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Review article

Emerging technologies, opportunities and challenges for microgrid stability and control

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ABSTRACT

This work conducts an extensive survey that provides a complete overview of various control methodologies and stability considerations pertaining to Microgrids. Microgrids primarily function in a grid-connected manner, but they possess the capability to transition to standalone operation during emergency situations. Factors such as stability and operational control are of paramount importance in both modes of operation due to considerations such as frequency, voltage, optimal power transfer, and islanding detection, among others. The control topology and stability of microgrid applications and system modelling vary depending on the specific applications. This paper elucidates the stability considerations associated with remote and utility-based microgrids, encompassing various control and operation techniques pertaining to network characteristics. Various elements, including small-signal analysis, transient response, and voltage stability, have been proposed and their potential for enhancement has been examined. Following a concise examination of existing microgrid control approaches documented in the literature, the current study delves into an analysis of diverse methodologies for microgrid control and stability assessment.

1. Introduction

A microgrid refers to a decentralized network operating at low voltage levels, whereby various dispersed energy sources, storage devices, and loads collaborate to provide efficient power distribution. Typically, microgrids function in either a grid-connected mode or an islanding mode (Abdelaziz et al., 2014; Ahmadi et al., 2016). The Microgrid is characterised by its composition of various demands and micro sources (Hu et al., 2022) operating as a unified system, capable of supplying both heat and power (Pandey et al., 2022a). The majority of micro sources mostly refer to power electronics-based devices that offer

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essential flexibility for attaining controlled operation, such as in the case of separate aggregation systems. Moreover, the ability to govern flexibility enhances the presence of the Microgrid (Michaelson and Jiang, 2021) within the bulk power system, allowing it to function as a distinct and controllable entity.Additionally; they exhibit a user-friendly plug and play feature that simplifies the integration of each micro source, catering to the specific requirements of the customer at a local level. The architecture of the basic Microgrid (Radwan et al., 2016; Mariam et al., 2013) consists of a cluster of radial feeders. The point at which a utility grid is connected is sometimes referred to as the point of common coupling (Das et al., 2017). The characteristics of energy generation and transmission are being altered by economic, technological, and environmental incentives. The trend in the energy sector is shifting towards smaller and more distributed generation (Gui et al., 2017; Aderibole et al., 2019) facilities, as opposed to centralised ones. This transition is driven, in part, by the aim to reduce the inefficiencies associated with traditional economies of scale. Distributed generation comprises a diverse array of prime mover technologies, including internal combustion (IC) engines, gas turbines, micro turbines, solar systems, fuel cells, and wind power (Pandey et al., 2022b; Manditereza and Bansal, 2016). The aforementioned developing technologies (Hirsch et al., 2018) has the capacity to reduce costs, hence counteracting the conventional economies of scale. Small-scale generators are commonly situated near the premises of users, where the energy they produce is utilized to satisfy the increasing demands of customers for improved reliability and power standards (Khooban and Gheisarnejad, 2020). Given the proximity of local loads to distributed generators (Mo and Sansavini, 2019), and in certain cases, even within the same building, the waste heat generated by these generators can be effectively utilized alongside the electrical energy produced. The majority of current power plants can be classified as either central or distributed power plants. There exist several strategies to mitigate this energy loss, namely enhancing the fuel-to-electricity efficiency of the power producing facility and/or harnessing the residual heat. The increasing imperative to mitigate carbon emissions has rendered the notion of microgrids increasingly appealing. The use of microgrids has been found to possess the capacity to mitigate emissions in comparison to conventional centralized utility systems (K. R et al., 2022). Numerous nations and research organizations have actively participated in Microgrid initiatives.

The conventional approach to power generation is characterized by a high degree of centralization, whereby power and energy are transmitted in a unidirectional manner from the source to the end users. Furthermore, the presences of technological anomalies in conjunction with traditional utilities, as well as the environmental challenges arising from the combustion of fossil fuels, have served as catalysts for research and development in power system technology. The emergence of Distributed Energy Resources (DER) units, such as photovoltaic (PV) systems (Ali et al., 2022), wind turbines, batteries, micro turbines, biomass generators, and fuel cells, has been seen. Microgrid-based technologies are increasingly garnering attention as an effective means of integrating diverse distributed energy resource (DER) units into the electricity system. Moreover, a universally accepted and precise definition for the microgrid remains elusive, as the idea varies across different countries and locales. The European technology-based platform for smart grids recognises the microgrid as a platform that promotes the integration of distributed generation (DG) systems, storage systems (Tan et al., 2013), and loads. This integration aims to enhance the power grid's ability to provide sustainable, cost-effective, and reliable electricity. Fig. 1 illustrates a comprehensive microgrid model consisting of several distributed generation sources, such as combined heat and power units, photovoltaic units, micro turbines, wind-based power systems, fuel cells, and others. A distributed generation (DG) storage facility encompasses several technologies such as flywheels, battery banks, electric vehicles, and supercapacitors, in addition to variable load options equipped with control devices.

Microgrids can be categorised into two types: alternating current (AC) and direct current (DC). AC microgrids have been integrated into the existing AC grid. However, the implementation of sophisticated control technologies is necessary to achieve synchronization and maintain the stability of the power system. In contrast, the implementation of DC microgrids has been shown to offer enhanced short circuit protection capabilities (Vilathgamuwa et al., 2006; Islam and Gabbar, 2012; Dagar et al., 2021) as well as notable improvements in efficiency. In addition, a limited number of synchronous units, such as diesel generators, as well as diverse non-synchronous units, such as machines based on micro turbines, are typically interconnected inside a comparable microgrid system. Fig. 2 represents a distinctive system configuration specifically developed for the hybrid AC/DC microgrid (Guerrero et al., 2011; Jin et al., 2016), which incorporates power electronics interfaces and several distributed energy resource (DER) units (Lasseter and Piagi, 2007).

Nomenclature

DG	Distributed generation
MG	Microgrid
MGCC	Microgrid Central type controller
FACTS	Flexible AC transmission system
RES	Renewable energy sources
MW	Mega watt
KW	Kilo watt
HC	Hysteresis Control
ICT	Information and Communication Tech
CCVSI	Current controlled voltage source inverter
DBS	Data bus signalling
DER	Distributed energy resources
EMS	Energy management system
LC	Local control
VR	Virtual resistor
VPD	Voltage active power
VCM	Voltage control mode
MPPT	Maximum power point control
PLL	Phased locked loop
PID	Proportional integral derivative
DPC	Direct power control
PC	Predictive control
VSC	Voltage source converter
CSC	Current source converter
THD	Total harmonic distortion
PCC	Point of common coupling
CC	Central control
CPL	Constant power load
DCL	Digital communication link
DFIG	Doubly fed induction generator
ESS	Energy storage system
ILC	Interlinking converter
VQD	Voltage reactive power
VI	Virtual impedance
SoC	State of charge
PEC	Power electronic converter

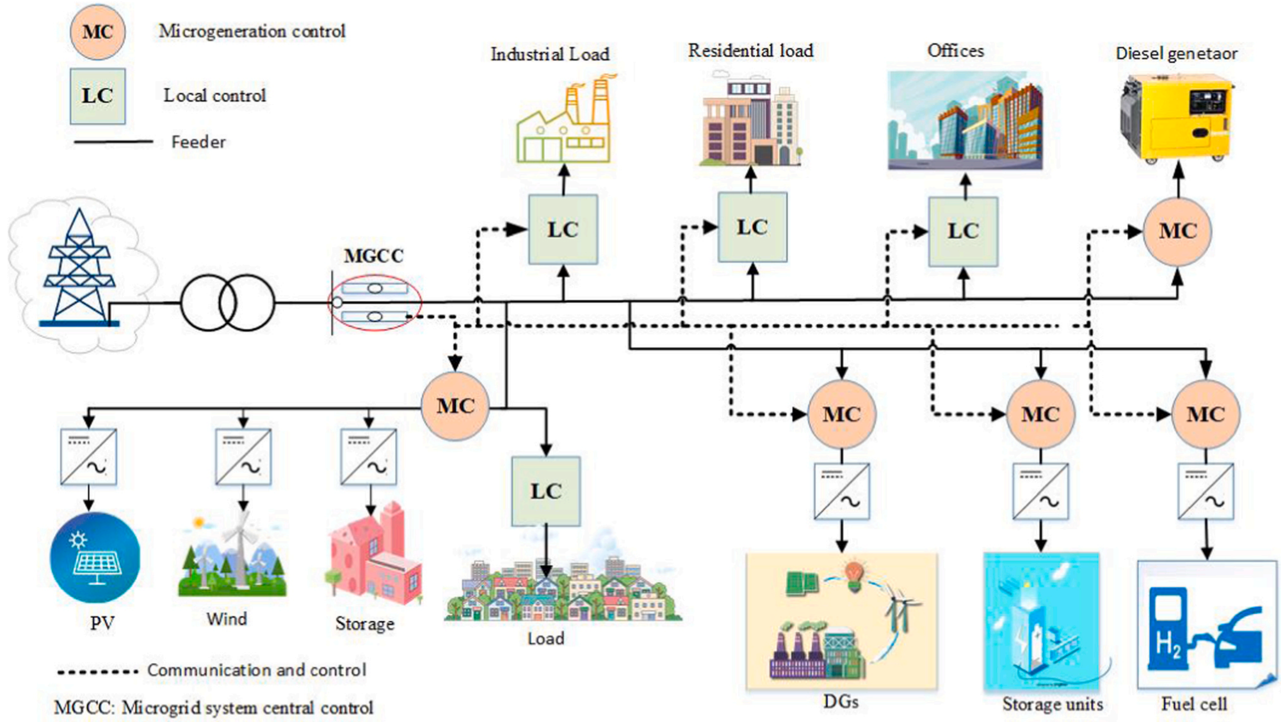

Fig. 1. Typical structure of Micro grid.

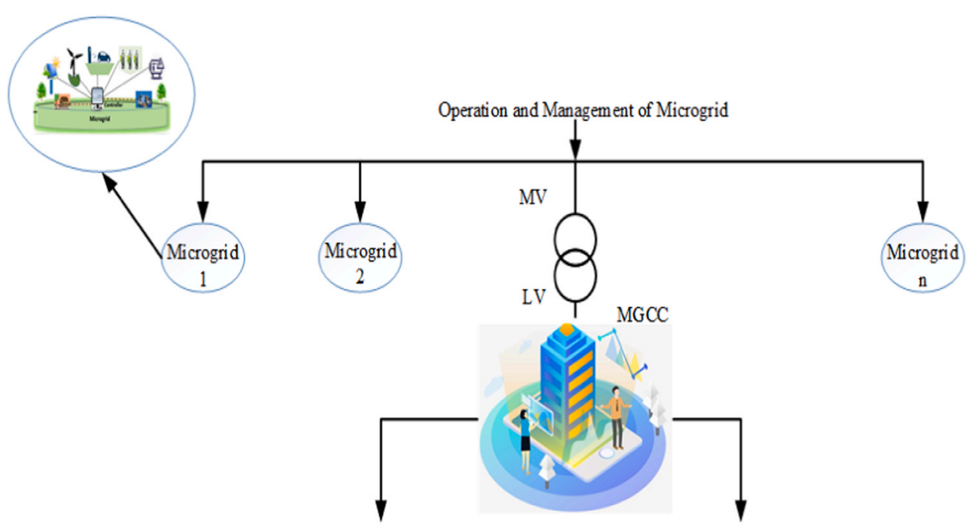

Fig. 2. operation and management of Microgrid.

