Control Techniques for Microgrids with Renewable Energy Sources – An Overview

*Sana Fazal, M. T. Arif, *Member, IEEE,* M. E. Haque, *Senior Member, IEEE,* S. Saha, *Member, IEEE* and AMT. Oo, *Senior Member, IEEE*

Renewable Energy and Electric Vehicle (REEV) Lab, Centre for Smart Power & Energy Research (CSPER)

School of Engineering, Deakin University, Waurn Ponds, Geelong, Australia

*sfazal@deakin.edu.au,

***Abstract*— Microgrids (MGs) are realised as a means of integrating renewable-based distributed energy resources (DERs); however, their seamless integration still remains a challenge owing to their intermittent nature. Control techniques are aimed at efficiently interfacing these energy sources for optimal, reliable and economic operation of a MG. Typical control topologies include centralised or decentralised systems where modern MG uses an amalgamation of both approaches. This is to minimise the problem of coordination among multiple autonomous controllers in fully decentralised systems, and remove computationally complex controllers in fully centralised systems. Contemporary MG control therefore, consists of three hierarchical layers; a) primary, b) secondary and c) tertiary. This paper presents an overview of this control configuration and analyses several control techniques as examples of basic MG control principles. The aim is to streamline these control methods, which are employed at each layer in a MG control for the benefit of future researchers.**

Keywords—Microgrid, hierarchical control, renewable DERs, grid integration

I. INTRODUCTION

Microgrid (MG) is a small scale power system which can integrate and control distributed generation (DG) units. This concept was first introduced by Lasseter as a means for reliable incorporation of both, renewable and non-renewable-based distributed energy resources (DERs) for supplying reliable electrical power to local customers [1], [2]. MGs can operate in islanding or grid connected mode, improve energy efficiency and reduce the control burden on the grid. Today, these small decentralised electricity generation units have replaced conventional centralised power systems due to environmental, economic and technical benefits.

Renewable energy sources are one way of realising the penetration of DG in MGs; however, integration of these sources still remains a challenge, given their intermittent and unreliable traits. Power electronically interfaced renewable DG units can be made more reliable by either, costly system over-sizing or having a back-up system (battery energy storage and/or diesel generator) to meet the power unbalance between demand and supply [3]. However, integration of these multiple components results in a complex system with different active elements which requires proper control and management at each level, i.e. from control of DG interfacing power converters to scheduling resources safely and securely [4]. Hence, a key feature of MG control is to extract maximum power from sources and dispatch them in an economical way.

Moreover, as multiple microsources can be electronically connected in a parallel fashion under grid-connected or islanded mode, it gives rise to the additional challenge of achieving load power sharing under variable power generation and consumption conditions [5]. MG controllers need to regulate active and reactive (P and Q) power flow between MG and local power grid in grid connected mode, and voltage and frequency (V and f) under islanded mode. Therefore, another key attribute of MG control is to achieve accurate power sharing among parallel connected converters. Hence, design for an effective control system integrating these features has been an active area of research [5], [6].

Several approaches in literature mitigate power fluctuations associated with renewable-based resources and achieve accurate power sharing in different MG architectures as reported in [7], [8] and [9]. A model predictive control (MPC)-based supervisory power management strategy (PMS) with a forecasting technique is developed in [10] for a standalone dc MG, incorporating multiple renewable-based DERs, load, and energy storage system (ESS). The control method not only achieves accurate power sharing among multiple MG components, but also predicts environmental and load demand parameters. An MPC power and voltage control (MPPVC) method is developed in [11] to control voltage and power sharing in a hybrid MG under grid connected and islanded modes of operation. Grid synchronization and connection together with development of a system-level energy management scheme is achieved to ensure stable operation under variable operating conditions.

MG control can be implemented in two different topologies; a) centralised and b) decentralised. Fully centralised approach is characterised by; i) a central controller which is in charge of all required calculations and ii) control actions determined at a single point for all the active elements, requiring extensive communication in large power systems [12]. A fully decentralised control, on the other hand, is identified by highly autonomous dedicated local controllers for each MG element, which use local information to make control-related decisions [13]. While this approach removes the need for extensive communication and computations, it is prone to disturbances arising from control units of various MG sub-systems, and requires minimum coordination level to be achieved. Hence, a hierarchical control scheme comprising of multiple centralised and decentralised control methods is used [14]. There is a need for an overview and comparative analysis of these approaches for ease of understanding. Therefore, this paper presents an overview of state-of-the-art control strategies for MG and classifies them in three levels (i) primary, (ii) secondary and (iii) tertiary. The different control levels are discussed in detail, based on the existing literature and a general overview of main MG control principles such as droop, multi-agent system (MAS), etc. is also presented.

