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Unbalance mitigation strategies in microgrids

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A.S. Vijay[1], Suryanarayana Doolla[1] ✉, Mukul C. Chandorkar[2]
[1]*Department of Energy Science and Engineering, IIT Bombay, Powai, Mumbai, India*
[2]*Department of Electrical Engineering, IIT Bombay, Powai, Mumbai, India*
✉ *E-mail: suryad@iitb.ac.in*

Abstract: Unbalance or asymmetry in the distribution network is a well-known power quality issue. In the modern active distribution system, with the increasing penetration of renewables, this phenomenon becomes more pronounced. In the context of microgrids (MGs), several works have been proposed for the management and mitigation of the unbalance, for both the sharing of unbalanced load and maintaining the voltage quality in the islanded mode and for the control of distributed generators in the grid-connected mode during unbalanced conditions. This study comprehensively reviews, summarises, and classifies the various strategies of the unbalance mitigation techniques for the islanded and grid-connected modes of operation for three-phase MGs and presents the possible challenges and avenues for future investigations on the topic.

1 Introduction

Increasing concerns of global warming and higher energy demands have led to the integration of renewable energy sources in the grid. These systems are typically integrated at the medium and low voltage (LV) levels, i.e. at the distribution level. The power quality of these active distribution networks and microgrids (MGs) is an important aspect [1, 2]. A system is said to be unbalanced if either the currents or voltages or both of any phase in a three-phase system are not the same in magnitude or phase difference or both (the system is also said to be asymmetrical or imbalanced). From an operator's point of view, a balanced system at all times is advantageous both in terms of efficiency and protection. Unbalance can be viewed to be caused by two reasons: (i) structural and (ii) operational [3]. The distribution system is inherently unbalanced as the lines are not transposed – which is a systemic/structural issue. The transformer connections and wiring structure: three-wire or four-wire, both of which are structures, have a vital role in the nature and propagation of unbalance voltages and currents [4]. The operational/functional aspect is due to the presence of single-phase loads in the distribution system, which further adds to the degree of unbalance. Also, renewable energy sources can be integrated across all three phases or only at a single phase of the system which aggravates the issue. Unbalance, beyond a limit, leads to unwanted effects such as increased losses in the system, deteriorated voltage profile, stresses on distribution transformer, malfunctioning of protection equipment, adverse effects on sensitive loads, rise in neutral currents and neutral-ground voltage and power oscillations [5]. Owing to these problems, various standards by several organisations to limit the degree of unbalance have been proposed, which have been summarised as shown in Table 1. As can be seen, the degree of unbalance is measured using various indices in different standards such as voltage unbalance factor (VUF), phase voltage unbalance rate (PVUR), line voltage unbalance rate (LVUR), average percentage voltage unbalance (VU) etc. [6]. However, newer definitions such as complex VUF, unbalance factor, unbalanced over/under and equal voltages, maximum and total deviations, phase difference rate (for imbalance quantification in the angle differences), percentage unbalance, approximation functions etc. are used [3]. These definitions can be used for the currents as well. Predominantly, the International Electro-technical Commission (IEC) proposed a standard that negative sequence (NS) VU factor (VUF) should be <2%, while the Institute of Electrical and Electronic Engineers (IEEE)-1547 standard proposes a VU limit of $\pm 3\%$ nominal magnitude and phase displacement to within $\pm 3°$ in case of a neutral connection.

Table 1 Summary of standards pertaining to unbalance

Standard	Limit	Calculation
IEEE Std. 141-1999	<2 to 2.5%	% VUF-true, definition, % unbalance
IEEE Std. 1547-2018	$\pm 3\%, < \pm 3°$	deviation, phase displacement
IEEE Std. 446-1987	<2.5 to 5%	% PVUR
	5–30% (load unbalance)	
IEEE Std. 112-2017	<0.5%	% imbalance
IEEE Std. 1159-2009	<3%	%VUF
IEC 61000-2-2	≤2%	%VUF
ANSI C84.1	≤3%	%VUF
EN 50160	≤2%	%VUF
NEMA MG 1-1993 CGC, India	<1%	LVUR
	≤3%	<132 kV, % imbalance
	≤2%	<220 kV, % imbalance
	≤1.5%	>400 kV, % imbalance

IEC, International Electro-technical Commission; IEEE, Institute of Electrical and Electronic Engineers; ANSI, American National Standards Institute; NEMA, National Electrical Manufacturers Association; EN, European Standards (norms); CGC, Central Grid code.

In the context of MGs, the issue of unbalance can be viewed from the mode of operation of the system – unbalance in the islanded mode and unbalance in the grid-connected mode. Conventionally the problem of unbalance was mitigated in the distribution network by over-sizing the conductors and equipment (to handle the larger currents during unbalance) employing tap changing transformers, reactive power injection devices to improve the voltage profile such as capacitor banks, active and passive filters. With the advancements in voltage source converter (VSC) technology, compensators such as static synchronous compensators (STATCOMs), unified power-quality conditioners, and dynamic voltage restorers (DVRs) were employed [7]. These could also provide additional support in terms of harmonic and reactive power compensation. However, these additions are costly and are effective only when the issue is concentrated at a particular node. With the distributed generation (DG) integration in the network today these may not be an efficient solution. Hence, the state-of-

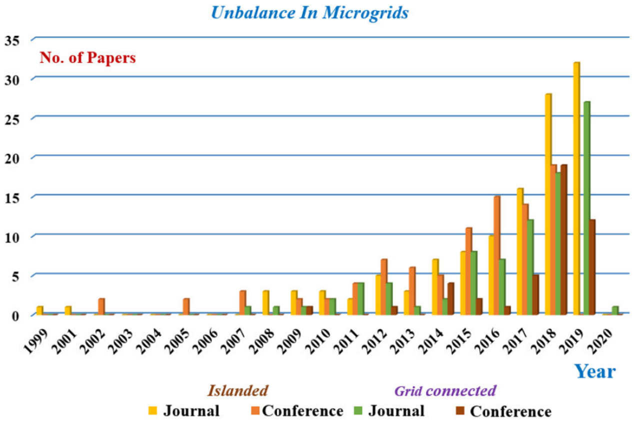


Fig. 1 *Year-wise publications on unbalancing mitigation in MGs: journals (Journal) and conferences (Conference) for both the islanded and grid-connected modes of operation)*

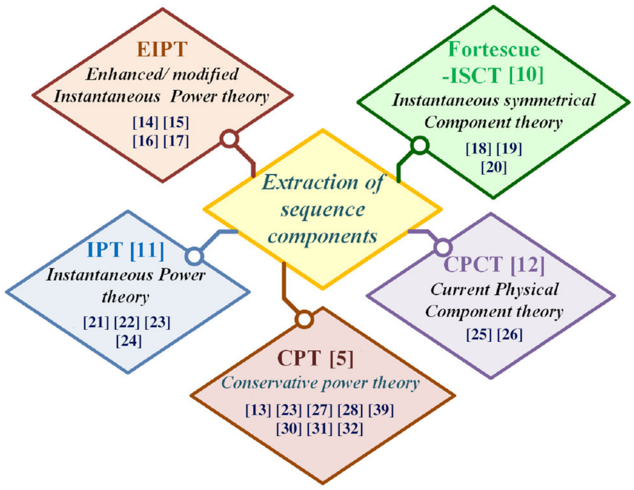


Fig. 2 *Approaches for extraction for symmetrical components in unbalanced systems*

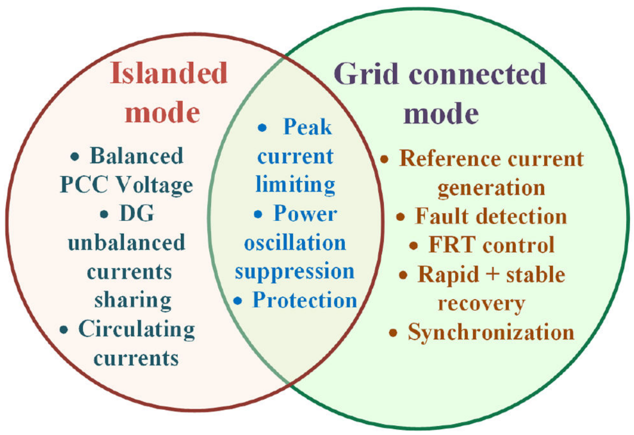


Fig. 3 *Challenges in MGs under asymmetrical conditions*

the-art is to use the available capacity of the DGs themselves to mitigate the issue (multi-functional capability). Again, these multifunctional units can be classified according to their control strategies into voltage control (VC), current control (CC), and hybrid control (HC) [8] depending upon the mode of operation. The management and mitigation of unbalances in the modern distribution system have been a hot spot for recent research as can be seen in Fig. 1, which shows the year-wise publications which clearly shows an increasing trend.