2. MG control: classification and functional layers

2.1. MICRO GRID control and related issues

One notable characteristic that distinguishes a microgrid from a normal distributed generation (DG) system is the controllability methodology (Hajar et al., 2016).The primary objective of this endeavour is to illustrate microgrids as manageable and synchronised units. Multiple control methodologies have been employed in Microgrids (MG), such as droop control (Kim et al., 2011; Guerrero et al., 2011), voltage and frequency regulation, active and reactive power allocation, energy management (Do et al., 2019), MG optimisation, and multi MG interaction.

The fulfilment of these controlling criteria in the MG is facilitated by the implementation of established controller design methodologies (Jagatheesan et al., 2019), including centralised, decentralised, distributed, and hierarchical frameworks. This paper examines the comprehensive control methods for MG systems, considering numerous important functionalities, both in classical and modern control principles (Cominesi et al., 2016). Several control strategies based on model predictive control (MPC) (Dimeas and Hatziargyriou, 2005) are discussed in this paper. As delineated in the introductory part, the control systems based on MG (Microgrid) are categorised into four distinct areas, including centralised, decentralised, distributed, and hierarchical frameworks. It is noteworthy that there is no singular control mechanism peculiar to this particular MG that is dependent on the MG's structural model, design, and components utilised. Microgrids can be operated either in a centralised or decentralised fashion (Goitia-Zabaleta et al., 2023). The optimisation of the microgrid (Bugade and Katti, 2015) is primarily facilitated by the central type controller (MGCC) of the microgrid in the centralised mode. The decision (Lenhart and Araújo, 2021) on the quantity of power to be procured from the utility is determined by MGCC, taking into consideration factors such as energy costs, petrol prices, and security information. In the context of a decentralised process, the primary objective is to optimise power generation to fulfil the load demands and perhaps distribute excess electricity to the utility grid.

The successful execution of both centralised and decentralised control approaches (Almada et al., 2016) necessitates the utilisation of load forecast, accurate calculation of renewable energy power generation, and electricity pricing information. In addition to its application in forecasting, state-based estimate is closely linked to the control of microgrids. The reduction of ambiguity can be achieved through state-based estimate at the transmission side, which is facilitated by the inclusion of unnecessary measurements.

Moreover, once reaching the distribution endpoint, all decisions will be executed without the availability of adequate data pertaining to the intermediate voltage stage or lower voltage stage. Moreover, the indeterminate parameter of this model is expected. Typically, an estimation-based problem consists of a parameter derived from the estimation principle, accompanied with an algorithm for parameter type estimation. The primary principles employed include least squares, reduced variance, maximum likelihood, and minimum risk, among others. Fig. 3

2.2. Centralized control scheme

The utilisation of a centralised controlling mechanism is commonly recommended for small-scale microgrids. In this particular scenario, data from all the individual sensors that have been graded are collected at the MGCC through a more efficient communication procedure (Tsikalakis and Hatziargyriou, 2011). The relevance of MGCC (Multi-Goal Decision Making and Control) is further emphasised in the context of processing and decision management, as determined by the state variable. In order to comply with the new directive, it is necessary to make appropriate modifications to their responses. Within the distribution system, there is an additional type of controller present for both grid-linked microgrids and multi-microgrid based systems. Hence, the centralised control strategy can be further categorised into a three-tiered structure based on the sizes of the components and the relevant areas involved.

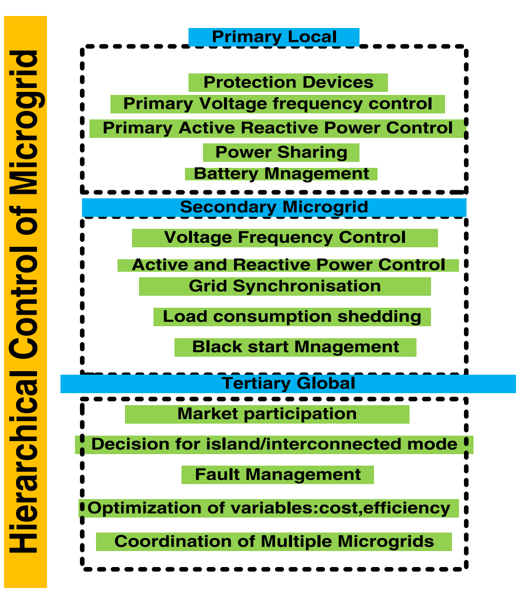

Fig. 3. Different Micro grid controlling approaches.

2.3. Decentralized control

Decentralised control is responsible for determining actions at the individual component level. This control methodology mostly consists of two-stage designs, encompassing both upper and lower level controllers (Etemadi et al., 2014). Decentralised control is commonly implemented in the context of more intricate microgrids that consist of a larger number of components. This approach is favoured over centralised control systems, which tend to exhibit sluggishness due to the challenges associated with collecting and processing vast amounts of data in a single location, typically referred to as the point of common coupling (PCC).

2.4. Distributed control

The distributed control (Bersani et al., 2017) architecture (Gong et al., 2020) is an enhanced version of the decentralised approach, in which the local controllers communicate with nearby units (using a reduced bandwidth channel) to use the benefits of the centralised design that is often employed for the entire microgrid. This suggests that each device has been controlled using local measurements, taking into consideration the responses of neighbouring devices.

2.5. Hierarchical control

The hierarchical control structure is derived from the differences in timeframes associated with various control requirements (Ding et al., 2013). The classification consists of three distinct categories, namely primary, secondary, and tertiary. The individual in a leadership position assumes the major responsibility for the direct administration of the device type state variable of microgrids, such as voltage-frequency (V-f) based control (Adhikari and Li, 2014). This operates inside both the millisecond and second time intervals. The secondary regulating layer has exhibited sluggishness in addressing steady-state type deviations resulting from the primary layer's actions. The tertiary layer, also known as the auxiliary layer, serves as the least expedient layer and is responsible for governing the power transmission within the upstream grid. The present study incorporates the economic dispatch (Duan et al., 2023)and optimisation of the entire microgrid (MG) system.

2.5.1. Primary control

It has the below said characteristics:

1. Stabilizes the Volt. & Freq of the power system
2. Alleviates fault resulting in O/C incidents observed in PE equipments

It also gives a set point in order that the low handler (volt.) of the DER & the end in the current control. The internal handling ends also called as "zero-level controls".

2.5.2. Secondary control

Secondary controls (Ahmadi et al., 2016; Dehkordi et al., 2017) generally exhibit a sample interval of minutes, indicating the deconstructed tactics of both primary and secondary control systems, so facilitating the understanding of their respective structures. The development of these controls should be undertaken with the objective of fulfilling the energy consumption associated with hiking activities. Classical secondary control in transmission systems of a wider interconnected grid focuses on ensuring overall system stability and maintaining a balance between generation and load on a greater scale. Secondary control functions by modifying the setpoints and outputs of generators in response to fluctuations in system frequency, thus maintaining a constant balance between power supply and demand. On the other hand, islanded systems, which function independently during power disruptions, necessitate a more self-sufficient strategy. In situations when an islanded network is present, secondary control plays a crucial role in regulating the local frequency and voltage levels. It effectively manages the dynamic interaction between power generation and demand inside the isolated network. The control mechanisms implemented in islanded systems aim to maintain stability and reliability in a smaller and self-sustaining environment, which is different from the broader cooperation observed in transmission systems within interconnected grids.

2.5.3. Tertiary control

The present study (Meng et al., 2014; Moayedi and Davoudi, 2016) focuses on the final stage of the sampling process, which is characterised by a somewhat slow handling range spanning from minutes to hours. This stage specifically addresses the analysis of financial issues in conjunction with the effective functioning of Micro Grid systems. The transfer of energy between the Micro Grid and the principal network is effectively maintained. This stage frequently entails forecasting future load patterns to facilitate the development of weather predictions, grid tariffs, and financial savings.

Various control methodologies have been employed to assure the dependable operation of microgrids, both in their connected state to the main power grid and when operating independently. After conducting an analysis of distributed generation (DG) and its operating status, three primary methods of control can be discerned: power quality (PQ) control, droop control (Planas et al., 2013), and voltage-to-frequency (V/f) management (Qureshi and Alvi, 2018).

2.6. PQ control

The primary objective of power quality (PQ) management is to ensure the stability of both active and reactive power of micro sources, even in the presence of fluctuations in frequency and voltage within specified ranges. In a power quality (PQ) based control system (Hajilu et al., 2015; Wang et al., 2021a), the active and reactive power are initially segregated to enable independent control. Additionally, a power type controller that is active in nature is responsible for maintaining a consistent active power output at a predetermined reference level within a specific frequency range. The proposed controller ensures that the active power output remains constant at a predetermined level within pre-defined voltage limits by utilising reactive power. Nevertheless, it should be noted that this particular control approach may not effectively maintain both frequency and voltage uniformity (Das et al., 2020). Consequently, an additional distributed generation (DG) unit is required to regulate voltage and frequency within an acceptable range, as depicted in Fig. 4.

2.7. V/f based controlling

The primary objective of V/f based control (Adhikari and Li, 2014; Hajilu et al., 2015) is to regulate both the frequency and voltage of the system, regardless of the true active and reactive power output. V/f control (Diaz et al., 2009) has been widely utilised in micro grids operating in islanded mode (Gui et al., 2018).

*Droop control

*Active power control

In case of micro grid, load always changes, which forces the generators to change the power output depending upon the frequency variation. $\Delta P = P_2 - P_1 = S_p(f_1 - f_2)$

ΔP=change in output power of generator

S_P=Reciprocal magnitude of slope of curve

Reactive power and Active power (Diaz et al., 2009) are directly proportional to Voltage and Frequency. Voltage management of the system is done through adjustment of outputs of the micro sources. Fig. 5

3. Control architectures in micro grids

In comparison to a generalized power grid mode, micro grid consists of two dissimilar modes; ie.grid connected (Mizani and Yazdani, 2009; Vijayan et al., 2012) as well as islanded mode (Mariam et al., 2016;

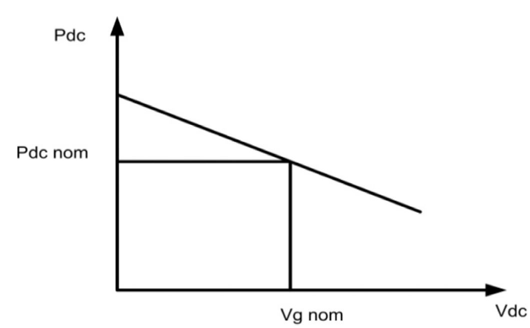

Fig. 5. P-Vg droop control.

