.

An enhanced transition from the SA mode to the GC mode using process control switching was designed for DG systems [40]. During the GC mode, the proposed method employed combination of a PI regulator and a Luenberger observer to regulate the power fluctuation on the main grid. During the transition phase, a super-twisting algorithm

technique was utilized to ensure the load voltage control and handle the non-linear characteristics of the DG-inverter, resulting in a smooth transition phase with minimal disturbance effects. Another strategy based on switching SCS for GC and SA mode in smart distribution systems was explored in [41]. This method relied on the SCS action and investigated three different approaches, including power drooping current controlled, power drooping voltage controlled, and current drooping voltage controlled. The characteristics of these approaches were studied and analyzed. In [42], a predictive voltage controller, a predetermined sinusoidal waveform detection, and an intermediate current compensator were incorporated to enhance the dynamic response of the static switch in single-phase microgrid applications. This proposal enabled grid fault detection, reduced the turn-off delay of the SCS, and achieved a rapid steady state in the SA mode.

A flexible, controller-algorithm-based synchronization system, which allowed easy adaptation of the operation mode, was designed in [43]. This algorithm was implemented and tested for the micro-wind system. In [26], a novel smooth transition technique between the GC and SA modes was proposed based on a robust control scheme for a modular multilevel converter (MMC) interfacing with a PV generator. This control scheme enabled a seamless and rapid transition from standalone to the GC mode and vice versa. The control scheme was simulated using MATLAB/Simulink, and the simulation results were validated using an OPAL-RT OP4510 real-time simulator.

To facilitate smooth transitions between MG operation modes by dampening power, frequency, voltage, and current signals, a strategy based on a supplementary controller using Port-Controlled Hamiltonian (PCH) modeling and control in a synchronous reference frame (SRF) was designed in [131]. This work proposed a systematic approach for injecting damping into Higher-Relative-Degree (HRD) states of inverters, in addition to relative-degree-one (RD1) states.

6.1.2. Switch at the Dispatching Unit Level

Among the common proposed industrialized transition techniques proposed in the literature, one technique relies on the use of an additional DG system, often a dedicated storage unit, to achieve a smooth transition [58]. The principle of this strategy involved using a supplementary energy unit to relieve the state transient; otherwise, boost current or voltage during the transition phase. Figure 11 illustrates the general overview of the dispatching unit strategy. However, there are two main limitations to the use of this solution. Firstly, it incurs additional costs due to the supplementary mechanism. Secondly, this strategy is only applicable in regions with very low grid frequency variations, typically within the range of 0.02 Hz [51].

Various recent research works propose dispatching resources as technical solutions to remedy transition issues [52–54,130,173–175]. To attenuate the transient effect, a dispatch unit (DU: “Dispatch Unit”) was introduced for the application of several inverters [53]. During the disconnection from the GC mode to the SA mode, the DU manages power imbalances by absorbing or injecting the necessary amount of power. Similarly, during reconnection, the DU can adjust its output power to match the voltage of the distribution network and microgrid (MG).

On the same principle, the authors in [53] utilized a generator set “Diesel Generator” to enhance the hybrid MG (photovoltaic plus wind). With the proposed approach, the microgrid operated satisfactorily in island mode, in grid-connected mode, and during the process of synchronization and desynchronization with the main grid. In [54], a resistive-type fault current limiter suggested by the storage unit was employed to improve the transient phase performance of a microgrid during faults. In [130], a Monte Carlo method with probability distribution functions was proposed to calculate the probability of a successful islanding transition in a microgrid. This method was useful for assessing the impact of various devices that could be used to reduce the likelihood of an unsuccessful islanding transition. The method’s success was validated by analyzing the islanding transition of a hybrid RE-storage-diesel microgrid using either a storage unit system (Battery Energy

Storage System or Flywheel Energy Storage). In [174], a smooth transition during planned and unplanned islanding and reconnection was facilitated by the energy storage system (ESS) as the main facilitator, utilizing state-saving techniques, active synchronization, and emergency dispatch. A rule-based dispatch was proposed, given the priority to the diesel generator and then the storage, based on the state-of-charge of the ESS.