Various control techniques have been proposed by researchers around the globe to manage the unbalance issue. Initially, studies were focused on unbalance management at the converter level. The unbalance compensation issue was initially investigated by Charles P. Steinmetz in 1917 [9], and a year later the Fortescue symmetrical component theory [10] was proposed. For linear circuits, the superposition principle provides the opportunity for individual sequence control of these components. Most literature on unbalances is based on this concept, with several strategies being proposed for the effective (fast and accurate) extraction of these components for the control. Some power decomposition theories such as the instantaneous reactive power theory [11] (and its modifications), the current physical component theory (CPCT) [12], and the conservative power theory (CPT) [13] have been proposed over the years for defining the components of the currents/powers for control. Fig. 2 presents these approaches which are currently being employed for the component extractions to achieve unbalance mitigation. Furthermore, the control can be executed in any of the three frames: the natural *abc* reference frame (NARF), the α–β stationary reference frame (STRF) or the *dq* synchronous reference frame (SRF). The quantities in the former two frames are sinusoidal and thus need proportional–resonant (PR) or proportional–integral–resonant (PIR) controllers, while the quantities in the SRF are DC and thus need proportional–integral (PI) controllers. Most of the works use the decoupled dual SRF (DDSRF) for separately controlling the positive sequence and NS components, wherein two frames of reference in the opposite directions along with filters are used for the component extraction. Often along with the unbalance mitigation, multiple parallel controllers are employed in appropriate reference frames for the harmonic mitigation as well. For the grid-connected case, a phase-locked loop (PLL) is essential and several methods to separate the positive sequence and NS components of the AC grid voltages were proposed [33]. The various challenges that need to be addressed for both the operation modes under unbalanced operation have been summarised in Fig. 3. This study focuses on the aspect of unbalance management in MGs and is a first attempt to comprehensively classify and summarise the various attempts proposed in the literature on the aspect. The main motivation is to provide the readers with the different approaches proposed until now for unbalance mitigation and list down the avenues for further work. The organisation of the paper is as follows: Section 2 categorises and discusses the various schemes for the unbalance management in the islanded mode of operation. Section 3 discusses the schemes for unbalance mitigation and fault ride-through aspects for the grid-connected mode of the MG. The discussion is presented in Section 4 wherein challenges and avenues for future work are highlighted. Section 5 concludes the paper.

2 Unbalance mitigation in the islanded mode

The objective of the unbalance compensation or mitigation depends upon the conditions of the MG and the operating mode (islanded or grid-connected). Unbalance mitigation in islanded MGs [18, 21, 22, 23, 25, 27–32, 34–218] focuses either on current unbalance or VU mitigation in the MG lines, depending on which quantity would congest the network. Accordingly, the control would be directed towards better power distribution across the three phases of the DGs, i.e. on a better unbalance sharing between multiple DG systems or maintaining balanced voltages (good voltage quality) at the point of common coupling (PCC). Various approaches have been proposed such as modified droop control strategies, modified topologies, use of virtual impedance (VI) and advanced control techniques for addressing the issue. This section elaborates on the unbalance mitigation approaches for the islanded mode of operation, in which the DGs are controlled in the VC mode. The predominant issues in this mode are overloading of the DGs due to over-currents in the phases, unbalanced voltages at the PCC, high-circulating currents, disproportionate power-sharing among DGs and power oscillations. Major research focuses on maintaining the PCC voltage balanced under unbalanced loading conditions. In the islanded mode, the strategies can be broadly classified into (a) injection of compensatory NS voltages/currents/combination of both and (b) use VI/conductance control for overcoming the line parameter effects to ensure proportional power-sharing, and (c) improved damping in the control. The compensation of unbalance components always results in alteration of the NS currents and thus there exists a compromise between the good PCC voltage quality (balanced voltages) and accurate unbalanced powers/currents sharing. Thus the DGs must be controlled with both the aspects of proper power sharing and good power quality. Some strategies, therefore, apply secondary and tertiary control loops based on communication to achieve enhanced performance across the system.

2.1 Droop modifications

Works have been reported which modify the conventional droop control to achieve enhanced performance under unbalanced conditions. The research in [34] proposed a triple droop strategy (three voltage-real power (V versus P)) for each phase in LV MGs resulting in accurate unbalanced current injection and minimal circulating powers. The strategy proposed in [35] uses a frequency droop control with an additional disturbance and VI to handle unbalances. The drawback is that it is assumed that the load is fixed and that the lines are inductive. A NS reactive power versus conductance (Q versus G) droop control has been discussed in [36], which can be integrated easily with the existing droop control to achieve unbalance mitigation. An enhanced droop-based approach is proposed in [37], which appends a V_{dc}-based loop to the conventional frequency versus real power (ω–P) droop for improved performance under asymmetrical conditions. An adjustable per-phase droop control in real-time (RT) with no-load voltage adjustment and improved reactive power versus voltage (Q versus V) droop is discussed in [38] to restrain the impact of voltage asymmetry. Liu *et al*. [39] proposed a small signal-based unbalanced power droop strategy for the mitigation along with the use of adaptive VI. A droop strategy based on the summation of individual phase powers for four-leg inverter-based systems with VI is shown to achieve good performance under unbalanced and non-linear loads in [40]. The NS conductance versus NS reactive power (G versus Q) droop with a NS current controller and adaptive VI is discussed in [41], which achieves minimised circulating current. The virtual conductance is drooped over the NS reactive power along with an *ad hoc* communication network in [42]. A new droop control for four-leg inverters using voltage angle control for per-phase real power-sharing in the unbalanced condition is discussed in [43]. Two conductances to control power and VU with the (G versus Q) droop with coordinated operation between inverters is discussed in [44].

2.2 Modifications in converter topology

Typically in LV MGs, two-level three-leg and four-leg inverters are used. These can be modified to enhance performance under unbalanced conditions. Full bridge converter modules are proposed in [45] that can independently inject series voltages into each phase to mitigate unbalances. The four-legged voltage source inverter (VSI) is completely decoupled into three buck-converters through analogue controllers in [46], which allows independent control over the phases. A four-switch inverter topology with a Lyapunov function-based non-linear controller with equal sampling and switching frequency is discussed in [47]. A distribution static compensator (DSTATCOM) with a small AC capacitor connected between the negative DC bus and system neutral in [48] is shown to achieve better unbalance compensation. On similar lines, the DC link negative is connected to the neutral of the inductor–capacitor (LC) filter along with a modified control strategy in [49] resulting in better performance under unbalances at the cost of higher stresses and device ratings. A new concept and approach for topology control and switching based on near-optimal per-phase topology control are discussed in [50], which proposes an approach to coordinate smart plug-in electric vehicle charging to mitigate unbalances. Special winding connections for distribution transformers for DSTATCOMs with a sequence component-based feedback controller are proposed in [51]. A dual-output inverter operated in equal frequency mode with a lesser number of semiconductor switches is used to mitigate unbalances in [52]. A new algorithm is developed and tested for its performance on three different topologies for its performance under six different types of voltage sags at the PCC in [53]. A per phase optimised control strategy for a modified three-phase inverter is proposed in [54] to achieve VU mitigation.

2.3 Control strategies

Among the early efforts to control the negative and zero sequence components in a single inverter system were attempted in [55–57], which proposed a DDSRF employing PI controllers for the positive sequence and NS component control, and PR control for the independent zero-sequence voltage regulation. Notch filters (with a notch at twice the fundamental frequency) were suggested for the component extraction and the results showed suppressed DC-link oscillations. The evaluation of a CPT-based four-leg compensator is discussed in [5]. The coordinated control of three- and single-phase inverters is suggested in [9] for a master–slave MG architecture system to assign compensation tasks among the DGs. Enhanced control with the three-phase droop control strategy which provides good performance under both unbalanced and non-linear loads is proposed in [58], which aims to control the circulating currents and minimise the DG synchronisation transients as well. A model predictive control (MPC) technique that results in faster dynamics and higher damping under unbalanced conditions based on global positioning system synchronisation is proposed in [59]. The research in [60] discusses a linear quadratic control approach that enables unbalanced local load powers can be shared with utility in any desired ratio. The strategy proposed in [61] achieves compensation through the multiplication of the fundamental NS reactive power with a constant unbalance compensation gain. A strategy for NS impedance control (NSIC) is proposed in [62] for sharing NS currents which assume that the load information is available through a phasor measurement unit. Dynamically varying limits for positive sequence and NS currents are proposed in [63], which ensure that single line to fault currents are limited to 1.5 p.u. Another secondary control scheme which discusses the stability aspects is presented in [64]. The combination of deadbeat and repetitive control with feed-forward terms to mitigate load dynamics impact is discussed in [65]. A dual-loop control method based on predictive CC is proposed in [66], which eliminates the need for coordinate transformations. Compensation control based on a Lagrangian function to extract factors for compensation with the aim to reduce to reduce real power oscillations and VU is explained in [67], which validates results for different inductive impedance–resistance (X/R) ratios of the lines. A consolidated control scheme to minimise real power oscillations caused due to unbalance is proposed in [68]. A voltage-based droop (VBD) control strategy with a negative damping resistance is discussed in [69] for phase unbalance mitigation, which highlights that for VU issues negative damping may lead to instability.