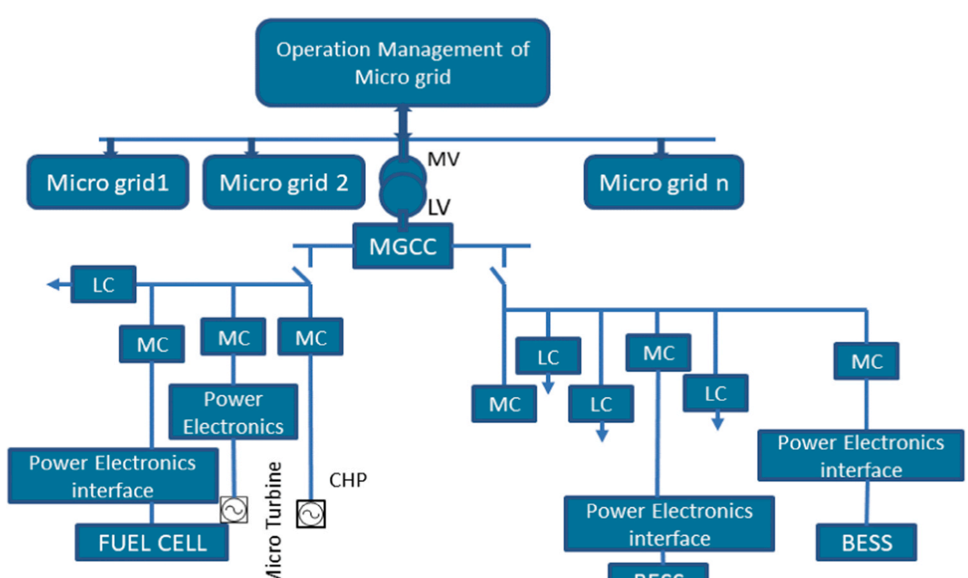

Fig. 4. Management of Micro grid in different layers.

Jadav et al., 2017).In principle the micro grid has operations in both the modes. Considering the functions of distributed generation inside the Micro grid, control architectures (Arif and Hasan, 2018) have been divided into master-slave, hierarchical or peer to peer type control. The investigation into the significance of distributed generation is becoming more and more crucial, especially in isolated power systems, where independence and resilience are of utmost importance. Comprehending the influence of distributed generation, particularly the extent to which renewable sources are integrated, is essential for guaranteeing the dependability and longevity of isolated power systems. Islanded modes, in contrast to typical centralized power systems, depend on localized sources for generating electricity, with renewables playing a crucial role in diversifying the energy mix. Evaluating the incorporation of renewable energy sources necessitates a detailed analysis of variables such as irregularity, voltage control, and overall system robustness.

3.1. Master-slave control

The topology of the master-slave controlling system, as seen in Fig. 6, has been previously discussed (Cavraro et al., 2016). When operating in islanded mode, the microgrid relies on either the distributed generation (DG) or energy storage system (ESS) within the main unit to assume the V/f control position. This is done in order to provide voltage and frequency reference signals to both the DGs and ESS units within the microgrid. Currently, several types of Distributed Generators (DGs) operate under the Power Quality (PQ) regulating mode. The controller that utilises the V/f controlling mechanism has been designated as the master type controller, while the remaining controllers are classified as slave type controllers. The aforementioned Slave type controllers are designed to execute comparable actions based on the instructions received from the master type controllers (Cai and Mitra, 2014). Moreover, microgrids often operate in a grid-connected fashion in many scenarios. The primary grid provides voltage and frequency to the micro grid, where the controllers operate in the PQ controlling mode. In the event of a failure occurring in the main grid, the micro grid smoothly transitions from the interconnected state to the islanded state. Among all the distributed generators (DGs), there is one designated as the Master DG, which is required to bypass the V/f control technique. Furthermore, the most prevalent master's degree programmes have been classified into three distinct categories. If the ESS is selected as the primary controller, the microgrid (Lidula and Rajapakse, 2011) may not be able to operate in an islanded mode for an extended period of time due to the discharge of the ESS and subsequent loss of power. When the micro turbine is employed as the distributed generator (DG) acting as the master controller, the micro grid is able to run in an islanded mode for an extended duration. An alternative approach, as proposed, involves the utilisation of both the Distributed Generation (DG) and Energy Storage Systems (ESS) for the master controllers (Zheng et al., 2013). The proposed approach is recommended for renewable energy generators such as photovoltaic systems and wind turbines, among others. The utilisation of Energy Storage Systems (ESS) (Othman, 2020) is crucial in mitigating voltage and frequency fluctuations in micro grids operating in islanded mode, owing to the intermittent and stochastic nature of renewable energy supply.

3.2. Peer to Peer control approach

For this controlling activity of the isolated micro grid, ever DGs along with ESS type units become identical with having nil master slave (Cavraro et al., 2016) relationship, as pictured in Fig. 7. To eliminate the problems that centralized control inherently possesses, being a single point of failure, the idea of peer-to-peer (Engels et al., 2016) or autonomous micro grids have been developed.

4. Stability issues in micro grids

The issue of system stability within microgrids (Shuai et al., 2016) has been widely recognised and extensively investigated by numerous scholars over an extended period of time. The stability aspect of microgrids varies depending on the type of microgrid, control topology, and network-based characteristics. The stability margin in a microgrid (Mohanty et al., 2019) is heavily influenced by the control topology; particularly with the growing utilisation of voltage source converter (VSC) based interfaced source integration. However, various other factors, such as micro sources, storage devices, protection mechanisms, compensating methods, and others, also contribute significantly to the overall stability of the system (Farrokhabadi et al., 2020). The investigation of the stability margin of the microgrid has been extended to include small signal analysis. This study examines the topic of dynamic stability from two perspectives: the use of power electronic-based distributed generators and the enhancement of stability through the use of induction motors. This case study examines the topic of load sharing, specifically focusing on the utilisation of control loops that operate based on both current and voltage. The accompanying stability (Jayawarna et al., 2006) of these control loops is also explored. Furthermore, this study has also tackled the topics of modelling and stability analysis in relation to voltage source converter (VSC) based sources. The utilisation of eigen value analysis in conjunction with time domain analysis has been proposed as a means to illustrate the significance of feedback-based controllers in system stability.The present study highlights the significance of stability-related concerns associated with VSC-based sources (Ahmed et al., 2020). In order to enhance system

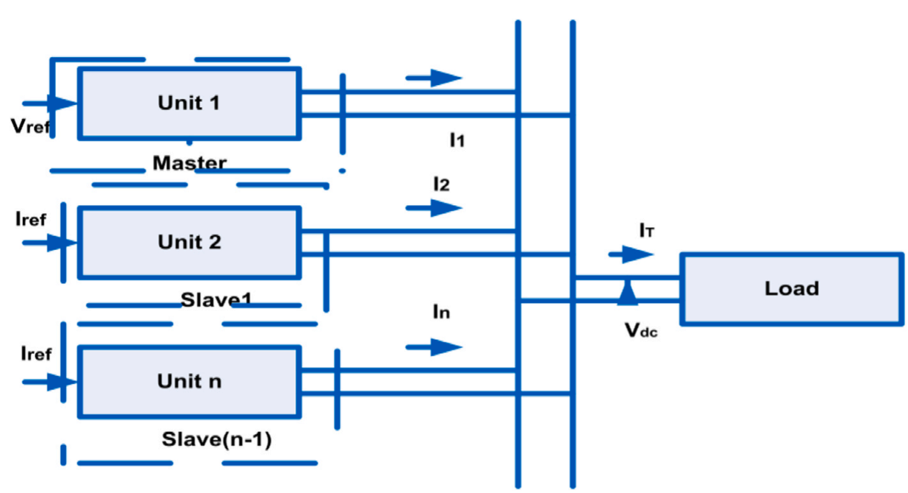

Fig. 6. Master Slave control.

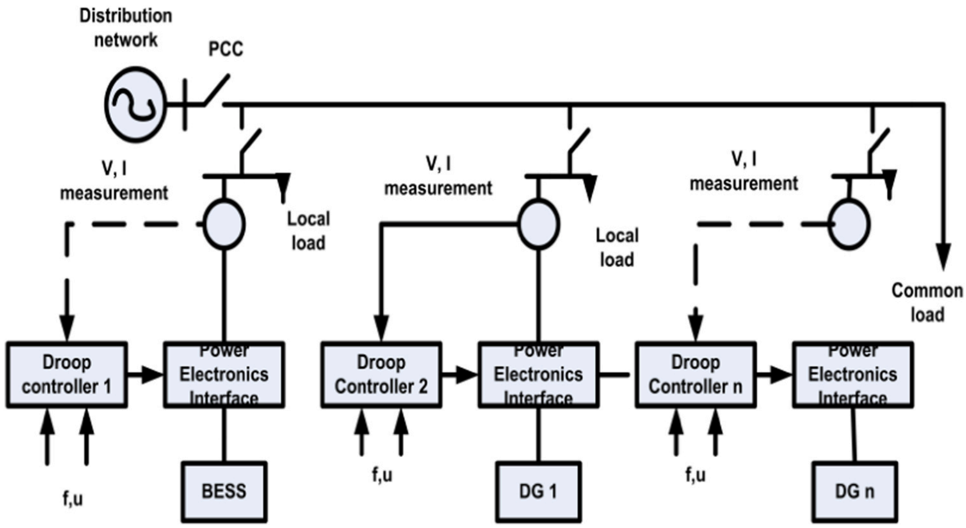

Fig. 7. Peer-to-peer control.

stability, a supplemental control loop has been suggested.

Further micro grid based stability in case of islanding (Andishgar et al., 2017) has been investigated, where impact with different loading environment as well as uniform power loads inside the micro grid during the islanding are addressed. Here an active type damping controller having a virtual type resistance has been proposed, where efficacy of the frequency controller with the internal oscillator as well as voltage feedback based signal to manage islanded voltage inside VSCs are established after islanding.

A facility micro grid is normally attached to the host utility along with a solo business entity based micro grid. Thus a facility based micro grid continues to function in a deliberate or unintended island. Further Facility based micro grids can be instrumental for industrial or institutional micro grid. Inside this work, an institution or campus-based micro grid (Huang et al., 2021) (with lesser number of micro sources along with diesel backup) functions in the island for a larger period is discussed.Fig. 8

Similar to larger power systems, stability challenges (Hirsch et al., 2018) associated with a microgrid can be categorised into three main aspects: Small Signal stability, Transient stability, and Voltage stability. The stability of small signals (Wu et al., 2009) inside the microgrid is influenced by factors such as the use of feedback-type controllers, the switching of uninterrupted loads, and power limitations in micro-sources. The occurrence of islanding in a microgrid gives rise to transitory stability issues (Xu et al., 2018).