Hence, the paper is organsied as follows: **Section II** presents general knowledge on MG structure, architectures and critical components, while **section III** summarises hierarchical MG control. A table based on several control techniques identified from literature is formatted in **section IV**, which classifies them into three control levels and highlights their key features. This section also discusses and elaborates these methods in more detail with **Section V** finally concluding this paper.

II. MICROGRID TECHNOLOGY

MGs can be viewed as single complex systems with non-linear elements or as systems of systems (SoS) [15], whereby each microsource (PV, diesel generator, etc.) constitutes a sub-system and collaborates with others to deliver secure, safe and reliable electrical power. MGs can be broadly classified as AC, DC or hybrid, contingent upon the type of power handled and can further be classified as fully renewable, partially renewable or fully non-renewable, based on DERs interconnection.

A generic MG structure consists of 4 main modules; a) generation, b) storage, c) distribution and d) control and communication as shown in Fig.1. Microsources, which are electronically interfaced with power converters, constitute the generation module. They are usually equipped with storage system to enhance their reliability. Point of common coupling (PCC) connects/disconnects a MG from the main grid, causing it to operate under two modes; a) grid-connected mode, where system parameters of V and f are determined by the utility and b) islanded mode, where system parameters are regulated locally. Control in MGs is a combination of various strategies employed in communication and integration of DERs. Control based on communication comprises of communication lines and controllers, such as microsource controllers (MCs), load controllers (LCs) and microgrid central controllers (MGCCs). While MCs regulate microsources and their converters to meet system power requirements, LCs control load to manage demand side. MGCCs control MCs and LCs for achieving global optimisation in islanded mode.

III. HIERARCHICAL MICROGRID CONTROL

A MG's control architecture can be analysed from a centralised or decentralised perspective. A centralised approach relies on a central controller gathering all the required information and processing it to determine control actions for various controlled units [16]. A decentralised control, on the other hand, makes decisions based on localised measurements, where MCs interact with LCs and MGCCs for achieving system control objectives [12]. As centralised control architecture uses a single point of control, it requires all-encompassing communication and could suffer from potential single-point failures or cyber-attacks [17], [18]. Similarly, decentralised control methods can be costly due to requirements of additional equipment installation [14]. Hence, an amalgamation of both approaches, i.e. hierarchical MG control, is used which consists of three main layers; a) primary, b) secondary and c) tertiary as shown in Fig. 2.

A. *Primary level*

Primary level, or internal level, is the first and most basic layer of control in a MG. It operates on the fastest timescale and relies on local measurements; hence, communication infrastructure is not needed. It is responsible for [19];

1. Regulating internal V and current (I) control loops of converters.
2. Stabilising f and V during normal operation of MG or when switching modes.
3. Eliminating circulating currents and, thereby protecting microsources.
4. Providing independent P, Q sharing under varying load conditions.
5. Providing a plug-and-play flexibility of DERs.

1) *Inner control of power converters*

As already established, microsources (AC or DC) are interfaced with power electronic converters as either current source inverters (CSIs) or voltage source inverters (VSIs). Both inverter types can exist in a MG which could be operating in grid-connected mode or islanded mode; therefore, control and management becomes challenging from this perspective [20]. A generic model of a microsource interface is shown in Fig. 3. It contains three critical parts; a) AC or DC DER, b) DC interface and c) VSI. Inner control of power converter is essential for controlling converter output V or I, and for accurate implementation of outer loop control commands such as droop control, power sharing and maximum power point tracking (MPPT) [21]. Control strategies for regulating inner currents and voltages can be executed under different reference frames in open-loop, single-loop or dual-loop configurations. Figs. 4 (a) and (b) represent one such instance, whereby dual-loop implementation in synchronous reference frame is realised for control of VSI's output parameters in islanded and grid connected modes, respectively. Park's transformation transforms abc quantities in dq reference frame for PI controllers to ensure zero-error regulation of the DC components. The transformed voltages and currents are compared with reference values to generate required PWM signals for the modulator.