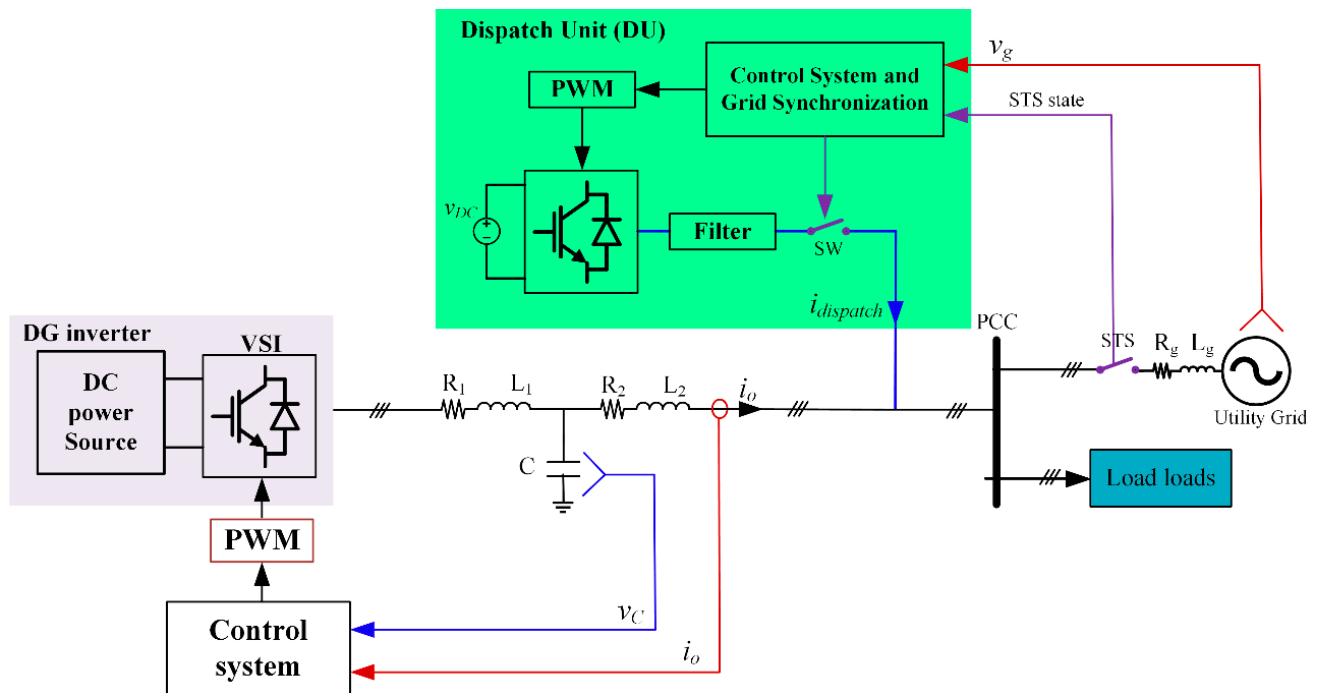


Figure 11. Block diagram of the dispatching smooth transition structure.

The potential of the storage system to stabilize power fluctuations and enable load shifting capabilities by supplying voltage and frequency references to all other generators has been implemented and tested using the HIL test bench for the recommended microgrid (MG) topology, following the required IEEE standard. The storage system's potential to stabilize power fluctuations and enable load shifting capabilities by providing voltage and frequency references to other generators was implemented and tested using a Hardware-in-the-Loop (HIL) test bench, following the required IEEE standard for the recommended microgrid topology.

In [175], similar work was investigated for a hydro-powered microgrid to achieve a smooth island transition. A PI-based droop frequency controller was proposed for the Battery Energy Storage System (BESS).

6.2. Strategy Based on Voltage Feedforward Scheme

The second group of strategies aimed at addressing the transition issue involves the use of an additional feedforward compensator. The primary principle of this control structure group is to incorporate an anticipatory voltage loop alongside the current loop when a fault in the utility grid occurs. The general block diagram of the feedforward control strategy is depicted in Figure 12.

As the feedforward control is classified as neither robust nor adaptive, this control group has limited performance in mitigating the transition problem. Furthermore, implementing the feedforward scheme necessitates extensive knowledge of system parameters.

Addressing the transition problem through feedforward action has been the subject of several studies [32,44–46]. In [32], a sophisticated control strategy based on a feedforward voltage loop was proposed to protect critical local loads under grid fault trips. The proposed strategy involved adding a feedforward voltage control loop to the current controller loop in order to mitigate the overvoltage stress of renewable energy and the critical load under

the grid fault. The smooth operation of the DG inverter was validated through experimental implementation using a real-time digital simulator.