Issues such as reactive power compensation, load dynamics, and tap changers can lead to significant voltage stability challenges inside a microgrid. Fig. 9 depicts a range of stability management techniques. The utilisation of storage with load shedding facilitates the enhancement of transient stability (Ayar et al., 2017) during the operation of the supplemental controlling loop, stabiliser, and coordinated controlled Micro Source, hence enhancing tiny signal stability.In the context of micro-grids, voltage stability can be achieved by the implementation of several techniques. One such approach involves voltage-based regulation, which incorporates distributed generators (DGs) and reactive power compensation. Additionally, the utilisation of a modified current limiter in conjunction with micro-type sources, together with an enhanced load controller, further contributes to maintaining voltage stability inside the micro-grid. When considering the classification of micro grids, it is important to acknowledge that certain stability-related

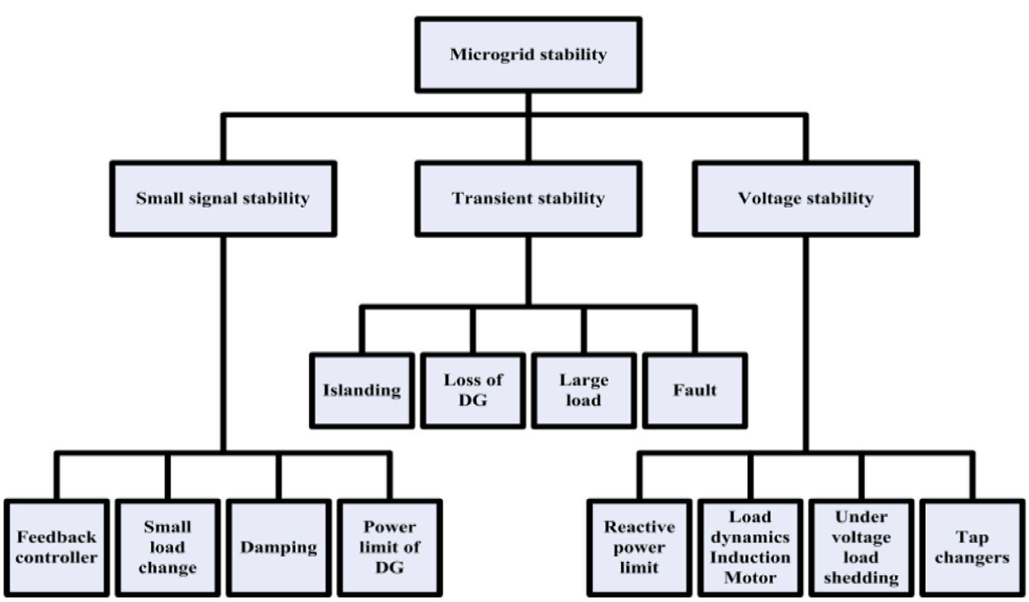

Fig. 8. Different stability issues in micro grid.

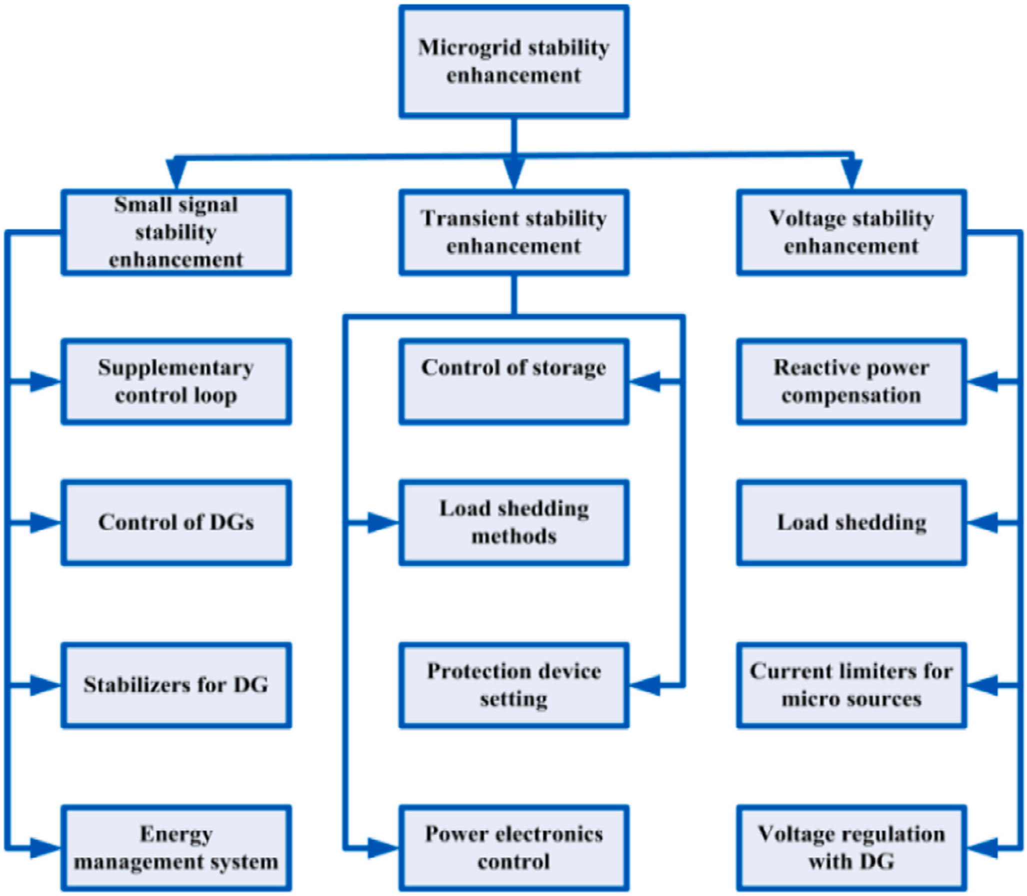

Fig. 9. Different methods of stability improvement.

concerns may arise from the most commonly occurring anomalies. The use of a decentralised control approach in a standalone microgrid, namely a DG feedback based controller, has been found to result in numerous tiny signal stability issues (Qin and Yu, 2013). Conversely, in a utility microgrid, current limiters are of utmost significance. In the context of a facility microgrid, the occurrence of frequent load fluctuations inside a confined area sometimes gives rise to tiny signal-based stability issues.

Transient stability phenomena in many types of microgrids are caused by faults. The stability of voltage inside a remote microgrid (Yildirim et al., 2021) has been found to be linked to the correction of reactive power in this network.The presence of limited sources and constrained loads, along with voltage-based load shedding mechanisms, gives rise to various voltage-related stability issues inside microgrids.

4.1. Small signal stability

Small signal stability refers to the power system's capacity to recover and maintain synchronism following a disturbance caused by a minor load or generation fluctuation.The fundamental classifications of power system stability encompass rotor angle stability and voltage stability. The analysis of tiny signal stability inside a microgrid has been conducted by utilising the transfer function representation of the microgrid's sources and loads.This section presents an analysis of the speed of control-based loops within the voltage source converter (VSC). The primary cause of stability concerns within the converter-controlled loops of a microgrid stems from the outermost power controllers and their associated controller gains.

4.2. Transient stability

The assessment of transient-based stability in microgrids involves the utilisation of a nonlinear model that combines all converter-type droop-based controllers (Nguyen et al., 2015). One of the ways of analysis relies on the development of a Lyapunov-based function. In order to apply the direct technique pertaining to transient stability, it is important to incorporate a Lyapunov-type function (Noman et al., 2021).

The function has yielded a constant value for all state-level variables that satisfy the criterion based on Lyapunov.The inclusion of constant type loads within functions is often not observed. Furthermore, this particular approach exhibits dynamic loading capabilities and also incorporates transient voltage reliance on the load. The source and load-related behaviour are split into several slow and fast subsystems for the purpose of transient analysis.

4.3. Voltage stability

The voltage stability crisis inside a micro grid appears because of various reasons. This phenomenon in the micro grid is demonstrated utilizing the P∼V and the Q∼V type curve. Here this P∼V curvatures indicate the utmost load ability as Q ∼V based curve displays the requisite quantity of the reactive power next to the load end to have the desired voltage (Hou et al., 2021).

For reactive power with an abrupt variation in power, the supply side should get managed in order to keep away from the converter reactive limitation or the system oscillation.

Considering various varieties of load demand, the need of reactive energy may alter with the load characteristics. This system becomes stable whenever positive as indicated.

5. Stability enhancement in Micro grid

In this section several methods for improving stability inside a micro grid have been discussed.

5.1. Stabilizer

Stabilizers are used near the VSC linked micro sources for improving the small signal based stability. Here the voltage, frequency along with power output related to the connected DG has been fed to the stabilizer. Separate stabilizing equipments or supplementary type of control loop improves the stability of the VSC interconnected to DG.

5.2. Reactive power compensation with FACTS devices

Reactive power compensation inside the micro grid is quite essential to preserve voltage magnitude within the acceptable range. These voltage regulation irregularities are higher in utility as well as remote type micro grids.

1) In case of grid connected (Lv et al., 2016) manner, regulation problem comes out on load side of feeder.

During the islanded mode, the voltages go below the acceptable range at any time and therefore identification of the compensation position is harder. The FACTS device ($author1$ et al., 2020) connected in vicinity to critical load ensures power quality. The FACTS device is controlled with local measurements at the site where it is placed depending on communicated measurements as well as coordinated controlling with DGs. The flow of islanded systems, a crucial factor in voltage stability analysis, entails a sequence of carefully coordinated actions to guarantee the dependable functioning of an electric distribution system when a section becomes electrically disconnected. Triggered by efficient islanding detecting methods, the procedure requires the separation of the impacted area using protective measures. After being separated, the islanded system must face the ongoing task of preserving steady voltage levels. During this phase, voltage stability studies, which include load flow assessments and dynamic simulations, are essential for evaluating the system's capacity to maintain appropriate voltage values. Controlling generators, implementing load shedding techniques, and closely monitoring through communication systems are essential for the autonomous operation of the islanded system while maintaining stability. Finally, a meticulously planned reconnection to the main grid occurs, indicating the end of the islanding event and preparing for the creation of post-analysis documentation and suggestions for improving the system.

5.3. Energy storage system: flywheel

Storage systems play a crucial role in enhancing stability within microgrids by injecting active or reactive power during power shortages. The industry currently offers a wide range of storage-based products to fulfil this purpose. Moreover, the flywheel has emerged as a prominent energy storage technology known for its exceptional performance capabilities. Moreover, the utilisation of a flywheel-based system 2020) enables the sustained provision of power within the megawatt range.

5.4. Load shedding for improvement of stability

The vital activity played during load shedding in micro grid-related stability happens during the islanding. Further a sudden disappearance of a grid generates an imbalance in power along with the load shedding in the micro grid. The Load shedding is achieved through various processes.

Breaker interlock- This type of method seems fast as well as effective.

Under the Frequency Relay- The commonest method to bring download inside micro grid under frequency followed by tripping the relays. However, the demerit of this process is that the method seems slow and becomes much slower during the presence of the larger storage.