2) *Outer control of power converters*

- $\boldsymbol{P - Q}$ **Control**: $P - Q$ control can be used in both, grid-connected and islanded mode of operation. Under this control, VSI regulates output powers based upon (1) and (2), where V is inverter's output voltage, E is MG's voltage, X is the coupling inductor's reactance between microsource and MG, and δ is the power angle.

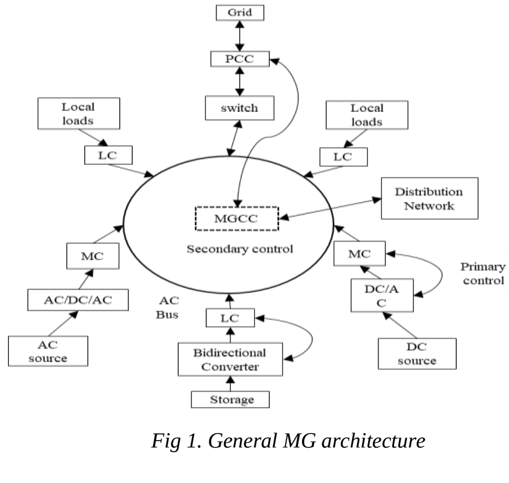


Fig 1. General MG architecture

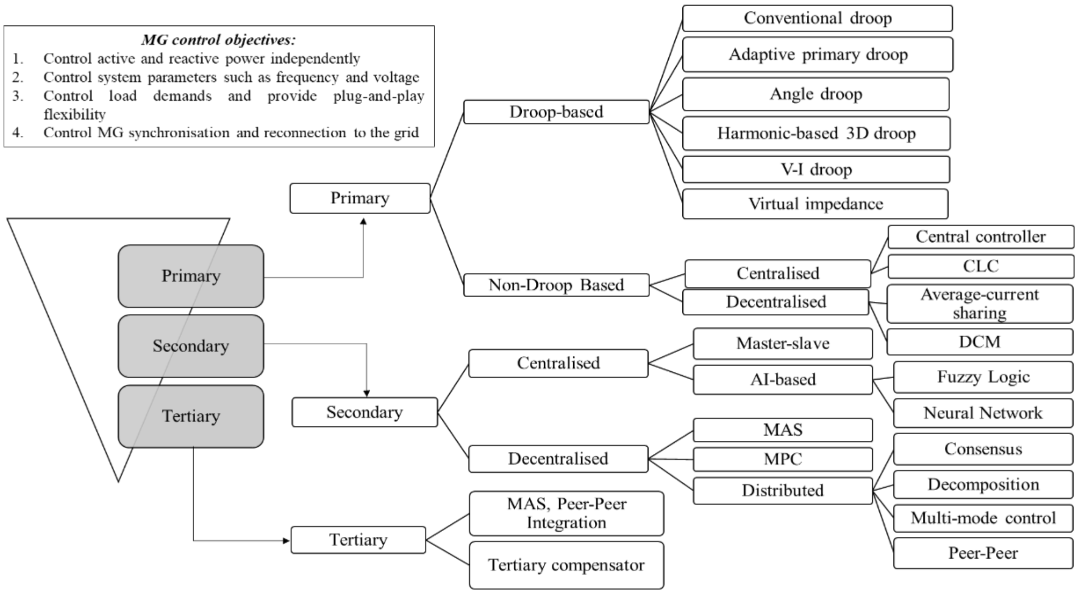


Figure 2. Hierarchical control in microgrids

$$P = \left(\frac{3}{2}\right) \times \left(\frac{VE}{X}\right) \times sin\delta \quad (1)$$

$$Q = \left(\frac{3}{2}\right) \times \left(\frac{V}{X}\right) \times (V - Ecos\delta) \quad (2)$$

- **$V - f$ Control**: $V - f$ control is employed in islanded MGs to regulate system parameters of V and f and meet load requirements. PI controllers are used to dampen oscillations in system parameters as in [17], represented by (3) and (4) below;

$$\Delta w = K_{pw}(w'_{MG} - w_{MG}) + K_{iw} \int (w'_{MG} - w_{MG})dt + \Delta ws \quad (3)$$

$$\Delta V = K_{pE}(V'_{MG} - V_{MG}) + K_{iE} \int (V'_{MG} - V_{MG})dt \quad (4)$$

where K_{pw} , K_{pE} , K_{iw} and K_{iE} are $V - f$ control compensator's control parameters, ΔV and Δw are V and f amplitude correction signals, and Δws is a synchronisation term.