A load unbalance compensator including its control algorithm is discussed in [70] for three-phase four-leg inverters. A strategy for independent control of the fourth leg of a four-leg grid forming VSC is proposed in [71], which uses multiple second-order generalised integrators (SOGIs) for component extraction. Another work [72] based on SOGIs and low-bandwidth communication (LBC) for unbalance mitigation presents results for unbalanced and non-linear load cases and the effect of communication delay on the control outcome. A linear parameter varying controller based on Fortescue component extraction is discussed in [18] using the voltage-oriented control (VOC) approach. A novel control strategy to reduce real power oscillations under unbalances using a redundant interlinking converter for hybrid AC/DC MGs is proposed in [73]. A centralised control of single-phase inverters in four-wire MGs based on CPT is explained in [27], which does not need the line and load information for the compensation. A decentralised sliding mode control (SMC) based on Lyapunov function theory and fractional order SMC based on neural networks is suggested for compensation in [74]. A tunable sequence impedance control strategy for four-leg converters is proposed in [75], which considers the zero-sequence components in the unbalance mitigation. A harmonic and NS CC technique is

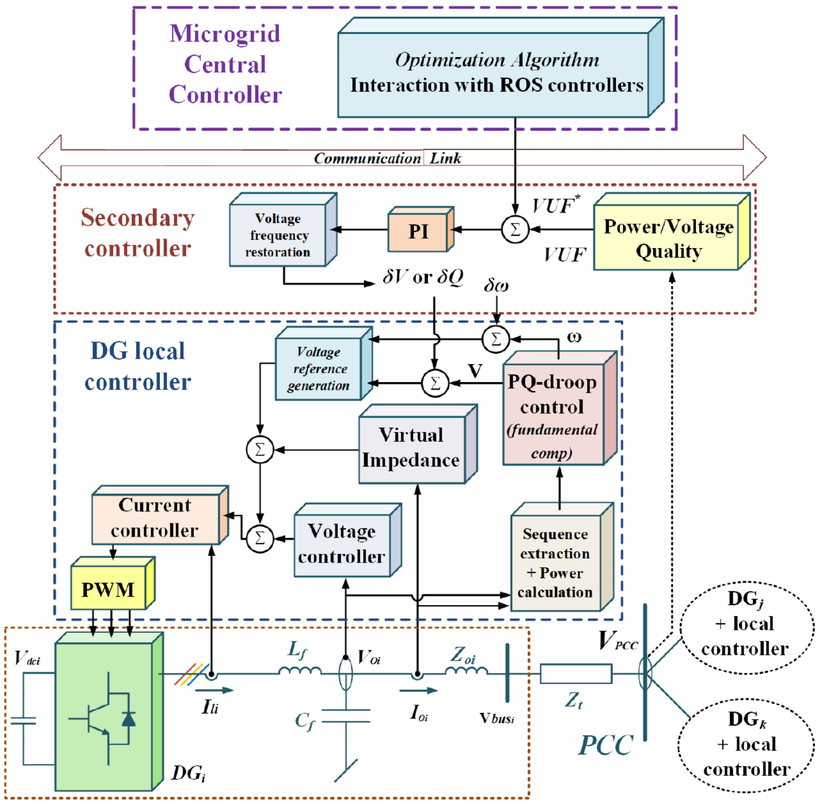


Fig. 4 *Block diagram of a typical control scheme for addressing the issue of unbalance in the islanded mode (involving communication)*

explored in [76], which uses multiple PR controllers along with harmonic impedance and virtual NSIC loops. The coordinated control of multifunctional inverters for unbalance and harmonic compensation is discussed in [77], which investigates the effect of communication delay. A hybrid AC/DC MG hierarchical control scheme based on SMC Lyapunov function theory and harmonic VI is discussed in [78]. A multi-input multi-output control strategy based on the internal model principle and enhanced PLL (EPLL) is discussed in [79] to achieve better performance. A decentralised MPC-based scheme for VU mitigation is proposed in [80], wherein the results are compared with a robust controller as well. A control scheme with the capability to independently regulate powers in the phases is discussed in [81], which uses a new transformation (*x–y* frame). An expert system based on decoupled power/current decomposition employing CPT-based indices is investigated for its performance under unbalanced conditions in [28]. A robust controller for the unbalance case designed using linear matrix inequalities is discussed in [82] based on the load current availability assumption. Single-phase inverter units are controlled independently to achieve unbalance mitigation in [83].

A typical control scheme for addressing the issue of unbalance in MGs is as illustrated in Fig. 4 which is based on communication architecture. As is shown, the fundamental positive sequence droop control is typically augmented with a VI control scheme at the local level. Based on the PCC voltage quality measurements, compensatory actions are taken by the secondary and tertiary control loops at regular intervals to maintain a good voltage quality. An analytical approach has been proposed in [84] to assess the load ability of the network under unbalanced conditions, which suggests injection of reactive power to counter the effect of unbalance in the heavily loaded phases. A robust control strategy based on the H_∞ optimisation is proposed to control unbalance in [85], which assumes that the load current is measurable and bounded. The compensation for unbalance and harmonics using a modified VI is discussed in [86], which elaborates on the comparison of impedance models of the DGs under various controls. A tertiary control strategy using a tertiary compensation gain is proposed in [87] for unbalance compensation based on optimisation (genetic algorithm) for mitigating the VU issue. An adjustable VI with a variable harmonic impedance loop at harmonic frequencies is discussed in [88] for improving the power quality and power-sharing among DGs. A unified mathematical model of a DG with control aspects is elaborated upon in [89], which also suggests a new definition for the instantaneous reactive power. To mitigate the voltage regulation problem in LV networks with high photovoltaic (PV) penetration, work in [90] proposes an optimal reactive power control strategy, which assumes the presence of two-way communication in the system. A state observer-based disturbance estimation and control algorithm is discussed in [91], which improves performance under non-ideal conditions. A sequence-based control strategy is discussed in [92], which uses six PI controllers in the SRF to nullify the NS and zero sequence voltages at the PCC. However the tuning of the controllers is a challenge. Castilla *et al.* [93] discussed the modelling and design of voltage support control schemes in which the small-signal model of the sequence extractor has been described. However, the zero-sequence components have not been considered. A new control based on decoupled real and reactive power control of individual phases is proposed in [94] using a three-phase four-leg VSI, which provides six degrees of freedom. A hybrid controller structure incorporating MPC and SMC with a reduced chattering issue for a four-leg inverter for unbalance mitigation is discussed in [95]. An adaptive neuro-fuzzy inference system-based control strategy is discussed in [96] for unbalance compensation, which uses a delayed signal cancellation approach for sequence extraction.

A distributed virtual NSIC based on consensus algorithm is used to suppress circulating currents and achieve better unbalance compensation in [97], which does not require the line impedance estimation. An active power oscillation cancellation strategy based on coefficients using secondary controls is discussed in [98] for parallel interlinking flow converters in a hybrid MG. The control strategy for a virtual synchronous generator (VSG) for maintaining balanced currents is proposed in [99]. A coordinated control strategy for dual converters (one operated in voltage control mode and other current control mode) using a negative VI is proposed in [100] for unbalance mitigation. A high-performance second-order controller for balanced VC using the robust negative imaginary approach is presented in [101], which shows superior performance over MPC and linear quadratic regulator (LQR) controllers and provides stable performance under large parameter variations.

Weighted values of currents are calculated for a HC for instantaneous torque and power control in [102], which showed good performance under asymmetrical conditions. A two-stage adaptive virtual resistor control scheme employing three nested loops for enhanced control under unbalances is discussed in [103]. A SMC-based approach for a master–slave converter system is shown to have a black start, seamless mode transition, and good performance under unbalances in the work presented in [104]. A CPT-based cooperative control employing a secondary control loop and a more robust VI loop is proposed in [29] for unbalance and harmonic power-sharing. The model, analysis, and suppression strategy for zero-sequence circulating currents for paralleled inverters is discussed in [105]. A strategy to enhance the neutral current compensation for four-leg inverters has been proposed in [106], which is shown to achieve better unbalance sharing. An approach to minimise unbalances in the system considering demand-side management capability using thermostatically controlled loads is discussed in [107] with a NS compensation loop for the control. A SMC strategy using hysteresis switching that eliminates the need for sensing capacitor voltage for a VSI is elaborated in [108], which achieves robust performance under unbalances.

Tables 2 and 3 summarise the various approaches suggested in the literature for unbalance mitigation and control in the islanded mode of operation of the MG. The references have been classified according to the control strategy, reference frame, and details of the test systems. A NS voltage component suppression strategy based on adaptive VI is discussed in [109] with a fractional frequency harmonic control strategy for harmonic mitigation too. The simultaneous regulation of positive sequence and NS voltage is achieved in [110] for a STATCOM, which uses line frequency switching. An unbalanced SRF regulator is discussed in [111] that is shown to have a higher stability margin than the PR controller. A distortion-free saturation methodology for limiting the currents/voltages is discussed in [112], which is an important aspect under unbalanced conditions. A CPT-based strategy for improved unbalanced load sharing is discussed in [30], which is validated on a hardware-in-loop (HIL) platform. An instantaneous power theory (IPT)-based strategy with the combined use of energy storage (electric spring) is described in [21], which is aimed at minimising the average oscillating power under unbalances. A radial basis function neural network-based hierarchical VI-based control scheme with a complementary control loop for small and large signal stability enhancement is discussed in [113]. Mortezaei *et al.* [31] used CPT to achieve enhanced performance under VUs and to achieve harmonic mitigation. Over voltage and VU mitigation are achieved through a three-phase damping control strategy in [114]. A minimally switched active power filter (APF) control method to compensate voltages under unbalanced and non-linear loads is discussed in [115], which results in reduced losses. A flexible control methodology based on isochronous control, which enables precise regulation of the output voltages and frequency of four-leg inverters is proposed in [116]. A SMC along with iterative learning control for compensation in four-leg inverters as discussed in [117]