PLC type of load Shedding-These are activated depending on the generators number functioning under the frequency condition as well as the volume of load given to the network. But it needs better monitoring and care. Also during the transient, load shed duration often remains longer.

Advanced type Methods-In case of advanced type load shedding technique we can implement monitored data as well as network-based models for the optimization process (Thirunavukkarasu et al., 2022; Dawoud et al., 2018).

6. Eigen Value analysis with time domain-based outcome

In this particular scenario, the discussion revolves around the topic of stability issues and the many ways that might be employed to enhance stability. This work examines various techniques to enhance stability in the context of small signal, transient, and voltage stability, with the aim of elucidating these concepts. The identified stability matters and improvement techniques have been associated with the cases. The simulations have been illustrated in Figure. These schemes can be regarded as simpler versions.

6.1. Small signal stability

The most prevalent cause of tiny signal stability concerns within a microgrid is attributed to the feedback-based controller (Qin and Yu, 2013). The system stability has been further impacted by gradually increasing the power control gain, resulting in feedback gains. The trajectory associated with eigenvalues, which exhibits variations in the gains of the controller, has been illustrated. As a consequence, the system encounters instability when the feedback gain reaches higher magnitudes. However, in numerous cases, it is necessary to get a greater advantage in order to develop proper load distribution. Furthermore, the implementation of a supplementary controller loop serves to enhance system stability when employing higher feedback gain. To achieve a comparable type of modification within the controller gain, a trajectory based on Eigen values is utilised, accompanied by an additional controlling loop.

It has been noticed that the implementation of a damping type signal within a current-based control loop (Shahgholian, 2021) consistently yields optimal responses, particularly in terms of rising time. Therefore, the settling period is more efficient in the remote microgrid as opposed to the microgrid facility. The duration of the rising time and settling time exhibits variability, however, the alterations in the governing loops demonstrate minimal influence throughout the settling phase within the facility microgrid.

6.2. Islanding transients

The transient stability related issues after an islanding (Teymouri et al., 2019) are demonstrated where there are several factors responsible for the fault along with subsequent islanding. There is need to shed few loads to manage power balance. Thus, charge of the DC capacitor is managed during the energy need all through the transition. Inside a micro grid, storage acts a vital role in islanding. Power injected injected from storage should ensure.

1) Stability of the system 2) power quality 3) Normal functioning of DGs.

Storage systems offer stabilising effects (Astero et al., 2012) during system operations in both grid-connected and islanded modes (Bidram et al., 2014a). The implementation of battery storage (Goransson et al.,

2017) enables the provision of extended power supply durations, which proves advantageous in addressing significant power imbalances. The results provide a description of the system's outcome when islanding occurs with the support of storage (Tushar et al., 2016). The selection of an additional load constraint with the assistance of a battery is seen to occur for duration of 0.15 seconds during islanding, as well as for duration of 0.65 seconds.

6.3. Load shedding

Impact created by this load shedding upon system's overall stability has been shown. With the micro grid, an islanding having 20% more load has been simulated. The islanding has been supported by the load shedding for achieving the power equilibrium. Responses of the system with various load shedding method have been shown.

- It is worth to notice that the presentation of the usual frequency based relay fails to perform with the application of motor loading.
- For any critical type system it suggests to utilize the superior Load shedding technique with better-quality performance.
- Settling periods of various micro grids have been compared. It is observed that having the motor loading, the frequency change has a larger settling time.

6.4. Reactive power Compensation

Reactive power compensation phenomena, employing FACTS-based controllers such as Static Var Compensator (SVC) and Distribution Static Compensator (DSTATCOM), have been implemented in diverse micro-grid configurations. Compensation is facilitated through the coordinated control of Flexible AC Transmission System (FACTS) devices, namely Static Var Compensators (SVC) and Distribution Static Compensators (DSTATCOM), along with supplemental Distributed Generators (DGs), as highlighted in multiple scholarly works. Moreover, this enhances the root mean square (RMS) value of voltage within the feeders, as seen. It is observed that in the absence of correction, the voltage decreases significantly below the designated threshold. The figure labelled as Fig. 15 (a-f) illustrates the percentage of voltage decreases associated with different microgrids after reactive compensation. To ensure the operational effectiveness and efficiency of isolated microgrids (Song et al., 2019), it is imperative to maintain voltage drop below acceptable limits. This enables the microgrid to function optimally while providing the desired facility and utility.The magnitude of the voltage drop consistently hovers within the range of 6–8%, which falls within the allowed limit of 10%.Figs. 10–14

Linear type relationship in between the parameters ie. Reactive power and terminal voltage, is mentioned as shown.It is similar to the relationship between active power and the frequency. Voltage control (Elkhatib et al., 2011) of the system can be accomplished by adjusting reactive power linked with the micro sources. Fig. 15, Fig. 16, Table 1–3

A typical Microgrid Energy Management System (MEMS) (Rathor and Saxena, 2020) is comprised of many modules that are responsible for executing decision-making strategies, such as Distributed Energy Resources (DER) and load forecasting, Human Machine Interface (HMI), supervisory control, and data acquisition (SCADA). The efficient implementation of Energy Management decisions is ensured by transmitting optimal decisions to the generation, storage, and load components.

Moreover, the Microgrid Energy Management System provides a range of functionalities, including the monitoring and analysis of load

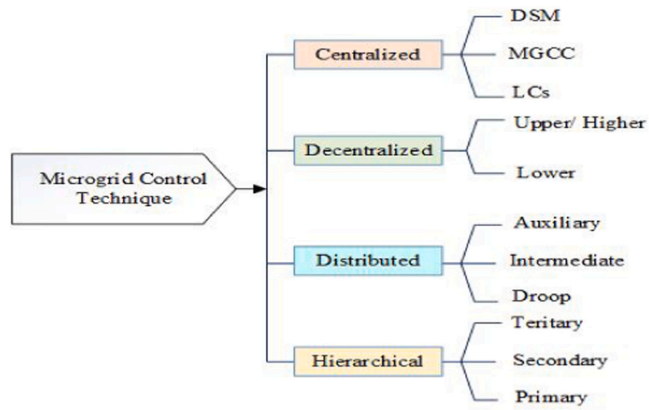

Fig. 11. Different Microgrid control techniques.

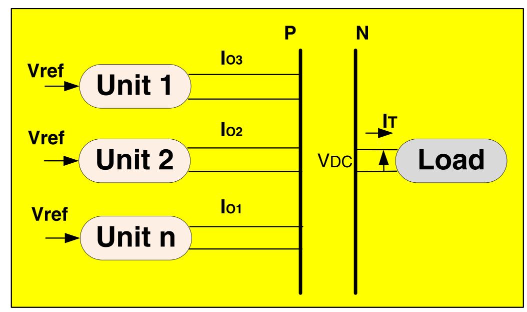

Fig. 12. Voltage droop control.

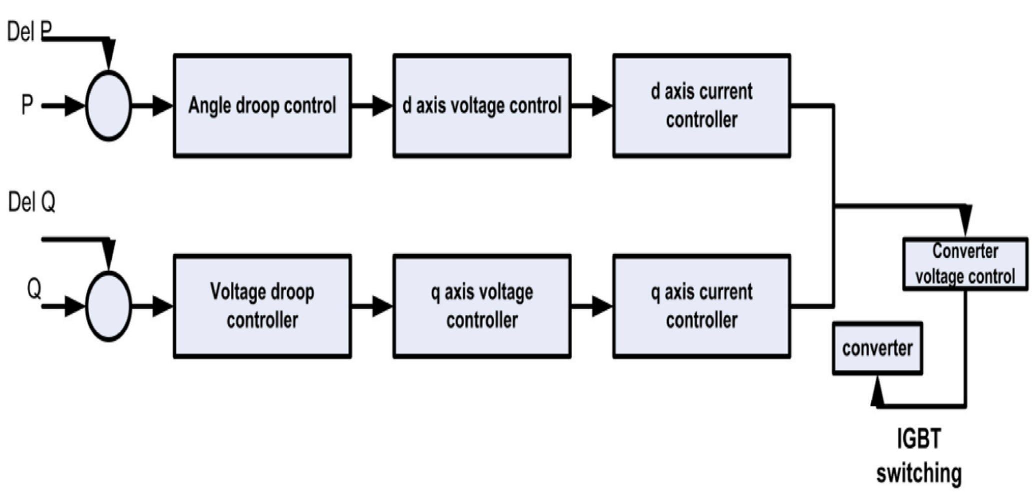

Fig. 10. Small signal stability droop control.

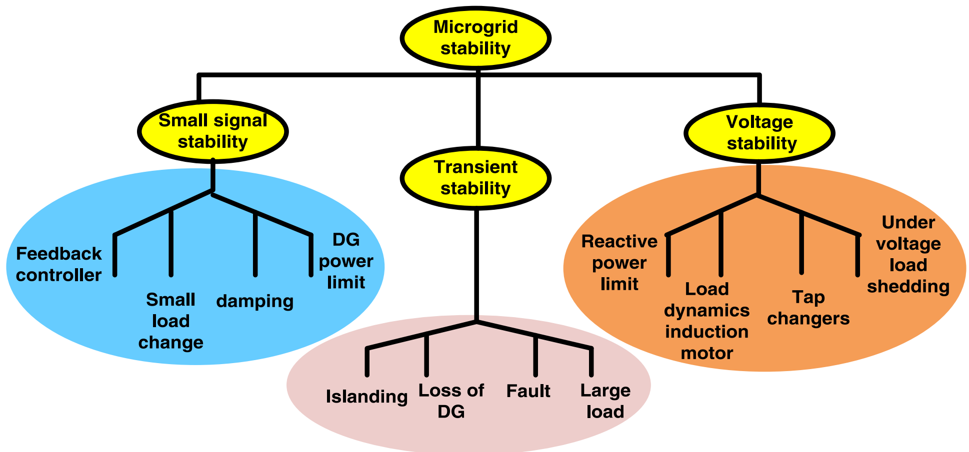

Fig. 13. Different divisions of Microgrid stability.

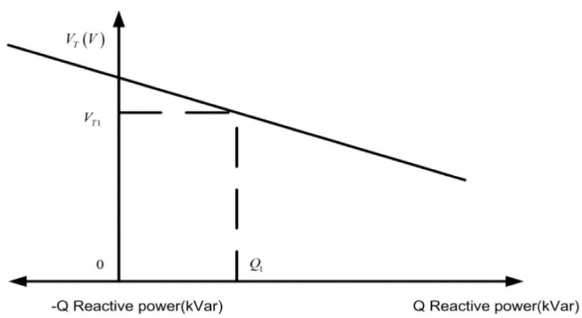

Fig. 14. Relation between the reactive power & output voltage.

usage, energy and ancillary market pricing, forecasting of power generation, and consideration of meteorological aspects. It is recommended that a comparative analysis be conducted in order to more effectively evaluate the performances exhibited by different control systems (Adhikari et al., 2014). The aforementioned control methods have been subject to extensive analysis and evaluation in order to assess their effectiveness in managing various aspects, such as current management, active and reactive power control (Bolognani and Zampieri, 2011), PNS extraction, and controllability of active and reactive power oscillations, using FCP numbers. The subsequent handling of both variables P and Q, pertaining to active power and reactive power, has been extensively examined in numerous scholarly works (La Bella et al., 2017; Berkel et al., 2013).