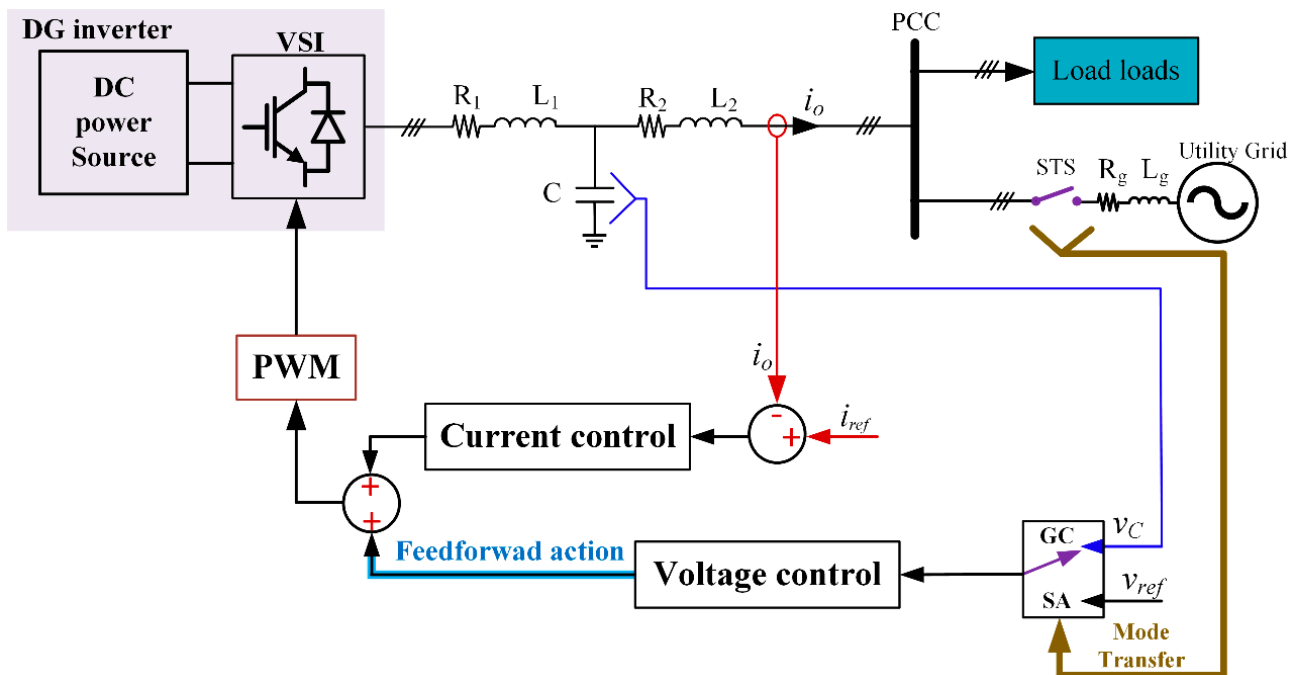


Figure 12. Block diagram of the feedforward smooth transition structure.

In [44], an improved seamless transition flowchart based on a phase-locked loop process was proposed for a three-phase grid connected inverter between the GC and SA operations. The current controller and the feedforward voltage controller were both designed to achieve smooth mode transfer under an overvoltage condition. The control method involved adjusting the PLL process based on the operation mode, synchronizing the output inverter voltage to the grid voltage in GC operation, and generating an angle with the desired frequency during SA mode. This proposed operating sequence ensured seamless PLL increases without sudden jumps, even during voltage drops and mode transitions. In [45], a similar transfer was made based on PLL, and feedforward voltage was used to avoid the transition's negative effects on a three-phase, smart-grid-connected PV inverter. The proposed control scheme combined rotating reference frame theory (d-q axis) and ensured that the outputs of the d-q voltage control loop were connected to those of the d-q current control loop to maintain consistency at the transition moment. The PLL-based approach was used to minimize the negative effects of the transition.

In the context of micro- or nano-grids, a flexible feedforward control solution was established by employing a large-bandwidth triple-loop control structure [46]. The controller's multi-loop architecture enabled effective management of the GC and SA operation modes. Additionally, two nested deadbeat-type controllers were adopted to regulate the inner loop variables and minimize disturbances during the transition phase.