Table 2 Summary of works for unbalance mitigation: islanded mode

Ref.	Communication	Ref. frame	Controller	Filter	Voltage level	Power level	Expt. Results
[5]	✗	STRF	PR	L	600 V	—	✓
[34]	✗	NARF/SRF	PR(out) PI(in)	LC	400 V	—	✗
[36]	✗	DDSRF	PI	LC	220 V	1 kW	✓
[38]	✗	SRF	PI	LC	—	—	✓
[40]	✗	STRF	PR(out) P(in)	LC	380 V	—	✗
[42]	✓	STRF	PR	LC	415 V	—	✗
[44]	✗	—	—	LC	380 V	50 kVA	✗
[46]	✗	SRF	PR(out) P(in)	LC	110 V	5 kW	✓
[48]	✗	—	—	L	400 V	—	✓
[50]	✗	STRF	—	—	415 V	—	✗
[52]	✗	NARF	PR	LC	170 V	—	✗
[54]	✗	—	—	LC	—	—	✗
[56]	✗	DDSRF	PI	L	—	—	✓
[58]	✗	STRF	PR	LC	220 V	1.5 kVA	✓
[60]	✓	—	—	—	11 kV	—	✗
[62]	✗	STRF	PR	LC	—	2.5 MVA	✗
[64]	✓	STRF	PR + PI	LC	230 V	—	✗
[66]	✗	STRF	PR	LC	110 V	5 kW	✓
[68]	✗	DDSRF	PI	LCL	100 V	5 kVA	✓
[70]	✗	DDSRF	PI	LC	380 V	250 kW	✓
[18]	✗	—	proposed control	LC	200 V	1 kW	✓
[27]	✓	—	proposed control	LC	$180 V_{pk}$	—	✗
[75]	✗	STRF	PIR(out) P(in)	LCL	220 V	—	✓
[77]	✓	STRF/SRF	PI + PR	LCL	230 V	—	✓
[79]	✗	SRF	PI	LC	4.16 kV	—	✗
[81]	✗	*x–y* frame	PI	LC	—	—	✓
[82]	✗	SRF	proposed control	LC	600 V	—	✗
[84]	✗	—	—	LC	—	—	✓
[86]	✗	SRF	PI + MPR	LC	350 V	—	✓
[88]	✓	STRF	PI + MPR	LCL	380 V	—	✓ HIL
[90]	✗	—	—	LC	415 V	—	✓
[92]	✗	SRF	PI	LC	$300 V_{pk}$	10 kVA	✓
[94]	✗	NARF	proposed control	L	100 V	—	✓
[96]	✗	SRF	PI	LC	−230 V	—	✓
[98]	✓	STRF	PR	LC	100 V	1.25 kVA	✓
[100]	✗	STRF	PI(out)PR(in)	LC	300 V	—	✗

Ref.	Communication	Ref. frame	Controller	Filter	Voltage level	Power level	Expt. Results
[9]	✓	STRF	—	LC	13.8 kV	75 kVA	✓
[35]	✓	STRF	PR	LC	380 V/115 V	—	✓
[37]	✗	DDSRF	PI	LC	220 V	—	✓
[39]	✓	SRF	PI	LC	53 V	—	✓
[41]	✗	SRF	PI	LC	380 V	—	✓
[43]	✗	STRF	PR	LC	120 Vpk	3 kW	✓
[45]	✗	—	—	—	—	—	✗
[47]	✗	NARF	repetitive controller	L	120 V	—	✓
[49]	✗	STRF	PR	LC	110 V	—	✓
[51]	✗	DDSRF	PI	L	380 V	—	✗
[53]	✗	STRF	proposed control	L	350 V	—	✓
[55]	✗	DDSRF	PI	L	—	—	✓
[57]	✗	DDSRF	PI + PR	LC	115 V	30 kVA	✓
[59]	✓	NARF	PR	LC	400 V	45 kW	✗
[61]	✗	STRF	PR	LC	330 V	—	✓
[63]	✗	DDSRF	PI	LC	480 V	—	✗
[65]	✗	SRF	PI	LC	500 V	—	✗
[67]	✗	STRF	PR	LCL	240 V	20 kW	✓
[69]	✗	NARF	PR + VBD	LC	—	—	✗
[71]	✗	STRF/SRF	PI + MPR	LC	400 V	2.2 kVA	✓
[73]	✗	STRF	PR	LCL	110 V	4 kW	✓
[74]	✓	STRF	PR	LCL	0.6 kV	—	✓ HIL
[76]	✗	STRF	PR	LC	20 kV	1.8 MVA	✗
[78]	✓	STRF	PR	LCL	0.6 kV	—	✓
[80]	✗	STRF	PR	L	245 V	—	✗
[28]	✗	—	proposed control	LC	4.16 kV	—	✓
[83]	✗	SRF	PI	L	380 V	85 kW	✗
[85]	✗	—	proposed control	LC	110 V	10 kVA	✓ HIL
[87]	✓	STRF	PR	LC	220 V	6.5 kVA	✓ HIL
[89]	✗	STRF	MPR	L	40 V	—	✓
[91]	✗	SRF	PI + state estimato (SE)	LC	208 V	11 kW	✓
[93]	✗	STRF	PR	LC	155.6 V	2.3 kVA	✓
[95]	✗	STRF	SMC	LC	100 V	3 kW	✓
[97]	✓	STRF	PR	LCL	220 V	20 kW	✓
[99]	✗	DDSRF	PI	LC	220 V	15 kW	✓
[101]	✗	STRF	PR	L	—	—	✗

results in enhanced performance under non-ideal conditions. A three-phase damping control strategy, which behaves resistively towards the zero-sequence and NS currents is suggested in [118] for improved unbalance mitigation. Optimised controllers based on the H_∞ robust approach [119] are designed to achieve better power sharing under unbalanced conditions. Zero-sequence voltage compensation is achieved in a modular multilevel converter-based STATCOM in [120], wherein the fourth leg is controlled as a single-phase converter. A NS and zero-sequence current compensation strategy based on optimisation that can be run in RT is proposed in [121]. Small-signal sequence impedance models of the CC and VC VSGs are analysed in [122], which concludes that the CC VSGs are prone to instability. The participation of distributed resources and responsive loads is suggested in [123] to overcome unbalance, wherein an optimisation with the cost function defined based on VUF is carried out. A hierarchical control strategy is proposed for a four-wire MG in [124] for compensation of both NS and zero-sequence quantities. A dynamic phasor-based compensation technique to mitigate harmonics and unbalanced source voltage condition is proposed in [125]. A cost function-based method is proposed in [126] using continuous control set MPC for simultaneously compensating the bus voltage and negative and harmonic current mitigation. An adaptive VI-based control scheme proposed in [127] based on the injection of a small ac signal achieves VU mitigation without the need for communication or feeder information. A single-phase droop control augmented by three secondary control systems is used in [128] to achieve cooperative regulation of imbalances in four-wire MGs. A VC method to maintain balanced PCC voltages is proposed in [129], which is tested through HIL. Unbalanced current sharing in islanded LV MGs is achieved in [130] through NS and zero-sequence VI controllers. Details of a secondary control scheme for voltage quality enhancement are provided in [131], which uses communication and investigates the effect of inherent delays therein. Distributed VU compensation using a dynamic consensus algorithm is proposed in [132]. Another cooperative control strategy for unbalance mitigation based on CPT is discussed in [32]. A multi-agent system-based hierarchical scheme is elaborated in [133]. A VI-based scheme is proposed in [134] and a LQR in [135] for reducing the effects of unbalance in the system.

A two-level control scheme based on LBC using an unbalance compensator is proposed in [136] that ensures good performances under non-linear conditions as well. A LQR approach has been discussed in [137] and validated for its performance for unbalance mitigation using a HIL platform. An adaptive algorithm is discussed in [138], which combines a least mean square and sign algorithm, which is used to achieve VU in the network. Toman and Asumadu [139] explained a distributed finite control set MPC for the same, while the approach in [140] is to reduce NS impedance of the inverter to improve the performance. The impedances are synthesised separately for the sequences in [41] with a virtual resistance for the NS part to ensure unbalance control. Discrete LQR-based state feedback VC is discussed in [141], which shows