7. Smart management of microgrid

This section presents an analysis of several fundamental integrated technologies that significantly transform the Microgrid and introduce different modifications to its operation. This encompasses the incorporation of intermittent renewable energy sources (RESs) in order to achieve decarbonization, the commencement of a power and information exchange process, and the optimisation of resource or asset utilization (Balog and Krein, 2011; Akbari et al., 2011). Additionally, it encompasses the provision of dependable electricity and facilitates the effective management of fluctuating demand and client preferences. It also aims to establish a self-healing power system that is resilient to internal network disruptions. Furthermore, it demonstrates resistance in the face of both physical and cyber assaults. While the power system demonstrates intelligence during the transmission phase, it is imperative for it to attain such intelligence throughout the generating and distribution stages as well. Various measuring and control infrastructures (Tsikalakis and Hatziargyriou, 2011; Bersani et al., 2017) have been proposed to enhance and optimise the management of microgrids (Bidram et al., 2014a).

8. Challenges and issues-

While the development of MG shows potential, it is crucial to recognise the numerous obstacles and limitations that are linked with it, as previously explained. The fundamental challenges associated with MGs can be classified, as seen in Fig. 17.

8.1. Technical challenges in MGs

During the operational and management phases, an MG encounters several significant difficulties. The frequency and voltages of the system (Savaghebi et al., 2013) may experience alterations due to the significant influx of current during the initial phases of island mode initiation. The potential consequence of this scenario is the occurrence of generator tripping and subsequent shutdown during the starting phase. In order to tackle this issue, it is important to conduct an inquiry into the various techniques of energy generation in island mode, along with the formulation of tailored controls that are well-suited for microgrid (MG) (Sandelic et al., 2022) operations.Energy regulation typically encompasses multiple aspects that require careful adjustment. Subsequently, it is vital to simulate the parameters in order to ascertain the optimal solutions. Determining an optimal value within the context of MGs is a formidable undertaking due to the presence of diverse ambiguities and non-specific occurrences, alongside the existence of clearly defined unique events. In order to uphold power quality, it is expected to maintain a short-term equilibrium between the active and reactive power of a microgrid (MG). The control centres (CCs) and monitoring centres (MCs) of medium voltage (MG) systems should integrate metering, control, and protection (Islam and Gabbar, 2012; Memon and Kauhaniemi, 2015) functionalities based on SCADA technology. It is recommended that provisions be implemented to enable system diagnostics through the utilisation of state estimate functions. In order to optimise the performance of an MG, it is important to possess a well-crafted design and conduct a comprehensive functional study. The consideration of the mode of operation and configurations of the MG is crucial in the design of the MG control system. In order to effectively manage the operational scenario, it is imperative that the control system integrates all viable management strategies.

Load flow analysis is a crucial aspect of studying microgrid (MG) systems. It is necessary to conduct load flow analysis in various operating conditions and configurations to ascertain the current flow and voltage levels. The task at hand involves the identification and categorization of pertinent loads, as well as the assessment of their respective

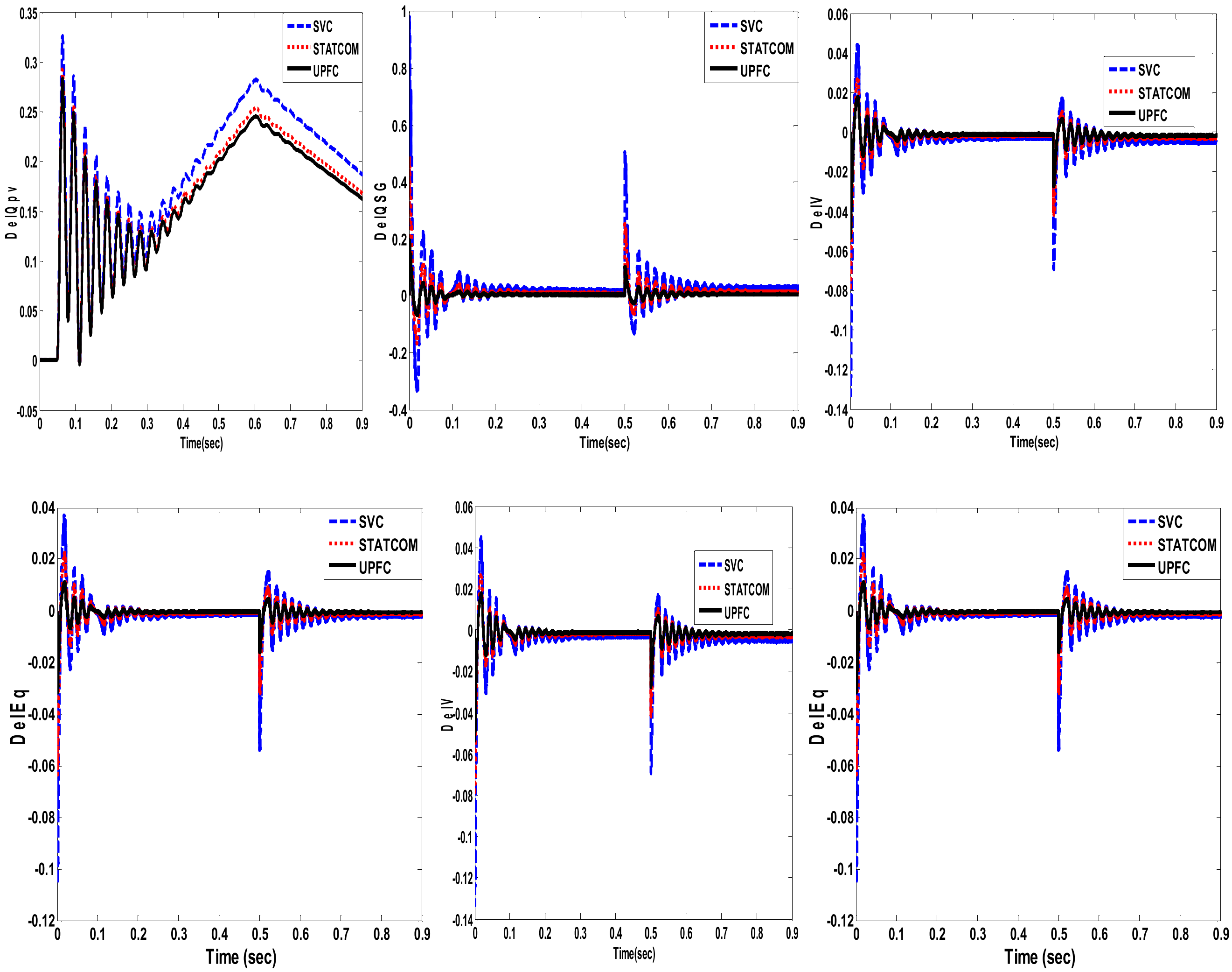

Fig. 15. (a-f).Terminal voltage and outputs of SG,IG and other parameters.

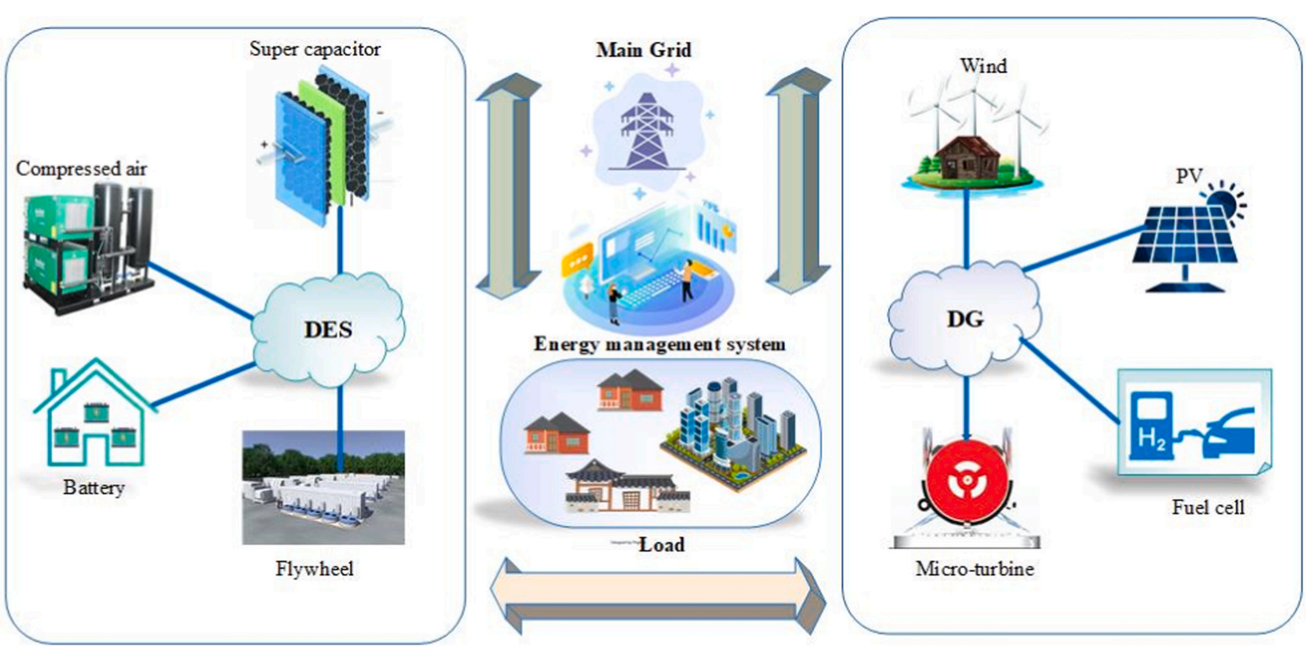

Fig. 16. Energy management in Microgrid.

Table 1
Advantages and drawbacks of different controllers.

Control Methods	Advantages	Disadvantages
PI based Controller	Simple and Easy to implement Applicable to both 1Φ and 3 Φ systems	Unable to track the sinusoidal reference under non linear load variation
PR based Controller	Provides fast and dynamic response Mitigate stability problems Less computational burden than PI controller	Sensitive to frequency variation Difficult to implement
Direct power control	Simple control structure Fast dynamic approach	Converter loss due non constant switching frequency, High THD due to non linear loads
Fractional order control	Provides fast and dynamic response.stable, robust and having flexibility.	Less sensitive to control parameters variation
Predictive Control	Precise current control with less harmonics Less switching frequencies. Deals with non linearities.	Sensitive to parameter changes More computation burden
Hysteresis control	Simple structure High dynamics, shows higher robustness and stability	Application is limited by switching losses.
Dead bit control	Faster load voltage regulation Mitigates voltage disturbances in power/current controller	Implementation in high frequency controller
Repetitive control	Performs robustly during Grid disturbance,provides zero steady state error during low and high order harmonics.	Shows slow response during fluctuation of loads

critical thresholds. Furthermore, the inclusion of changeable load profiles' temporal specifications may contribute to the intricacy of the situation. The challenge of achieving equilibrium between generation and load in island mode is a common concern faced by microgrids (MGs). Maintaining a consistent equilibrium between load and power generation is crucial. The occurrence of instability within the island system can be attributed to abrupt or substantial alterations in loads.