6.3. Strategy Based on a Unified Control Scheme

6.3.1. Unified Scheme without Droop Control Method

Transition control without reconfiguration at the control structure, also called unified control, was developed in various research works [51]. The general objective of this approach was to utilize the voltage control loop as a reference current generator during the GC mode and as a voltage regulator during the SA mode. The typical process of unified control is illustrated in Figure 13.

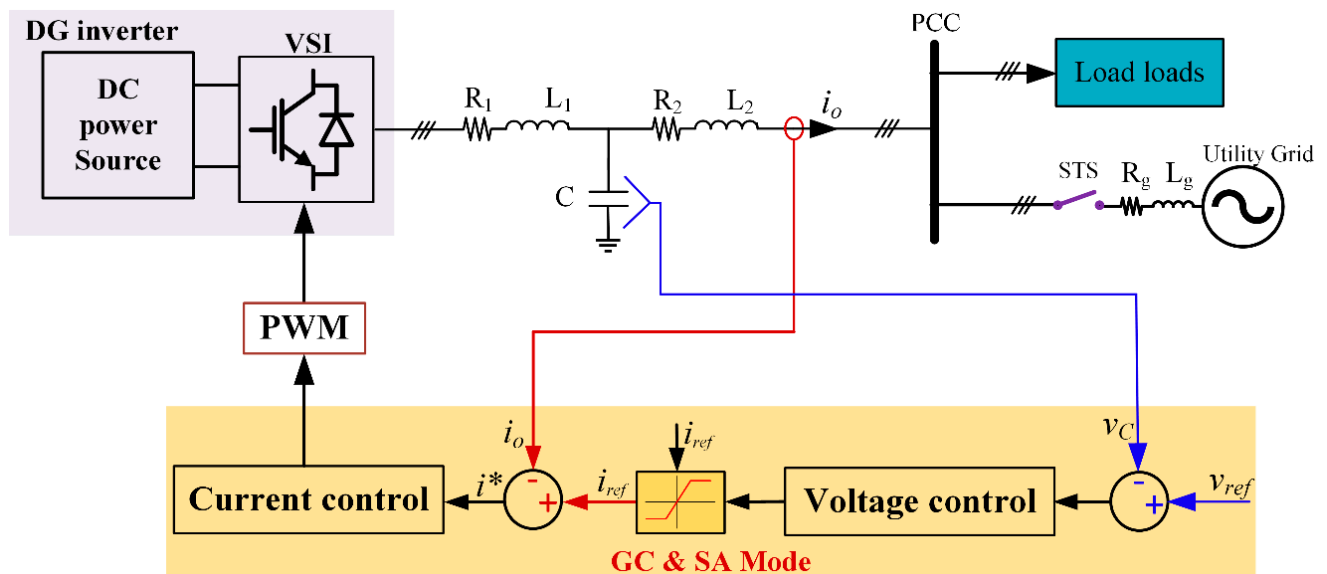


Figure 13. Block diagram of a unified smooth transition structure.

As expected, compared to other transition structures, this method does not require modification at the control level. Consequently, the speed and accuracy of the anti-islanding algorithm are not extremely critical for achieving better transition performance. However, this structure suffers from certain disadvantages. In the SA mode, the output voltage is regulated to the extreme limit of the allowable voltage range due to the utilization of the saturation stage. Additionally, this control strategy typically requires an additional control element, which increases the complexity of its implementation.

Variants of the universal control scheme have been proposed as remedies for transition problems [47–52,173,176]. In [47], the authors designed an indirect current control loop with an applied voltage loop for a three-phase DG inverter for seamless transfer. In addition, the bandwidth voltage loop was expanded by incorporating an inner capacitor current loop. With this approach, the voltage controller was automatically activated or deactivated according to the operation mode. The theoretical analysis was checked by simulation and experimental results.

A similar work was presented in [48], where the previous approach was enhanced by introducing a feedforward load current. This improvement focused on improving the waveform quality of both the grid current in GC mode and the load voltage in SA mode.

To improve the transition performance, a proportional resonant (PR)-based indirect control scheme was proposed for a 4.5 kw grid-connected inverter [49]. The PR controller was described for both controller loops, aiming to improve the transition performance.