- **Droop Control:** Voltage regulation with integration of multiple microsources is essential for avoiding oscillations and preventing circulating reactive currents under both operative modes of a MG [6]. Conventional droop-based power control techniques use differential control to determine power sharing among parallel-connected inverters using active power-frequency ($P - \omega$) and reactive power-voltage ($Q - V$) characteristics in an AC MG. It can be represented using (5) and (6) [21];

$$\omega = \omega' - s\,(P' - P) \quad (5)$$

$$V = V' - s\,(Q - Q') \quad (6)$$

where ω' and V' are grid parameters of frequency and voltage, P' and Q' are reference values for active and reactive powers, and s denotes the slope of the lines as shown in Fig. 5. DC MG's version of droop control is fairly simple as it consists of a single characteristic line, i.e. voltage-current ($V - I$), for regulating DC bus voltage. This can be mathematically represented by (7);

$$V = V' - I \times R \quad (7)$$

where V' is the reference bus voltage and R is the virtual resistance.

- **Non-droop-based control methods**: Non-droop/communication-based control methods can be centralised or decentralised to provide improved output V and f at the expense of extensive communication infrastructure and implementation costs [22]. One such implementation is realised in [23] whereby a central controller is responsible for deciding the power share of each DER unit. The inputs to the controller include total load current and characteristics of each DER unit under control. Several other non-droop based methods realised under the primary control of multi-DERs are discussed in more detail in section IV.

B. Secondary level/Microgrid Energy Management System

Secondary/Energy management control system (EMS) comes over the primary layer to correct any abnormalities arising from primary control in MGs. It consists of MGCC implemented in a *centralised* or *decentralised* manner to perform functionalities such as [24], [19];

1. Regulating secondary V and f deviations.
2. Improving power quality by reducing unbalances and harmonics.
3. Coordinating DERs by controlling primary controllers (MCs and LCs) via a communication link.

The difference between decentralised and centralised approach is realised by the location and functional roles assumed by MGCC. Under centralised control hierarchy, MGCC is situated far away from the microsources and controls LCs and MCs for optimising MG operation in grid-connected mode [19]. On the other end, LCs and MCs become more autonomous under a decentralised control setup in islanded mode, whereby they are responsible for dispatching maximum energy from resources [6]. Decentralised secondary control relies on local information for making control-related decisions. Examples of this control phenomenon include

MAS or MPC techniques. These are analysed further in section IV.

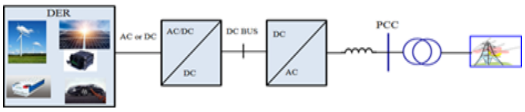
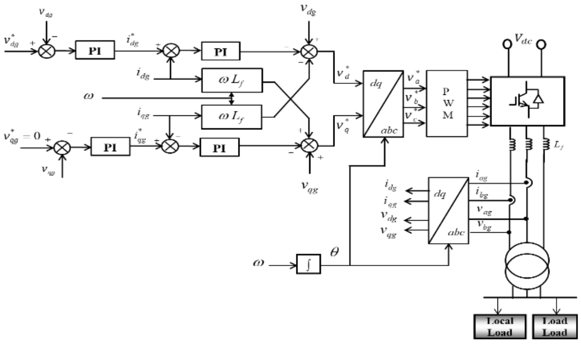
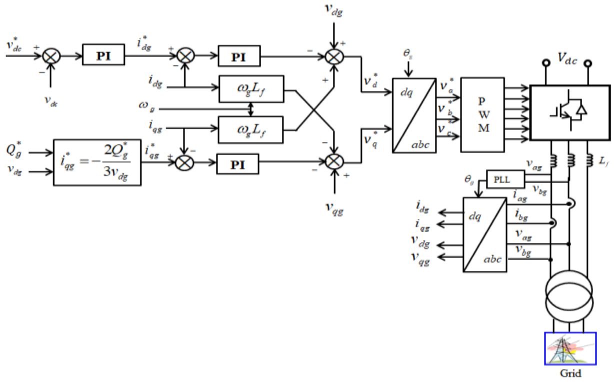