Ref.	Communication	Ref. frame	Controller	Filter	Voltage level	Power level	Expt. Results
[102]	✗	STRF	PR	L	133 V	—	✓
[104]	✓	SRF	proposed control	LC	12.47 kV	—	✗
[105]	✗	STRF	PI quasi-resonant	LC	110 V	—	✓
[107]	✗	DDSRF	PI	LC	11 kV	—	✓ HIL
[109]	✓	SRF	PI	LCL	700 V	—	✓
[111]	✗	STRF	MPR	LC	220 V	—	✓
[30]	✗	NARF	proposed control	LC	180 V	—	✓ HIL
[113]	✓	STRF	MPR	LCL	220 V	—	✗
[114]	✗	STRF	proposed control	—	400 V	—	✓
[116]	✓	STRF	PI	LC	—	—	✗
[118]	✗	NARF	—	LC	—	—	✗
[120]	✗	SRF	PI	L	24 kV	10 MVA	✓
[122]	✗	SRF	PI	LC	220 V	—	✓
[124]	✓	SRF	PI(out) P(in)	LC	—	—	✗
[126]	✗	STRF	MPC	LC	200 V	—	✓
[128]	✓	STRF	PR	LC	—	3 kW	✓
[130]	✗	STRF	MPR	LC	—	300 kVA	✗
[132]	✓	STRF	PR	LC	220 V	2.2 kW	✓
[133]	✓	SRF	FOPID	LC	311 V	—	✗
[135]	✓	SRF	PI	LC	360 V	—	✓
[137]	✗	DDSRF	PI	LC	318 V l–l	—	✓ HIL
[139]	✗	—	MPC	L/LC	208 V	—	✗
[41]	✗	STRF	PR	LC	380 V	—	✓
[142]	✗	SRF	PI	LC	208 V	30 kVA	✗
[144]	✓	STRF	PR	LC	20 kV	2,5 MW	✗
[22]	✗	STRF	PR	LC	—	—	✓
[23]	✗	SRF	PI	LC	$170 V_{pk}$	1 kVA	✓
[148]	✗	SRF	PI	LC	220 V	—	✓
[150]	✗	NARF	proposed control	LC	104 V	—	✓
[152]	✓	STRF	PR	LCL	415 V	—	✗
[154]	✗	STRF	PR	LC	240 V	15 kW	✗
[156]	✗	STRF	PIR	L	$90 V_{pk}$	—	✓
[158]	✗	SRF	PIR	LC	5 kV	5 MVA	✗
[160]	✗	SRF	PI	LC	480 V	55 kW	✓
[162]	✗	STRF	PR	L	35 V	—	✓
[164]	✗	STRF/SRF	proposed control	LC	220 V	—	✓
[166]	✓	SRF	PI	LC	220 V	—	✓
[167]	✗	SRF	PI(out) P(in)	LC	$155.56 V_{pk}$	—	✗
[57]	✗	SRF/STRF	PI + PR	LC	115 V	30 kVA/ph	✗
[170]	✗	SRF	PI	L	23 V	700 W	✓
[172]	✗	SRF	H_∞	LC	$400 V_{pk}$	—	✗

simulation cases for induction motor starting as well, while work in [142] is based on controllers in the negative and harmonic frames. Research in [143] explains a controller for the parallel operation of uninterrupted power supplies with VI control while the virtual NS impedance loop with a unified three-phase signal processor for component extraction is discussed in [144] and an adjustable version is discussed in [145]. A tertiary control approach using the artificial bee colony optimisation method for equalising compensation efforts among DGs using IPT has been discussed in [22]. MPC-based distributed control for the simultaneous voltage compensation and unbalanced and harmonic current sharing is proposed in [146]. CPT and IPT concepts are compared for their performance for unbalance mitigation in [23]. A distributed cooperative control based on communication for NS reactive power voltage with the Q versus G droop is presented in [147], which details the complete NS small-signal model of DG. Improved virtual power decoupling technique with adaptive adjustment of the compensation is discussed in [148]. The hybrid inverter interface concept is explained in [149], which achieves better VUF if the unbalanced loads are fed by a four-leg inverter than a three-leg one. Souza *et al*. [150] compared three-phase droop and per-phase droop for the performance and stresses on the need to have proper damping in the control. The limits to the fully decentralised droop control methods are discussed in [151]. Hierarchical control, which decomposes the traditional centralized controller into several local secondary controllers, is proposed in [152] while a four-leg inverter interface for the standalone system is suggested for better unbalance mitigation in [153] and is used as a shunt-connected compensator in [154].

The conventional droop is combined with a novel decoupling control in [155] to address the unbalance issue based on symmetrical component decomposition. CC structures have been compared in [156] for their filtering, tracking, and disturbance rejection capability in [157], while an enhanced control for grid-forming VSCs is discussed in [158], which does not need high-speed switching and provides the capability to track both DC and double frequency components. A composite control strategy for a PV–wind–diesel system, which achieves good performance under unbalanced loads with reduced converters and sensors is presented in [159] while another similar work is reported in [160]. A four-leg inverter with a reduced order generalised controller and frequency locked loop for enhanced sequence decomposition is discussed in

Ref.	Communication	Ref. frame	Controller	Filter	Voltage level	Power level	Expt. Results
[103]	✓	SRF	PI	LC	380 V	15 kVA	✓
[29]	✓	NARF	PR	LC	180 V	—	✓
[106]	✗	SRF	PI	LC	400 V	—	✓
[108]	✗	NARF	PR	LCL	230 V	—	✓
[110]	✗	SRF	PI	L	345 kV	—	✓
[112]	✗	STRF	—	LC	400 V	—	✓
[21]	✗	SRF	proposed control	LC	220 V	—	✓
[31]	✓	STRF	MPR	LCL	180 V	5 kVA	✓
[115]	✗	STRF	developed algorithm	L	220 V	—	✓
[117]	✗	STRF	SMC	LC	—	—	✓ HIL
[119]	✗	SRF	proposed control	LC	630 V	—	✓ HIL
[121]	✓	NARF	proposed control	LC	4.16 kV	—	✗
[123]	✓	NARF	—	LC	480 V	—	✓
[125]	✗	DDSRF	PI	LC	120 V	—	✓ HIL
[127]	✗	STRF	PR	LC	163 V	9 kVA	✓
[129]	✗	DDSRF	PI	LC	4.16 kV	—	✓ HIL
[131]	✓	STRF	PR(prim) PI(sec)	LC	230 V	—	✓
[32]	✓	SRF	PI	LCL	127 V	—	✗
[134]	✗	SRF	PI	LC	220 V	—	✗
[136]	✓	SRF	PI	LCL	230 V	—	✗
[138]	✗	—	adaptive	L	230 V	3.7 kW	✓
[140]	✗	STRF/SRF	PI(out) PR(in)	LC	230 V	—	✓
[141]	✗	—	State feedback (SF)	LC	440 V	—	✗
[143]	✓	SRF	PI	LC	45/385 V	—	✗
[145]	✗	STRF	PIR	LCL	—	—	✓
[146]	✗	SRF	PI	LC	200 V	10 kVA	✗
[147]	✓	SRF	PI	LC	—	—	✓
[149]	✗	SRF	PI	LC	415 V	10 kW	✗
[151]	✓	—	—	LC	—	—	✗
[153]	✗	SRF	PI	LC	112 V	—	✓
[155]	✗	DDSRF	PI	LC	380 V	60 kW	✗
[157]	✗	STRF	PR	LCL	400 V	16 kW	✗
[159]	✗	STRF	Anti windup proportional integrator + anti windup proportional resonant	LC	—	—	✓
[161]	✗	STRF	PR	LC	110 V	—	✓
[163]	✗	SRF	PI	L	311 V	—	✓
[165]	✗	—	SF	LCL	415 V	—	✓
[25]	✓	SRF	PI	LCL	120 V	—	✓
[168]	✗	STRF	MPR(out) P(in)	LC	100 V	3 kW	✓
[169]	✗	SRF	PI	L	230 V	70 kW	✗
[171]	✗	SRF	PI	LC	311 V	12 kVA	✗
[173]	✗	SRF	H_∞(out) P(in)	LC	20 kV	—	✗

P, proportional; PI, proportional integral; PR, proportional resonant; MPR, multiple frame proportional resonant; MPC, model predictive controller; FOPID, fractional order proportional integral derivative; VBD, voltage-based droop; AW, anti-windup; SMC, sliding mode controller; HIL, hardware in the loop; L, inductor; LC, inductor capacitor; LCL, inductor capacitor inductor; (out)(in), outer loop, inner loop; (prim)(sec) primary controller secondary controller communication: ✗-not based on Expt. results; ✓, based on Expt. results; ✗-not presented; ✓-presented.

[161]. A voltage sensorless control approach based on Lyapunov energy function is presented in [162]. A back stepping-based direct power control (DPC) scheme is suggested in [163] for mitigating the VU issue. A high-performance repetitive controller is proposed in [164] with a dual loop structure, which ensures good performance under unbalanced voltages. State feedback-based approach using the LQR method is shown to have good performance for unbalanced and harmonic loads in [165] while a self-adjusting VI is discussed in [166], while work in [25] suggests secondary controls for changing droop parameters as well based on CPCT component decomposition. A voltage decoupling feed-forward path for improvement of PCC voltage quality using four-leg inverters is discussed in [167], while Heydari *et al.* [168] used PR controllers under unbalance and non-linear loads for achieving the same. A combination of stationary and synchronous frame controllers is proposed in [57] for four-leg inverters. Symmetrical component-based controls in the SRF are discussed in [169, 170], which consider the zero-sequence components as well but present tuning challenges, while Hongbing *et al.* [171] add VI control to the approach to achieve system VU mitigation. Robust controllers based on H_∞ optimisation are proposed in [172, 173] to maintain balanced PCC voltages. Fundamental and harmonic VC structures are discussed in [174], while injecting NS components of the opposite sign is proposed in [175] for VU mitigation. A negative-sequence voltage compensation strategy is discussed in [176], while Savaghebi *et al.* [177] proposed VI and an unbalance compensation block for achieving enhanced performances under unbalances. Hierarchical schemes based on communications are used in [178, 179] for VU mitigation.