The importance of MG stability necessitates the need to predict, monitor, and assess the transient occurrences that arise from both typical and atypical disturbances. Microgrids (MGs) consist of a diverse array of power sources and components. Maintaining system stability can be a complex task when utilising inertia-based generators, static converter-based photovoltaic (PV) systems, wind turbines, and energy storage (Bracco et al., 2015) devices. Additionally, there exist alternative types of converters, including those that utilise power electronic devices and virtual synchronous generators (Bidram et al., 2014b; Yang et al., 2023a). In order to ensure the stability of the system, it is imperative for manufacturers and designers to undertake a thorough examination and establish a strong interconnection among the various equipment components. When preparing power system studies, it is crucial to give utmost consideration to the specifications and single-line diagrams of the system. These elements hold significant importance in the overall analysis and evaluation of the power system. Therefore, it is crucial to have a solid understanding of the basic principles that govern the illumination and demonstration of the operating behavior of the MG. Feeders are currently designed and constructed using reliable sources of power generation and distribution, in accordance with the established power system. Nevertheless, a significant obstacle arises when the need for feeders in microgrids (MGs) is not met. The present discourse pertains to the examination of telecommunication infrastructures and communication protocols. The comprehensive administration, protection, and control of energy need the presence of telecommunication infrastructures and the implementation of communication protocols.

8.2. Operational and Maintenance-

Microgrids (MGs) (Kakigano et al., 2013), especially those that rely on renewable energy sources, possess distinct design, modelling, and planning prerequisites in comparison to traditional fuel-based systems, a fact that is well acknowledged. Poor design is a significant contributing reason to the decreased lifespan of MGs. A comprehensive comprehension of both the energy resources accessible and the users' expectations is crucial for the effective design of renewable microgrids (Li et al., 2023). It is imperative to take into account the potential impact of shifts in both energy resource availability and demand on the dependability and accessibility of energy supply. Therefore, the design of MGs continues to provide a significant difficulty. It is important to identify and specify each integrated power source versus load scenario within the microgrid (MG), particularly in cases involving temporary switching or emergency shedding. The period of managing an MG becomes crucial and complex due to the presence of diverse loads and generators with different operating characteristics and behaviours.

Table 2
Summary of different control techniques in Microgrid.

Design techniques	Authors	Control Principle
Centralized	Tsikalakis AG et al. (2008), Abdelaziz M, Shaaban M, Farag H El-Saadany E (2014), Tenti P. (2017), Tan et al. (2012), Kupzog, F. (2008), Ding et al.(2010), Ambia et al. (2014), Almeda(2016), Hazar et al.(2016a)	Optimizing micro grids, islanded micro grid, self configuration, optimal control, PI Control, Heuristic Algorithm, Model predictive control
Decentralized	Ahn, C, & Peng H (2013), Bhattacharya S et al. (2016), Bhattacharya S et al. (2016), Cucuzzella M et al. (2017), Divshaali P et al. (2012), Baghee et al. (2017), Xia et al. (2016) Wu et al. (2015)	Cooperative control, Sliding mode, PI, PI/PID
Distributed Control	Guo L and Wang C(2009), Kakigno H, Miiura Y and Isse T.(2013), Bahrmara S,et al. (2016), Bersani C, Dagdougui H, Ouammi A & Sacile R (2017), Bahrmara S,et al. (2016). Bersanii C, Daggdougui H, Ouami A & Scile R(2017), Bindram A et al. (2013), Bersanii C, Daggdougui H, Ouami A & Scile R(2017), Bindram A et al. (2013), Bindram A,et al. (2014), Bolognani S et al. (2011), Hadjicostis C. N (2015), Cai H & Hu, G(2018), Chang C & Zhang, W(2015) Mattavelli P(2011), Jiang H (2018), El Taweel, et al. (2017).	inverter-interfaced micro grid, Voltage Regulation, Distributed control, Frequency regulation, Robust control, Islanded Microgrid, Islanded Microgrid, Fuzzy control
Hierarchical	Bela A.L,Cominesi S. R, Sandroni C & Scattolini R (2017), Bela A.L,Cominesi S. R, Sandroni C & Scattolini R (2017), Bindram A & Davoudi A(2012). Berkel F, Gorges D & Liu S(2013). Bindram A & Davoudi A 2012, Chamorro H. R & Diaz N. L. (2013).	Economic optimalty, Load frequency control, Predictive control, Load frequency control

8.3. Environmental and sustainability-

When a microgrid (MG) is interconnected with the main grid, there is a bidirectional flow of power between the main grid and the microgrid. The integration of several distributed generators into the grid poses a significant technological challenge, giving rise to issues over voltage growth. Due to its intermittent nature, solar photovoltaic (PV) power

Table 3
Infrasructures for smart management of Microgrid.

Infrastructure	Communication	Description
Communication Infrastructure	PLCC-Power line carrier communication	This utilizes all prevailing distribution lines and therefore gives a cheap information in the exchange medium for transmission of the modulated signals with a frequency range of (10 kHz - 490 kHz)
	DSL-Digital subscriber lines	cheaper option for the high-speed communication. It has been achieved through widespread telecom line infrastructure
	OPGW-Optical ground wire	Has low latency and has immunity towards the reliable medium.
Measurement /Monitoring Infrastructure	SMI-Smart metering infrastructure	This encourages two side communication and records the use of power in a timely manner. Further it communicates data towards utility grid based centralised management (Brandao et al., 2017) system for proper monitoring & calculation.
	SCADA-Supervisory control and data acquisition	This one works in a broad area and helps in decision making for the DSOs. Further it encourages in acquisition of data from selective buses, helps in supervisory controlling as well as activates alarms throughout critical operating scenario. Further it coordinates in between EMS & RTUs.
	PMU-Phasor measurement units	PMU technology (Wang et al., 2021b) is the most advanced technology meant for Wide Area Measurement System (WAMS).It gives an idea regarding current and voltage magnitudes with phase angles having accurate time management. This has been implemented for the multi-micro grids optimization as well as control.
	Advance forecasting techniques	Prediction of load with electricity generation and its pricing have been considered. Advance techniques supply statistics based on pseudo measurement, in order to decide strategies. It takes several RESs as well as load uncertainties.
Control Infrastructure	RTU-Remote terminal units	This acts as a local controller (LC) at every component of the Micro grid. These type of micro controllers (Kim et al., 2011) are considered as special type of computers that receive set point or status like the digital Input. They also generate digital controlling output.
	DCS-Distributed control systems	Because of the distributed nature of several entities inside the Micro grid, a distributed type control infrastructure is required. Thus it reaches global optimization (Bracco et al., 2015) as well as facilitates of PnP capabilities.
	EMS-Energy management system	The energy management system manages Micro grid as well as utility grid. It maintains demand supply balance,provides backup for thse devices. Further It enhances Micro grid operation.
	V2G-Vehicle to grid technology	It provides spinning reserve and load balancing. Further it improves the efficiency as well as reliability through charging/discharging of the EVs as required.
Protection Infrastructure	PR (Protective relays)	Protective relays have been remotely reconfigurable. There is primary requirement of minimum time based relays for fault isolation, equipment's protection (Xia et al., 1994) and for preservation of Micro grid's stability. These take care of the bidirectional type fault current.
	PLC-Programmable logic controller	This represents the extended (I/O) functions in real time.(Weaver 2009,1560–1067;Colson 2009,1–8) with several relays as well as the controlling architecture (Cai and Mitra, 2014). Further this PLL shows intelligent as well as backup features in case of the Micro grid technologies and is quite adaptable.
	STS-Static transfer switch	It optimizes the reliability of the vital loads through immediate transfer of the power sources. It also improvises ride through capability at a short span of power disturbances.
	IDM-Islanding detection method	This is highly needed to preserve reliability as well as stability of the Microgrid (Dagdougui et al., 2016) system at the time of utility grid fault, at a stipulated time at the PCC.

generation often leads to transient voltage fluctuations. These fluctuations can adversely affect the functioning of power regulation and protection systems, thus reducing the lifespan of associated equipment. The user has provided a numerical reference without any accompanying text. The existence of distributed generation (de Azevedo et al., 2017) (DG) units at low voltage levels inside the network might result in bidirectional power flows. This can give rise to several issues related to protection coordination, undesired power flow patterns, distribution of fault currents, and voltage (Rokrok and Golshan, 2010) regulation.The subsequent points outline the primary security concerns that a MG may encounter: The assessment of short-circuit current. The determination of short-circuit current (SCC) limits commonly involves the computation of the upper and lower bounds resulting from faults occurring inside the power system. The challenge arises from the considerable variability in the short-circuit current (SCC) across different operating configurations due to variations in power sources and loads. The issue of neutral earthing is of significant importance and complexity in the context of medium generators (MGs) with regards to their protection scheme. The reason for this phenomenon lies in the MG's ability to seamlessly transition between different power sources, employing a diverse range of energy generators such as spinning machines and converters (Gao et al., 2022), while also establishing connections with the primary power grid. The implementation of earthing systems is primarily regulated by local grid laws. However, the distribution and upkeep of neutral earthing can provide specific challenges. Given the evident fluctuations and low (SCC), it is imperative to do research on protective measures. The configuration of the MG should encompass the integration of efficient protective equipment and measures for staff safety, alongside the implementation of coordinated (Bhattacharya and Mishra, 2016) and scheduled operations for protective devices. The conventional safeguarding strategy may encounter challenges and prove ineffective, hence requiring the adoption (Cai and Hu, 2019) of innovative approaches and the willingness to make concessions.