Figure 3. Generic microsource structure



(a) Islanded mode



(b) Grid connected mode

Figure 4. Converter control in islanded and grid connected modes

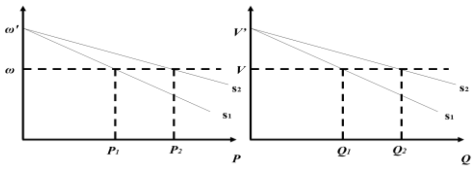


Figure 5. Conventional Droop characteristics in AC microgrids

C. Tertiary level/Grid level

Tertiary level is the highest layer of control in grid connected MGs which operates at the lowest timescale. It is responsible for [19], [24];

1. Managing economic and optimal operation between a MG and utility grid.
2. Facilitating bidirectional power flow between main grid and MG.
3. Optimising dispatch of DERs.
4. Providing load balance in a local power distribution network.
5. Detecting islanding conditions for disconnecting MG with the main grid.

Tertiary control is discussed in more detail in section IV.

IV. REVIEW OF CONTROL TECHNIQUES

Table 1 has been formatted for summarising several control techniques implemented in literature at each hierarchical level. They have been classified into three layers of hierarchical MG control with their main features highlighted.

A. Primary level

Droop-based techniques: It can be seen from table 1 that DG units with non-controllable primary energy (PV, wind) can be controlled with alternate versions of conventional droop algorithms as proposed in [25], [26], [27], [28], [8]. Several of these techniques have been described below;

i. A harmonic-based multidimensional droop control strategy for optimising P, Q power sharing in hybrid MGs is realised in [9]. It uses harmonic-based droop for the DC MG, and 3-D based droop for the AC MG. These have been represented by (8) and (9);

$$f_h = f_h^{max} - K_h^{dc} P_{dc} \tag{8}$$

$$Q_{I'c} = \beta(V_{ac}^{max} - V_{ac}) + |Z_{vir}^{VSI}| * |I_{ac}|^2 \tag{9}$$

ii. where f_h is the dominating frequency, f_{max}^h is its upper limit, K_{dc}^h is the $P - f_h$ droop gain, β and Z_{vir}^{VSI} are droop coefficients of VSI's output V and I respectively, and V_{ac} is the estimate of common bus voltage. By using multi-purpose 3D droop for ICs and optimally tuning 3D droop gains, circulating currents/reactive power among parallel ICs in hybrid MGs can be reduced.

iii. $(V - I)$ Droop is used in a DC MG for regulating output voltage in [25]. Measured output converter current (I)passes through a virtual resistance (R) and is fed to the input of controller for voltage regulation. The output voltage (V) is then given by (10);

$$V = V' - I * R \tag{10}$$

where V' is the no load voltage.

iv. Angle-based droop uses voltage angle and magnitude to regulate P and Q, respectively. It can be represented by (11) and (12) [27];

$$\delta_i = \delta_{rated} - m(P_{i,rated} - P_i) \tag{11}$$

$$V_i = V_{rated} - n(Q_{i,rated} - Q_i) \tag{12}$$

where δ_{rated} is rated voltage angle, V_{rated} is the rated voltage of DG, and m and n are droop coefficients. This technique has superior performance in controlling power flow and frequency than conventional droop method however, high gain selection can lead to unstable MG operation.

v. It was already established earlier that $(P - \omega)$/ $(Q - V)$ droop methods represented by (5) and (6) achieve efficient output voltage and power sharing under nearly inductive line impedances$(X > R)$. However, in low voltage DC MGs where $R > X$, an inductor can be added in series to reduce the effect of parasitic resistances as proposed in [28]. The result is accurate reactive power sharing achieved in DC MGs.