Li *et al.* [180] proposed an adaptive discrete variable structure SMC and similar work is discussed in [181]. In [182], an optimization algorithm is used to adaptively tune controller gains to achieve VU mitigation. Imbalance and harmonic compensation is achieved through PR controllers in [183] while sequence-based controllers are used to compensate unbalances in a four-wire MG through three- and four-leg converters in [184]. VI along with a unified unbalance compensator is supplemented with droop control in [185]. A neutral point clamped (NPC) converter is controlled as to maintain the PCC voltages balanced in [186] while a two-level hierarchical control with VI is suggested in [187] for maintaining balanced voltages. The injection of imbalance in the local bus with the aim to maintain a balanced voltage at remote bus is discussed in [188]. Unbalance and harmonic controllers are used in [189], while strategies in [190–192] use communication to achieve unbalance compensation. An adaptive resonant control method for variable frequency for a VSG is discussed in [193], while Samadhiya and Namrata [194] discussed an energy management strategy and a VC strategy for the cascaded H-bridge (CHB) multilevel inverter-based DG source to mitigate unbalance. A distributed MPC based on augmented Lagrangian relaxation and auxiliary problem principle is proposed for the control of unbalance in [195]. A decoupled current controller is designed

Table 3 Summary of works for unbalance mitigation: islanded mode

Ref.	Communication	Ref. frame	Controller	Filter	Voltage level	Power level	Expt. results
[174]	✗	SRF	PI + MPR	LCL	$300V_{pk}$	—	✗
[175]	✗	NARF	PI(in)	L	230 V	—	✗
[176]	✗	STRF	PI + PR	LCL	380 V	—	✓
[177]	✗	STRF	PR	LCL	$300V_{pk}$	—	✓
[178]	✓	STRF	PR + PI(sec)	LC	$300V_{pk}$	—	✗
[179]	✓	STRF	PR + PI(sec)	LC	$300V_{pk}$	—	✗
[180]	✗	STRF	SMC	LC	220 V	28.9 kW	✗
[181]	✗	SRF	SMC + PI	LC	—	—	✗
[182]	✗	STRF	MPR	L	—	2.5 MVA	✗
[183]	✗	STRF	MPR + P	LCL	—	100 kW	✗
[184]	✗	SRF	PI	LCL	—	—	✗
[185]	✗	SRF	PI	—	$300V_{pk}$	—	✗
[186]	✗	SRF	PI	LC	40 V l-l	300 kW	✗
[187]	✓	STRF	PR	LC	—	—	✓
[188]	✗	DDSRF	PI	L	—	—	✗
[189]	✗	STRF	PR	—	69 kV	—	✗
[190]	✓	STRF	PR	LCL	300 V_{pk}	—	✗
[191]	✓	—	cooperative control	LC	—	—	✗
[192]	✓	SRF	PI	LC	300 V	—	✗
[193]	✗	SRF	PI(out) P(in)	LC	$300V_{pk}$	10 kVA	✓
[194]	✗	SRF	MPR	—	2.4 kV	1200 kVA	✗
[195]	✗	—	—	LC	—	—	✗
[196]	✓	SRF	PI	LCL	11 kV	500 kVA	✗

Ref.	Communication	Ref. frame	Controller	Filter	Voltage level	Power level	Expt. results
[197]	✗	SRF	PI + PR	LCL	380 V	1 MW	✗
[198]	✓	—	—	—	—	—	✗
[199]	✗	SRF	PI	LC	$300V_{pk}$	—	✗
[200]	✗	SRF	PI	LC	$300V_{pk}$	—	✗
[201]	✗	SRF	PI	LCL	11 kV/420 V	—	✗
[202]	✗	—	—	LC	225 V	620 W	✗
[203]	✗	STRF	PR(out) PI(in)	LCL	310 V	—	✗
[204]	✗	STRF	PR	LC	480 V	—	✗
[205]	✗	SRF	PI	LCL	—	—	✗
[206]	✗	SRF	PID	LC	600 V	3 MVA	✗
[207]	✓	STRF + SRF	PR + PI	LC	320 V	—	✓
[208]	✗	STRF	PR +	L	230 V	—	✓
—	—	—	repetitive control	—	—	—	—
[209]	✓	SRF	PI	LC	220 V	—	✓
[210]	✓	SRF	PI	LC	$105V_{pk}$	—	✓
[211]	✓	DDSRF	PI	LCL	200 V	2.2 kW	✓
[212]	✗	DDSRF	PI	L	230 V	—	✗
[213]	✓	DDSRF	PI	LCL	—	—	✓ HIL
[214]	✗	STRF	ROGI	L	110 V	—	✓
[215]	✗	SRF	proposed controller	LCL	540 V	130 kW	✗
[216]	✗	DDSRF	PI	LCL	400 V	—	✗
[217]	✗	STRF	PI	LCL	391 V ($l-n$)	5 kW	✓
[218]	✓	—	proposed algorithm	—	480 V	530 kW	✗

PID, PI–derivative.

using an internet of things (IoT) platform in [196] for four-leg smart inverters to mitigate unbalances. Resonant controller and VIs are suggested in [197], while a distributed secondary control strategy is used in [198] for unbalance mitigation. A linear active disturbance rejection control with a linear extended state observer is proposed in [199], while another disturbance observer is proposed in [200] for handling voltage asymmetries. The control over zero-sequence currents in four-leg PV VSIs is discussed in [201], while a VU mitigation technique using three-phase damping control is suggested in [202]. A hierarchical control strategy proposed in [203], a combination of three- and four-leg VSIs in [204], switching of single-phase inverters between the three phases with the lowest phase voltage [205], and model adaptive reference control for an adaptive PI derivative controller [206] are some of the other approaches that have been proposed for VU mitigation in the network. Zhu *et al*. [207] proposed a coordination control strategy for a hybrid energy storage system consisting of a battery and ultra-capacitor, for good performance under unbalanced and non-linear load conditions in which the battery provides the fundamental powers, while the ultra-capacitor provides the compensating power. A repetitive-based control scheme is discussed in [208] for four-wire systems, which estimates the impedance for better performance and eliminates the need for additional sensors. A power-based coordinated control strategy is discussed in [209] for three-wire MGs that achieve unbalance mitigation under both the islanded and grid-connected modes. Ninad and Lopes [210] proposed a per-phase control strategy for a four-leg grid-forming inverter for achieving voltage balance at the PCC without sequence extraction and is shown to have a good performance even when the DG has to supply power through two phases and absorb through the third one. Peng *et al*. [211] presented the small-signal analysis of voltage unbalance correction strategies for islanded MGs through a detailed state-space model using dynamic phasors, and proposed a new compensation technique, while Ismail *et al*. [212] presented a strategy based on supercapacitor storage for improving the dynamic performance of the system under unbalanced and non-linear loads. A control strategy enabling seamless system transition during unbalanced dynamic MG reconfiguration, and ensuring proportional power-sharing using a distributed secondary control strategy is developed in [213] for DGs with grid forming inverters in unbalanced dynamic MGs, which is validated through HIL. A novel control algorithm using double reduced-order generalised integrators for a four-leg shunt converter is presented in [214], while Sedhom *et al*. [215] proposed another robust H_∞ based controller for unbalance mitigation in islanded MGs. Hoseinnia *et al*. [216] proposed a double SRF (DSRF) control scheme without the need for load current sensors, while Hart *et al*. [217] investigated the impact of harmonics and unbalance on the performance dynamics of grid-forming converters modelled using the dynamic phasor approach. A novel control demand-side management algorithm based on voltage sensitivity is proposed in [218] as a possible solution for unbalance mitigation for an islanded MG having thermostatically controlled loads.

3 Unbalance mitigation in the grid-connected mode

In grid-connected networks, the DGs are typically controlled in the CC mode. However, alternative strategies to control the power flow such as the VOC and DPC are also prevalent. The unbalance mitigation majorly focuses on mitigating the unbalance provided by the utility, i.e. current imbalance mitigation. The unbalance control in the grid-connected mode comes into effect predominantly during grid faults [219]. With the advancement in grid codes, the LV ride through (LVRT) of grid-connected renewables is an important aspect. A review of the various LVRT techniques as per the various grid codes, generators, and turbines specific to wind energy conversion systems is carried out in [220, 221]. Reviews of LVRT strategies for PV systems are presented in [222, 223]. The CC of the inverters has to be done as per the specifications of these codes to ensure voltage support and stable operation [19]. The injection of the positive sequence currents is needed for the voltage and frequency support while the NS current injection ensures minimisation of the effect of the VU. The different issues in this mode of operation are fast detection of faults, proper synchronisation, fault ride-through control, proper resynchronisation with a grid in case of disconnection during fault and stable ramping up of the power after the fault. During the stages, it is essential to ensure that the current limits of the DGs are not exceeded and ensure protection as power electronic-based DGs have low-overloading capacity due to thermal constraints. The typical constraints on the DG operation under unbalances would be imposed by the output AC voltage and current limits and the DC bus voltage oscillation limits. Since this is a complex problem most literature to date only focus on the control of a single grid-connected inverter (GCI) during unbalanced grid conditions, with very few of them looking at the parallel inverter/system management case. The other challenges in the grid-connected mode are the elimination of oscillations in the real and/or reactive power (which would otherwise result in DC link voltage oscillations) peak current limiting and maximising the power injection to the grid. Owing to the limiting constraint imposed by the converter rating and optimisation may be necessary to achieve the various objectives. Furthermore, a compromise may have to be made between avoiding the power ripples during unbalanced voltage sags in the grid and high-current harmonic distortion. Grid synchronisation under the unbalanced scenario is another important aspect [224, 225]. The other important aspect is the fast and accurate information extraction of the grid phase voltages for which several advanced PLLs have been proposed in the literature [226]. Fig. 5 shows a typical control scheme for the grid-connected mode involving a secondary communication-based layer. This section summarises the available literature [14, 15, 16, 17, 20, 24, 26, 162, 219, 226–366] on unbalance mitigation in the grid-connected scenario of both single and multiple inverters.