In [164], a three-phase universal controller (UC3) was proposed for flexible microgrids, ensuring operation in all operation modes without reconfiguration of the control structure. UC3 enabled control of active and reactive powers while providing voltage and frequency support. Furthermore, the synchronization system was integrated into the control structure, which explained the agile and robust responses and the reduced transient phase impact. In [51], the authors proposed a unified control and power management system for a hybrid PV–battery application with DC and AC charging buses. The proposed method successfully regulated the voltage on both DC and AC buses, achieved a smooth transition between the grid-connected and island-connected operating modes, and automatically balanced power flows into the system under different operating modes, regardless of disturbances.

In [52], for achieving a seamless state transition, a nonlinear-simplex algorithm was proposed for searching the optimal controller parameters with the aim of minimizing voltage deviation. The proposed control improved voltage stability and phase synchronization under state transition. The effectiveness of the proposed control strategy was checked through PSCAD/EMTDC and RTDS simulators. Similarly, in [176], a simplified model of

an industrial facility microgrid was developed and simulated using RTDS Technologies' real-time digital simulator. The study focused on proposing and evaluating the performance of an IEC 61850 Generic Object-Oriented Substation Event Protocol (GOOSE)-based control strategy for managing the transition of the microgrid from the grid-connected to the island mode.

In [173], the investigation explored the diversity and connection between control structures in different operating modes of a microgrid. A unified inner loop based on 2-DOF (Two-Degrees-of-Freedom) theory was introduced, allowing all operating modes of the converter in the microgrid to share the same inner loop. This approach eliminated the need for reconfiguring the entire control structure when switching between operation modes and instead adjusted the inner referring instructions. The simulation and experimental results from a low-voltage prototype model were presented to validate the efficiency of the proposed strategy. The findings provided a theoretical and practical foundation for future experiments in high-voltage applications.

6.3.2. Unified Scheme with Droop Control Method

The principles of droop techniques have been widely applied to the parallel operation of DG inverters, incorporating voltage and/or current control loops. This approach can be applied to all the control scenarios mentioned earlier [58]. Figure 14 shows the general block diagram of the control strategy employing the droop regulator. However, a significant limitation of this strategy is its poor dynamic performance, as the bandwidth of the external droop control loop is considerably lower than that of the internal voltage loop.

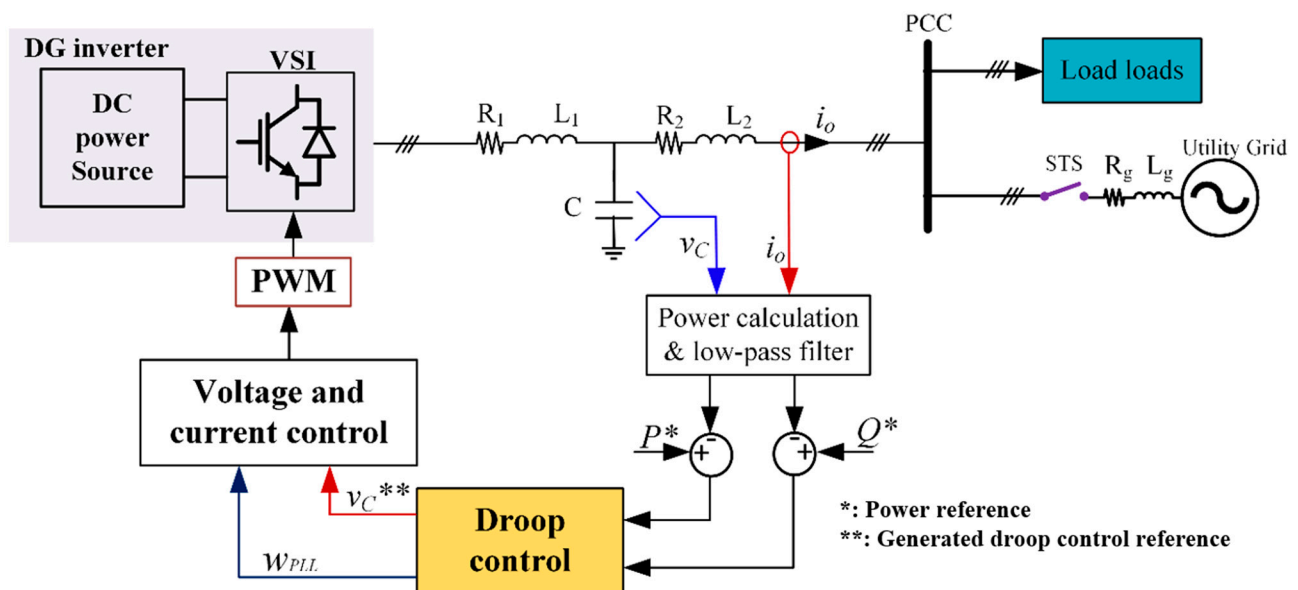


Figure 14. Block diagram of droop smooth transition structure.