Non-droop-based techniques: As established earlier, MG architectures incorporating parallel converters can use centralised or decentralised non-droop-based methods for achieving accurate power sharing under transients and various load conditions [29], [30], [31]. Some of these methods have been presented below:

i. Central-limit control (CLC) strategy is described in [29] which uses weighting functions to determine current share of each power converter for regulating V and f. A central controller determines the set points of converters based on total load current measurement. For CLC to work, sum of weightages must equal unity however, under varying system conditions when this is not possible, new and improved approach towards CLC has been proposed in [30].

ii. The distributed control method (DCM) in [22] and [31] applies to parallel converters which uses a remote central controller. V regulation and fundamental f power sharing is achieved via low-bandwidth communication signalling, whereas high frequency components are locally regulated to zero. Advantages of DCM include high voltage balance and elimination of circulating currents during transients.

iii. Average-current sharing control technique is used for sharing equal load current among parallel converters in [32], and [33]. Each converter is controlled independently and reference average values of currents and voltages are shared using a common current sharing bus and voltage-reference synchronisation.

B. Secondary Level

Centralised methods: Centralised secondary control is characterised by remote location of central processors, away from the microsources [19],[34]. Some of the control techniques realised under this classification have been described below:

i. Complex islanded hybrid MGs incorporating non-linear loads and renewable energy resources can use master-slave control strategy as described in [35]. Master-slave strategy picks a strong micro terminal (master) to provide V and f set-points to other micro terminals (slaves). As this strategy heavily relies on communication and a single master source to share the load among micro terminals, reliability of a MG can be severely affected under fault conditions [36].

ii. AI-based energy management methods for optimising MG and microsources operation have been used in [37] and [38]. Fuzzy interference system (FIS) is used in [37] for minimising grid fluctuation (P_{grid}) and increasing energy storage life-cycle (P_{ess}) of a hybrid MG by deciding charging/discharging patterns. Reference [38] proposes a power management system comprising of Fuzzy logic (FL) and Neural network (NN) for controlling power flow in DC MG, and extracting maximum power from renewable resources in grid-connected mode. Controllers based on FL or NN are highly reliable as they can evolve and control systems with no models.

Decentralised methods: Decentralised secondary control relies on local information for making control-related decisions. It provides highest possible autonomy to each DER unit and load by using distribution network operator, MGCC and local/microsource controllers [14]. MGCC coordinates the operation of DERs and regulates P, Q and f fluctuations by communicating with local controllers. Examples include;

i. MAS techniques, which rely on several intelligent agents for achieving coordination in large power systems. One such implementation is presented in [39], which uses agents to model each production and consumption source for optimising energy and production cost. The control strategy is formulated by means of an optimisation problem whereby the objective is to minimise the Euclidean distance between consumption and production at any given time instance, t.

ii. MPC-based decentralised control strategy, which minimises a cost function associated with models of each MG component and their limitations over a finite number of future time steps as in [40] and [41]. MPC-based distributed coordination algorithm for several networked MGs can be used to achieve practicable energy plan at any time step.

iii. Other distributed secondary control techniques such as decomposition, consensus, peer-peer or multi-mode control, which are also being actively used for solving MG problems of;

   a. Minimising operational costs by dividing the optimisation problem into sub-problems [42].
   b. Balancing voltages and currents in DC MGs, whereby adjacent DERs communicate in real-time over a connected network for achieving global superior performance [43].
   c. Supporting bus V and f in islanded MGs, whereby each micro terminal utilises local information to support system parameters based on droop characteristics [36].

C. Tertiary level

Reference [44] proposes communication-based master slave-peer-peer integration control strategy for renewable-based MG. The control objectives are to smoothly switch between MG operative modes and achieve steady operation. When the communication system fails, MG runs under peer control strategy. Under normal operation, MG is able to regulate P, Q, f and power distribution system of ESS while ensuring stable MG operation. These functionalities can also be realised with the help of a tertiary control compensator as proposed in [45], which measures P and Q at the PCC and compares them with the desired values for power exchange between the MG and main grid. It should be noted however, that MG control and integration of renewable-based DERs, in general, present several unique operational challenges which need to be dealt with for enhancing system reliability and harnessing full potential benefits of DGs. These include [46], [47], [14];

- Power quality issues due to lack of power standards in isolated systems
- Stability issues arising from interaction of several control systems designed for multiple microsources
- Frequency deviation issues due to low inertia of electronically-interfaced DG units
- Interconnection issues due to lack of clear policies regarding renewable-based DERs
- Increased distribution feeders' protection requirement issues due to bidirectional power flows between MG and main grid