A current source inverter (CSI) is proposed in [227] to achieve good performance under unbalance using direct control with reduced sensors and no PLL. A comparative study of three-phase four-wire inverter topologies (split DC link, four-leg, and H-bridge types) is carried out in [228], which concludes that the three H-bridge inverter renders superior performance under unbalanced scenarios. A Fortescue component-based strategy using six PI controllers for grid-connected inverters is presented in [229] for the unbalance control, while Suul *et al*. [230] proposed a virtual flux-based voltage sensor-less approach using SOGIs for sequence extraction. An enhanced decoupled double synchronous is presented in [231], which simulates faulted conditions in the network. Ivanovic *et al*. [232] proposed two power flow control algorithms with current limitation validated on a HIL setup. Different reference current generator (RCG) strategies are compared in terms of the effects of the short-circuit ratio, angle of the AC system impedance, and PLL parameters in [233] under unbalances. A direct pole placement strategy from discrete state space offering fast reference tracking capability is discussed in [234]. Expressions for multi-objective optimisation-based RCG schemes such as minimised active power oscillation, minimised reactive power oscillation, minimised fault current, maximum allowable active power injection, and maximum allowable reactive power injection are presented in [235]. Voltage support schemes under faults are discussed in [236], which compensate for the zero-sequence component and consider the active power injection. A review and comparison of the various approaches for table-based DPC for grid-connected inverters, i.e. voltage-based DPC, resilient voltage-based DPC, virtual flux-based DPC (VF-DPC), and the proposed resilient VF-DPC is provided in [237], while a new DPC strategy achieving symmetrical grid currents under unbalanced grid voltage is discussed in [14]. An enhanced IPT-based control is compared for its performance versus a CPT-based approach in [15] for unbalance compensation. Another work [238] extends the IPT in the *pqr* frame to achieve CC of a four-leg inverter. A new fundamental sequence component extractor for use in distorted utility conditions is proposed in [239] based on multiple complex coefficient filters (CCFs) using third-order sinusoidal signal integrators. A robust scheme for GCIs based on an internal model-based current controller, robust PLL, and state estimator is

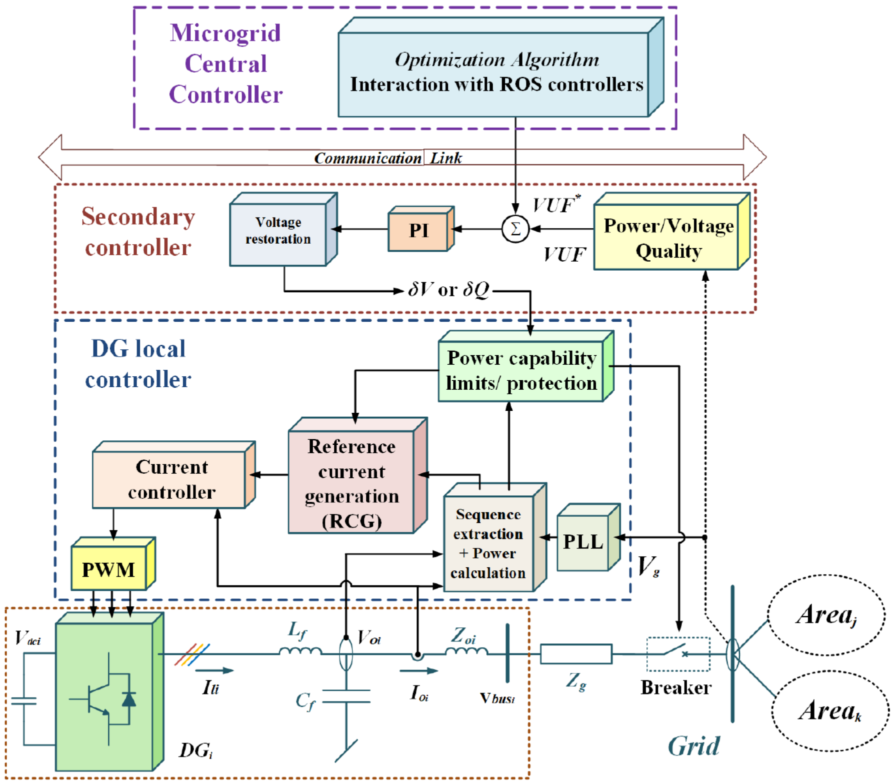


Fig. 5 *Block diagram of a typical control scheme for addressing the issue of unbalance in the grid connected mode (involving communication)*

demonstrated for its effectiveness under unbalances in [240], while an improved model predictive CC scheme ensuring the fast response is proposed in [241]. A novel control strategy to mitigate the double grid frequency power oscillations in two-stage DGs based on a new nominal power index is discussed in [242]. An optimised active power control strategy in [243], a robust and fast control strategy for load-voltage regulation in [244] and SMC-based DPC in [245] also show enhanced performances under unbalanced grid conditions. The issue of proper RCG under sags is discussed in [246] while new strategies to utilise the zero-sequence components are discussed in [247]. A simple formula is presented in [248], which allows the estimation of the maximum real and reactive power exchange under unbalanced grid conditions. A flexible grid connection technique based on DPC is discussed in [249] that incorporates multiple CCFs for component extraction. A pole-placement-based state observer grid-voltage sensorless strategy for synchronisation and control is discussed in [250], which results in superior performance. Other approaches under unbalanced conditions such as an algorithm to maximise the converter capabilities under sags in [251], an optimal virtual flux predictive DPC in [252], advanced dynamic voltage support method for asymmetrical faults [253], a power decoupling strategy to suppress oscillations in [254], energy-based control for peak current limiting in [255], control finite state MPC in [256], expression-based approaches to avoid oscillations and generate real and reactive power references in [257], and a simple CC without signal reconstruction in [258] have also been suggested.

Table 4 presents a summary of the various contributions for unbalance mitigation in grid-connected inverters/MGs. A controller is designed using the complex root locus method in [259], auxiliary voltage controller for fault ride through (FRT) in [219] for preventing over-current, and the combination of a feedback output controller with a disturbance observer in [26] are shown to achieve good performance under grid unbalances. An approach proposed in [260] extends the current physical component power theory to four-wire systems. The simultaneous active and reactive power control is proposed in [261] based on symmetrical components with a flexibility to achieve three objectives. A comparison of current limiting strategies under the various reference frames is carried out in [262] and a new strategy is proposed for superior performance, while Bottrell and Green [263] compared CC strategies and focused on the prevention of windup and latch-up. A distributed strategy for synchronisation and seamless reconnection to the grid after fault clearance is discussed in [264] and other controls for the same objective have been discussed in [265], which uses two adaptive filters implemented through SOGI and in [266] the three popular PLLs: the DDSRF-PLL, the dual second-order generalised integrator (DSOGI)-PLL, and the three-phase EPLL have been compared for their performance. Other works about unbalance in grid-connected mode include positive sequence- and NS-based control strategies in [267], a four-switch three-phase fault-tolerant structure based on finite states MPC in [268], an improved LVRT scheme in [269], a disturbance observer-based control in [270], an unbalanced current compensation strategy in [271] based on fuzzy control and compensatory neural fuzzy network with an asymmetric membership function, a new power control strategy under faults in [272], a current limiting strategy using sequence-based control in [273], a computationally efficient on-purpose asymmetrical and harmonic injection current controller in [274] to improve power quality and a novel algorithm to calculate fault currents for different controllers in [275]. A robust control strategy for a grid-connected MG using an adaptive Lyapunov function-based control scheme for NS components is discussed in [276], while Brandao *et al.* [277] explored how the existing strategies for active and reactive power injection cause variations in the short circuit ratios. An adaptive VI-based reference generation technique for FRT is discussed in [278], which summarises the existing strategies and proposes a sinusoidal current reference limiter and mid-pass filtering, the performance of which is not affected by fault severity, location or type. The control structure proposed in [279] reduces power oscillations using the quasi-Newton-trust region method. VU limiting is achieved by paralleling VI in [280] while Shuai *et al.* [281] investigated the fault current characteristics. Enhanced controls under unbalances have been presented in [282] to suppress power oscillations, in [283] for the AC/DC matrix converters, in [284] to control the unbalanced fault current, in [285] for power oscillation suppression, and in [286] to improve the power quality and stability aspects. Shabestary and Mohamed [287] compared the maximum allowable support control schemes for the performance under unbalances and concludes that the balanced positive sequence current strategy has the lowest maximum current. LVRT techniques based on positive-sequence and NS current injection are discussed in [288], while Jia *et al*. [289] carried out investigations on the short-circuit responses of a combination of DGs and synchronous condensers and proposed FRT schemes for the same. A generalised control scheme and control algorithms for control parameters tuning have been discussed in [290] for grid fault control and an adaptive notch filter-based multi-purpose control scheme for a four-leg GCI is discussed in [291] for achieving good power quality.