Researchers in [55] proposed a droop control to ensure robust operation of an MG with a smooth transition. In the GC and SA modes, the inverters used the droop control method to regulate the actual power flow without any external communication being required between them. Building upon this principle, the authors in [56] presented a smooth transition based on a droop control for several inverters connected to the networks. In addition, a virtual inductance loop was designed to reduce oscillating current due to the mode transfer between the SA and GC modes. The proposed method effectively improved the transient response of the current to an acceptable level without triggering the system's protection mechanisms.

In the literature [55,58,154,177–182], a unified control structure for automatic transition based on the droop command was proposed for multiple inverters. When the grid was available, the inverters operated in current control mode by injecting energy into the grid.

In the event of a grid failure, all inverters automatically switch to droop control mode to achieve proportional power sharing and return to connected control mode when grid availability is restored. Unlike existing control methods, the proposed strategy eliminated the need for communication-based supervisory control or a dedicated storage facility to achieve a seamless mode transition.

Studies such as [58,154,177–183] used non-conventional controllers to achieve a smooth transition between the GC and SA. In [58], a unified fuzzy droop trajectory was proposed for scheduling reference trajectories for ensuring seamless transfer operations without reconfiguration of the control structure. Indeed, the voltage regulator was activated and deactivated automatically according to the designer's fuzzy droop and the operating mode. Similarly, in order to achieve equal power sharing among parallel inverters during the transition of a microgrid (without significant oscillations, overshoots, or circulating currents between inverters), a novel hybrid control scheme was proposed. This scheme combined a unified robust droop controller (URDC) with a quasi-proportional resonant (QPR) regulator for parallel DG inverters [183]. Furthermore, an improved adaptive estimator for the reference current magnitude was integrated to accommodate dynamic load variations. A compulsory turn-off strategy based on the fuzzy logic control of the converter output voltage was proposed in [177]. Instead of detecting the polarity of the voltage or current, the strategy applied a variable reverse voltage across the conducting thyristor by dynamically adjusting the output voltage reference instruction and closed-loop control parameters based on the changing rate. In [178], the authors presented an intelligent transition control system for operating a 4 KW PV application in both the GC and SA modes. The approach was developed using machine learning (ML) algorithms and a hybrid control strategy. Initially, an ANN algorithm was trained in the simulation environment with various scenarios in SA and GC modes. Furthermore, the inverter control action was performed based on the trained classifier output to perform the transition and achieve both SA and GC controls. Within the same smooth transition with intelligent control tasks, numerous research works were created. By combining control techniques, inverse droop control, virtual impedance control, and current control, an intelligent coordinated control strategy based on the Adaptive Neuro-Fuzzy Inference system [180] was developed. To recover the voltage and frequency magnitudes to their nominal values versus all deviations, an intelligent approach based on brain-emotional learning (BEL) was proposed in [174]. Additionally, a Levenberg–Marquardt (LM)-algorithm-based Artificial Neural Network (ANN) was investigated for PV systems [176].

Other research papers have addressed concerns by focusing on predictive control methods. In [179], a novel hybrid control strategy for energy storage through model predictive controllers and a two-degree-of-freedom algorithm was proposed to realize a seamless microgrid with a unified control structure. The predictive controller model was adopted to reduce the control layer's PWM module. When switching microgrid operation modes, the smooth transition of the microgrid's voltage and frequency was realized in the application layer by adding decoupling inductance and introducing microgrid voltage and angular frequency feedforward compensation to carry out P-Q and modified droop controls. Similarly, a Predictive Fuzzy Logic-Based Energy Management System was used to determine the system's operation mode based on real-time data to establish smooth mode variations [181]. The proposed strategy was developed using a Dual Pulse (DP) optimization methodology for a magnetically coupled microgrid with 20 different grid-connected and off-grid operation modes.