TABLE 1. REVIEW OF CONTROL TECHNIQUES

Layer	Control Method	Main features (Inputs/Outputs/Comments)	Ref.	Layer	Control Method	Main features (Inputs/Outputs/Comments)	Ref.
Primary	Adaptive primary droop	**Inputs:** Normalised V, f **Outputs:** Impedance angle ($\emptyset$), active power control index (ΔP) **Comments:** Complex algorithm	[8]	Secondary	Master-Slave	**Inputs:** $P, Q/V, f$, state-of-charge (SOC) of batteries, $V_{battery}, V_{dc}$, **Outputs:** Instructions for each device **Comments:** Novel energy management method, MGCC controls master inverter which controls slave inverters.	[35]
	Angle-based droop	**Inputs:** P, Q **Outputs:** ($\Delta Vcref, \Delta \delta ref$) **Comments:** Accurate P, Q sharing, but, high value of droop gain affects stability	[27]		FL	**Inputs:** $P_{Balance}, SOC$ **Outputs**: $P_{ess,FIS}, P_{grid,FIS}$ **Comments:** Reduced P_{grid} and increasedP_{ess},	[37]
	Harmonic-based 3D droop	**Inputs:** DC V harmonic frequencies, 3D droop at AC side **Outputs:** Regulated P, Q sharing **Comments:** Robust control, 91% circulating currents eliminated	[9]		NN	**Inputs:** Parameters of MG components **Outputs:** P, Q of inverters, V_{dc}, ESS and other output parameters **Comments:** Tracked MMPT, regulated P, Q flow, minimised purchased energy, optimised utilisation of ESS but, with complexity	[38]
	(V-I) droop	**Inputs:** I through virtual R **Outputs:** V, P in DC MGs **Comments:** Simple control, but, hard to maintain P at fixed level	[25]		MAS	**Inputs/Outputs:** Minimise Euclidean distance between consumption and production **Comments:** Four agents assigned to each element of MG, consumption followed production, reduced battery requests	[39]
	Virtual impedance loop-based droop	**Inputs/Outputs:** I_{shared} of converters with inductive virtual impedance $Z_D(s)$ and open-loop amplitude correction **Comments:** Accurate P, Q sharing achieved for low voltage MGs ($R > X$)	[28]		MPC	**Inputs/Outputs:** Multi-variable control problem e.g. planning horizon, prediction horizon, etc. **Comments:** Novel MPC approach for networked MGs	[40], [41]
	CLC	**Inputs:** Weighting functions, total load I **Outputs:** Regulated V and I **Comments:** Accurate regulation, but, system affected by component aging and ambient conditions	[29], [30]		Distributed techniques	**Inputs/Outputs:** Multi-variable control optimisation problems **Comments:** Flexible problem formulation, but, subject to information availability in MG applications	[42], [43], [36]
	DCM	**Inputs:** Common bus V and I **Outputs:** I_{shared} communicated to DGs **Comments:** Control consists of distributed hierarchy (CCs and LCs), high V balance, circulating currents eliminated	[22], [31]	Tertiary	Master-slave & peer-peer control	**Inputs/Outputs:** Multi-variable control problem **Comments:** Combines advantages of master slave and peer-peer controls, smooth switching achieved between MG operative modes	[44]
	Average-current sharing	**Inputs:** $I_{inverter}, V_{ref}$ **Outputs:** Average output value of I_{ref} **Comments:** Control scheme consists of three loops; a)V, b) inner-I and c) outer-I	[32], [33]		Compensator	**Inputs:** MG V and I **Outputs:** $V$and I synchronised, exchanged P, Q with main grid **Comments:** Improper operation leads to large unbalanced I flowing along interconnecting feeder	[45]

V. CONCLUSION

MGs are seen as means of integrating DERs, particularly renewable, for supplying clean energy. Integration and intermittency of DERs pose challenges which need to be mitigated using a layered combination of control and supervisory commands. Therefore, this paper presented an overview of several trends in MG hierarchical control. Several droop and non-droop based control principles in primary, and multiple centralised and decentralised control principles in secondary control were discussed in MG. It was also mentioned that tertiary control is used when a MG is connected to the main grid for ensuring optimal and economic operation however, various issues pertaining to MG control and integration of renewable DERs need to be addressed for maximising MG benefits.

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