8.4. Economic challenges

The investments made by MG continue to be of significant magnitude. Certain components of the technology, like as fuel cells, energy storage technologies, smart grid infrastructure, and grid management software, currently lack commercial viability in the absence of financial support (Tu et al., 2024). Ensuring efficient economic functioning. In order to accomplish a cost-effective operation, it is imperative to employ

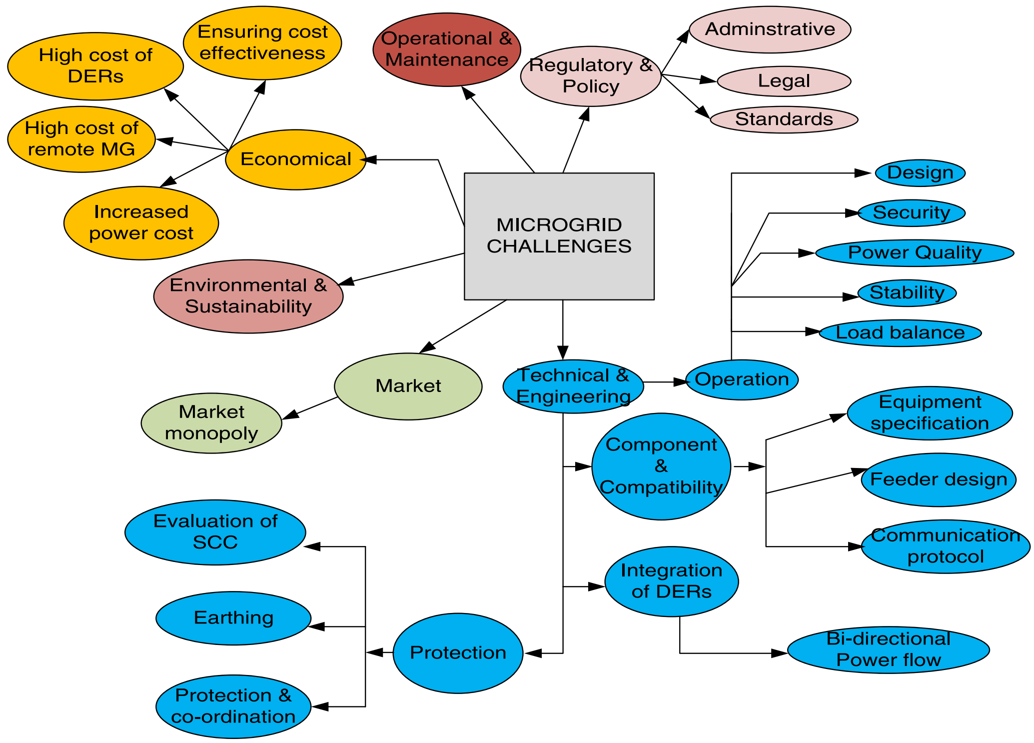

Fig. 17. Challenges faced for smooth operation of Microgrid.

generation schedules, economic load dispatch, and efficient power flow operations. The economic functionality of the MG must be guaranteed by the implementation of economic load dispatch, generator scheduling, and efficient power flow (Li et al., 2022a; Yang et al., 2023b) operations. The escalating cost of power generation: The introduction of a hybrid system is anticipated to yield a net escalation in intricacy, potentially leading to an associated rise in the production costs of power. The costs associated with infrastructure are taken into account while determining utility tariffs. If individuals are incentivized to create their own electricity, they will likely reduce their power consumption from the utility provider. Furthermore, certain systems will produce surplus electricity that can be sold to utility companies. Customers who opt for net metering will maintain their connection to the electrical grid, so enabling them to derive advantages from this infrastructure without incurring any costs associated with its fixed expenses. Consequently, individuals who choose not to implement net metering will be subject to the repercussions of infrastructure investments. Utilities are additionally apprehensive about the potential financial strain resulting from the increasing number of persons choosing net metering, since it may impede their ability to finance the extensive infrastructure enhancements required for a contemporary and environmentally friendly power (Ambia et al., 2014; Sun et al., 2023a) system.The installation of MG systems in rural areas poses challenges in terms of maintenance and leads to elevated transportation expenses.MGs exhibit a notable drawback with respect to the expenses associated with their installation. One potential approach to address this issue is to seek governmental subsidies as a means to incentivize investment. In order to meet environmental and carbon capture objectives, it is advisable to implement this measure on a temporary basis. There exists a worldwide objective to augment the production of renewable green energy and reduce carbon emissions by 50% by the year 2050.In the event that MGs are authorised to independently supply electricity to essential loads in the event of a disruption in the primary grid, a crucial inquiry arises about the party accountable for determining the pricing (Wu et al., 2022) of energy supply during the outage. In the event of the main grid becoming disconnected, the electrical market would experience a loss of control (Dimeas and Hatziargyriou, 2005; Bersani et al., 2017)over energy prices.

8.5. Market related challenges

Consequently, MGs may exploit their market monopoly by selling energy at exorbitant costs. Consequently, in order to facilitate the sustainable growth of MGs, it is imperative to build and execute appropriate market infrastructure. The MG industry is considered to be a very recent development. There is a need to define standards and norms pertaining to the integration and involvement of micro sources in both traditional and deregulated power markets. Additionally, it is recommended that measures be put in place to provide safety and protection in this context. In order to effectively integrate Microgrids (MGs) with active distribution networks, it is important to critically evaluate and restructure existing standards such as G59/1 and IEEE 1547. Furthermore, it is necessary to do research in order to critically evaluate IEEE 2030.7–2017, which is the IEEE Standard for the Specification of Microgrid Controllers (Ali and Kumar, 2021; Shao et al., 2023).

8.6. Regulatory and policy challenges

One of the primary challenges that organisations face is the presence of administrative and legal barriers. These barriers can impede the smooth functioning of operations and hinder the achievement of organisational objectives. The functioning of MGs is not often governed by standardised legislation or regulation in the majority of countries. Certain governments are actively advocating for the advancement of green electricity MGs, despite the absence of established legislation that would control their eventual implementation. Ensuring system security necessitates the implementation of contingency planning and emergency measures, such as demand-side management, load shedding, islanding, or unit shutdown. In the event of unforeseen circumstances, it is necessary to economically reschedule power generation in order to effectively manage system loads and maintain desired voltage and frequency levels at the load end. The preservation of system security in a microgrid (MG) can be achieved by using emergency operations and contingency planning measures. These measures include load shedding, distributed source management, islanding, and unit shutdown.

9. Future research areas in MGs

The discipline of MG is a captivating area of study within the realm of power engineering. In recent studies on MG, significant emphasis has been placed on addressing a range of research problems. Nevertheless, there are some crucial aspects that require attention and resolution. Both AC and DC MGs present unresolved research areas that warrant attention when contemplating future enhancements (Sun et al., 2023b). In future microgrids, there will be a growing demand for power sources, energy storage systems (ESSs), and loads to operate as plug-and-play modules, resulting in heightened complexity (Xu et al., 2021). In order to mitigate the increasing complexity, it will be imperative to undertake a redesign of the MG system in future iterations (Ahmad et al., 2023). An additional area for prospective investigation entails the examination and development of a system capable of facilitating the smooth transition of Microgrids (MGs) (Vidyasagar and Shanti Swarup, 2023; Shirkhani et al., 2023) from a state of being connected to the main power grid to operating autonomously. Fixed relay settings are widely employed in traditional distribution network protection schemes (Altin et al., 2023). The efficacy of this protective mechanism may be inadequate for individuals with MG (Chandak and Rout, 2020; Li et al., 2022b). Therefore, more investigation is necessary to formulate a safeguarding approach that can effectively ensure the secure functioning of the MG in various operational modes and transitions. In the context where the operational components of the MG exhibit diverse features, it becomes imperative to employ an effective methodology for regulating system parameters in standalone mode. The integration and management of renewable sources, storage systems, and load presents inherent complexities. Hence, the implementation of a strategic approach becomes crucial in order to effectively harness and sustain the power generated from renewable sources, generators, and energy storage systems (ESS), thereby optimising the economic use of these power sources. In order to ensure a balance between generation and load, it is imperative to implement an effective control strategy for Microgrids (MGs) running in standalone mode. In the future, it will be imperative to do research on the potential utilisation of Energy Storage Systems (ESS) that possess varied characteristics in order to uphold the inertia of Microgrids (MG). The adoption of electric vehicles (EVs) is experiencing substantial growth. Hence, placing a heightened emphasis on the integration of electric vehicles (EVs) (Alipour et al., 2017; Zhang et al., 2023a, 2023b) with microgrids (MGs) has the potential to provide significant discoveries in the realm of power system advancement. Subsequent investigations may be directed towards examining the potential for synergistic integration of nuclear energy and renewable energy sources (RESs) as a means to attain a harmonised and environmentally sustainable energy portfolio. This involves the examination of hybrid energy systems, the development of approaches for incorporating nuclear power and intermittent renewables into the microgrid (MG) (Taheri and Shahhoseini, 2023; Hadjidemetriou et al., 2018; Zhang et al., 2023c), and the investigation of energy storage technologies that may efficiently use the advantages of both nuclear and renewable energy sources.In order to facilitate coordination and collaboration across several mobile groups (MGs), it is important to develop a robust signalling (Mohamed and Radwan, 2011; Wang et al., 2023) and communication infrastructure. This will assist microgrids (Kanakadhurga and Prabaharan, 2022; Cao et al., 2020) in attaining operational equilibrium and ensuring a consistent provision of electricity to connected loadsThe integration of smart metering and network control is a necessary requirement in modern grid systems (MGs) (Che and Shahidehpour, 2014).The establishment of a generally acknowledged framework encompassing standards, rules, and procedures is imperative to facilitate and bolster the effective integration of MGs on a global scale.

10. Conclusion

This research examines different microgrids and their corresponding control methodologies, as well as the challenges related to their stability. A thorough assessment of different control strategies, in conjunction with synchronization approaches, has been conducted. This study presents additional benefits and limitations associated with various control systems. Stability-related issues arise as a result of diverse elements associated with many microgrids. Moreover, this study presents an examination of the stability-related applications of various microgrids, considering both general and systematic techniques. The control strategies employed in these applications are discussed, and the stability is evaluated using eigenvalue analysis and time domain analysis. Several research concerns and challenges have been highlighted for microgrids (MGs). The identification of concerns and obstacles has prompted the identification of future study areas that warrant attention. The comprehensive and up-to-date material on MGs presented in this study is likely to capture the interest of investigators, professionals, and researchers in the field.

CRediT authorship contribution statement

Abhay S Sathapathy: Writing – review & editing, Writing – original draft, Supervision, Software, Project administration, Methodology, Formal analysis, Data curation, Conceptualization. **Muhammad Mahmood Ali:** Validation, Methodology, Investigation, Formal analysis, Data curation. **MA Kalam:** Supervision, Software, Resources, Project administration, Methodology, Investigation, Formal analysis, Conceptualization. **Muhammad Nasir Bashir:** Writing – review & editing, Writing – original draft, Supervision, Resources, Investigation, Funding acquisition, Formal analysis. **Reji Kumar Rajamony:** Writing – original draft, Visualization, Supervision, Software, Investigation, Funding acquisition, Data curation. **Asit Mohanty:** Writing – original draft, Visualization, Supervision, Software, Project administration, Methodology, Funding acquisition, Conceptualization. **T. M. Yunus Khan:** Writing – review & editing, Validation, Supervision, Software, Resources, Formal analysis, Data curation, Conceptualization. **Manzoore Elahi M Soudagar:** Writing – review & editing, Writing – original draft, Visualization, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Sthitapragya Mohanty:** Writing – review & editing, Writing – original draft, Visualization, Supervision, Resources, Methodology, Funding acquisition, Conceptualization.

Declaration of Competing Interest

The authors declare that they have no competing interests.

Data availability

Data will be made available on request.

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