7. Future Trends

As presented in previous sections, several technical solutions have been developed for the detection and transition management of islanding in microgrids. Beyond the algorithmic aspects, economic and regulatory challenges and technological opportunities should be taken into account to successfully integrate detection and transition management solutions into the microgrids to be installed.

- **Economic Challenges:** The complexity of the islanding function can significantly increase investment and infrastructure costs compared to mini-grids that do not include this functionality and can thus be more cost-competitive. The costs and added value of islanding functionalities must, therefore, be estimated and promoted to encourage investors to adopt the full set of microgrid features;
- **Regulatory Challenges:** In addition to the question of the economic viability of microgrids, it remains difficult to define if they are private or if they have to respond to a public service mission. The regulatory framework can be different from state to state or even from region to region, which makes the transition functionalities completely justified in an open regulatory framework and less justified in a limited framework.

The regulatory framework and business models need to be studied to assess the extent to which transition functions should be integrated.

- **Technology Opportunities:** Nowadays, several technologies, either at the material level or at the communication level, can be applied to upgrade microgrid performances in the face of unexpected events such as unplanned islanding. Likewise, the rapidly advancing field of remote sensing and monitoring technology offers valuable assistance in implementing seamless transition strategies. Remote sensing technology in particular serves as a significant means of gathering data with benefits such as quick, extensive, and continuous monitoring capabilities while being less constrained. Consequently, this enables the regular extraction and monitoring of information pertaining to desired problems [184];
- **Development of Digital Technologies:** The emergence of low-cost, high-performance processors and IoT devices enables the design and implementation of improved solutions for the monitoring and transiting mode management of microgrids. Real-time data collection can play an important role in dealing with these challenges, thanks to technological advancements in communication and IoT devices. Hence, precise data forecasting, scenario generation, and artificial intelligence (AI) models based on historical data are all promising methods for developing a smooth transition. In this context, the incorporation of new technologies and numerous intelligent algorithms such as reinforcement learning, stochastic-based algorithms, deep learning, and heuristic optimization algorithms;
- **Superconducting Materials:** The use of superconducting cables and storages that have current-limiting characteristics can be an interesting solution in high-power microgrid applications [185–187]:
 - Superconducting cables can absorb short-circuit energy; thus, there are fewer overvoltage spikes during the interruption process;
 - Superconducting cables have a very fast response time to faults. As a result, vacuum circuit breakers do not need to open as rapidly, thus reducing the constraints linked to switching stress;
 - The SES can absorb short-circuit energy; hence, there are fewer over-voltage spikes during the interruption process.

8. Conclusions

This paper provided a comprehensive overview of the literature concerning the islanding function, which is one of the added values of microgrids. For this purpose, a brief reminder on microgrids and hierarchical controls was given before focusing on the islanding functions involving the detection and management of unplanned islanding.

This review will aid in developing future MGs to include a control structure, guaranteeing mode transition disturbance mitigation through early control schemes. To the authors' knowledge, this is the first time that an exhaustive MG review covering all the transition control structures associated with microgrid systems has been performed. Various definitions and descriptions from the literature have been compiled in this paper. A deep review of the microgrid frameworks and microgrid functionalities has been presented.

Moreover, we shall pay particular attention to islanding conditions (concept, types, IDM, and standard). This rigorous review highlighted islanding conditions, in particular the issues with unintentional islanding and their quantitative risks (material damage and economic losses). The control system analysis for all MG operation modes provided a comparison of the smooth transition strategy process. A review of the control transition structure revealed a distinct physical division as well as a comparison of the strategies involved in the MG concept. The transition control approaches were broadly classified into five types (unified control, switch process, feedforward control, droop control, and dispatching unit), and the techniques proposed in each category were extensively compared. The results of each transition strategy's analysis and review were suitably summarized and classified in Table 5 and Figures 9–13, allowing for a comprehensive overview of the main design options and relevant issues involved in each control scheme. On the whole, based on the preceding discussion, it is possible to conclude that each proposed transition strategy had its own set of characteristics, benefits, drawbacks, and applications. Major potentials such as design simplicity, additional cost, application control, reconfiguration at the control structure, and resiliency improvement have been highlighted. Finally, the future trends for the transition process in MGs are discussed. The operation of MGs is still the main topic of future research, notably with technological advancements: intelligent algorithms and superconducting storage systems as solutions for developing a smooth MG transition.

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