The various control strategies for tackling the issue of unbalance in MGs are summarised in Fig. 6. An adjustable strategy for eliminating real or reactive power oscillations is described in [292], while Kabiri *et al*. [293] proposed a simplified extraction method for control under unbalances eliminating sequence extraction. A strategy to inject balanced currents to the grid despite the VUs is presented in [20], while Kumar and Mishra [294] proposed an instantaneous symmetrical component theory-based control neutral clamped three-leg VSI for superior unbalance performance. A coordinated control strategy for parallel GCIs is discussed in [295] for peak current limitation, while Yarmohamad *et al*. [296] proposed a four-wire DSTATCOM for unbalance mitigation. SMC is modified by adding a fuzzy function in [297] for grid-connected VSI and a controller is designed in [298] for the simultaneous injection of both the current sequences into the grid. Other approaches under unbalanced grid conditions include an integrated controller for enhanced LVRT control in [299], injection of NS currents under sags in [300], neural network-based least mean sixth CC technique in [301], cascaded three-loop current controller in [302, 303], new algorithms for RCG under unbalances in [304], proper regulation in terms of the high voltage ride through in [305], PR-based compensation controller in [306], control of multi-functional four-wire DGs in [307, 308], and a simultaneous harmonic and unbalance compensation control in [309]. An improved DPC is studied in [310] based on the inductance estimation based on the gradient correction method. An LVRT strategy to eliminate NS currents is discussed in [311], while Restrepo *et al*. [312] proposed another DPC-based strategy. The method to maintain balanced PCC voltage and reduce the DC link oscillations is suggested in [313, 314], while Guo *et al*. [315] provided the theoretical analysis of the oscillation phenomena under unbalances. A study on the current limitation of the grid-connecting converters is evaluated on a HIL platform in [295], while an advanced NS droop control for the optimum injection of power under two different fault types is discussed in [316]. An

Table 4 Summary of works for unbalance mitigation: grid-connected mode

Ref.	Communication	Ref. frame	Controller	Filter	Voltage level	Power level	Expt. results
[227]	✗	STRF	PR	LC	80 V	—	✓
[229]	✗	SRF	PI	L	230 V	70 kW	✗
[231]	✗	DDSRF	PI	LC	230 V	5.5 kVA	✓
[233]	✗	DDSRF	PI	L	480 V	10 MVA	✓
[235]	✗	STRF	PR	LC	690 V	—	✓
[237]	✗	STRF	direct control	L	—	—	✗
[15]	✗	SRF	PI	LCL	120 V	—	✗
[239]	✗	STRF	PR	L	415 V	15 kVA	✓
[241]	✗	STRF	proposed control	L	150 V	—	✓
[243]	✗	STRF	PR(out)P(in)	LC	$300V_{pk}$	2.5 kW	✓
[245]	✗	STRF	proposed control	L	75 V	1 kVA	✓
[247]	✗	DDSRF	PI	LC	3.3 kV	10 MW	✓
[249]	✗	STRF	PIR	L	$90V_{pk}$	—	✓
[251]	✗	—	—	LCL	110 V	1.1 kVA	✓
[253]	✗	—	—	LC	690 V	1 MVA	✓
[255]	✗	DDSRF	PI	LCL	380 V	100 kW	✗
[257]	✗	STRF	PI(out)PR + AW(in)	LCL	480 V	3.3 kW	✓
[259]	✗	SRF	PI	LCL	175 V	—	✓
[26]	✗	STRF	PR	L	50 V	—	✓
[261]	✗	STRF	PR(out) P(in)	LCL	415 V	15 kVA	✓
[263]	✗	STRF	PR	LCL	220 V	—	✓
[265]	✗	STRF	PR	LC	$100V_{pk}$	—	✓
[267]	✗	STRF	PR	LCL	$155V_{pk}$	2.3 kVA	✓
[269]	✓	SRF	PI	LC	400 V	—	✗
[271]	✗	SRF	PI	LC	180 V_{pk}	—	✓
[273]	✗	DDSRF	PI	LC	400 kV	—	✗
[275]	✗	SRF	PI	LC	400 V	10 kW	✗
[277]	✗	SRF	PI	LC	220 V	—	✗
[279]	✗	DDSRF	PI	L	415 V	12 kVA	✗
[281]	✗	SRF	PI	LCL	311 V	32 kVA	✓
[283]	✗	SRF	PI	LC	70 V	—	✓
[285]	✗	—	—	—	150 V_{pk}	500 W	✓
[287]	✗	STRF	PR	LC	690 V	2.2 MVA	✓
[289]	✗	SRF	PI	LC	150 kV	—	✗
[291]	✗	—	proposed control	—	$350V_{pk}$	—	✓ HIL
[293]	✗	DDSRF	PI	LCL	110 V	5 kVA	✗
[294]	✓	NARF	hysteresis	L	400 V	—	✗
[296]	✗	SRF	PI	L	100 V	—	✗
[298]	✗	SRF	PI	LC	—	—	✓
[300]	✗	STRF	PR	LCL	−220 V	—	✓

Ref.	Communication	Ref. frame	Controller	Filter	Voltage level	Power level	Expt. results
[228]	✗	STRF	PR	LC	480 V	—	✓
[230]	✗	STRF	PR	LC	400 V	5.5 kVA	✗
[232]	✗	STRF	PR	L	6 kV	—	✗
[234]	✗	STRF	pole placement	LCL	400 V	20 kW	✓
[236]	✗	STRF/NARF	—	LC	690 V	1 MVA	✓
[14]	✗	SRF	proposed control	L	380 V	1.4 kVA	✓
[238]	✗	STRF	—	—	$380 V_{pk}$	—	✓
[240]	✗	SRF	PI	LC	220 V	2.5 kW	✓
[242]	✗	STRF	PR	LCL	381 V	2 kW	✓
[244]	✗	STRF	MPR	LCL	210 V	—	✓
[246]	✗	SRF	PI	L	690 V	300 kW	✓
[248]	✗	SRF	PI	LC	100 V	—	✓
[250]	✗	STRF	SE	LC	400 V	—	✗
[252]	✗	STRF	DPC	LC	150 V	—	✓
[254]	✗	—	DPC	LC	220 V	5 kVA	✓
[256]	✗	STRF	MPC	L	100 V	—	✓
[258]	✗	DDSRF	PI	L	110 V	22.5 kW	✓
[219]	✗	STRF	proposed control	L	208 V l–l	2 kVA	✓
[260]	✗	SRF	PI	L	100 V	—	✓
[262]	✗	NARF/STRF/SRF	PR/PI	LC	380 V	10 kVA	✓
[264]	✓	STRF	—	LCL	230 V	—	✓ HIL
[266]	✗	STRF/SRF	PR/PI	—	—	—	✓
[268]	✗	STRF	predictive control	L	380 V	—	✓
[270]	✗	STRF	proposed control	L	160 V	—	✓
[272]	✗	DDSRF	PI	L	110 V	3.3 kVA	✗
[274]	✗	STRF	PI	LC	—	5 kVA	✓
[276]	✗	STRF	PR	LC	380 V	—	✗
[278]	✗	STRF	PR	LC	5 kV l-l	5 MVA	✗
[280]	✗	STRF	PIR	LC	415 V	4 kW	✓
[282]	✗	STRF	Resistance-capacitor	L	220 V	—	✓
[284]	✗	SRF	PR	LCL	50 V	250 W	✓
[286]	✗	SRF	proposed control	L	208 V	20 kVA	✓ HIL
[288]	✗	STRF	PR	LCL	220 V	—	✓
[290]	✗	—	—	—	—	3 kW	✓
[292]	✗	DDSRF	PI	LCL	400 V	—	✗
[20]	✗	NARF/SRF	PI + deadbeat	L	120 V	1.5 kW	✗
[295]	✗	STRF	PR	LCL	—	—	✓
[297]	✗	STRF	proposed control	LC	$100 V_{pk}$	—	✗
[299]	✗	DDSRF	PI	LC	415 V	56 kVA	✓
[301]	✗	STRF	proposed control	L	$300\ V_{pk}$	—	✓

improved grid voltage-modulated control with power compensation is explored in [317], while a sequence-decoupled resonant control strategy is proposed in [318] for unbalance mitigation. The comparison of fuzzy and adaptive neuro-fuzzy controllers to control a seven-level inverter under unbalances is carried out in [319], while a Lyapunov-based current controller using DSOGI is proposed in [162] and the performance of a GI-based control scheme is explored in [24]. The relationships between maximum current amplitude and grid voltage drop and power factor during voltage dips are analysed in [320], which proposes a new over-current protection method based on the maximum phase current amplitude estimation based on IPT for a three-phase four-wire converter. A current-based droop control for the quick recovery after faults is discussed in [321], wherein the dynamic current limiting adjustment is combined with the power-angle limiting method to achieve good performances under unbalances without the need for power calculation. To overcome the challenges associated with stability during deep voltage sags, Wang *et al*. [322] developed a small-signal model of the system and concluded that weaker grid strength, deeper voltage sags, and higher PLL bandwidths are more likely to drive the current controller into instability. An improved dead beat control based on current predictive correction is used to control the GCI under unbalanced grid voltages in [323] results in a better transient approach and removes the uncertainties associated with the inductor filter parameters. Sabir [324] discussed a robust control scheme eliminating the need for a PLL for mitigating the unbalance problem wherein the dc–dc converter is controlled by the uncertainty and disturbance estimation controller and the dc–ac converter uses the repetitive controller. A strategy for wind turbines combined with a supercapacitor energy storage is presented in [325], which uses series inductances and modified control for better FRT performance. Miret *et al*. [326] proposed control for a three-phase inverter that minimises the peak values of injected currents under grid unbalance conditions, while an analysis dealing with the control of positive and negative current sequences is presented in [248], which proposes a simple expression for the power exchange with the grid during unbalance.

Two different approaches for unbalance mitigation are discussed in [327], wherein the inverter operates as a reactive power compensator or a load balancer for unbalance mitigation and the detailed expressions for the safe operating region of the inverter are developed. Wang *et al*. [328] proposed optimal NS current references for suppressing the dc-link current double-frequency

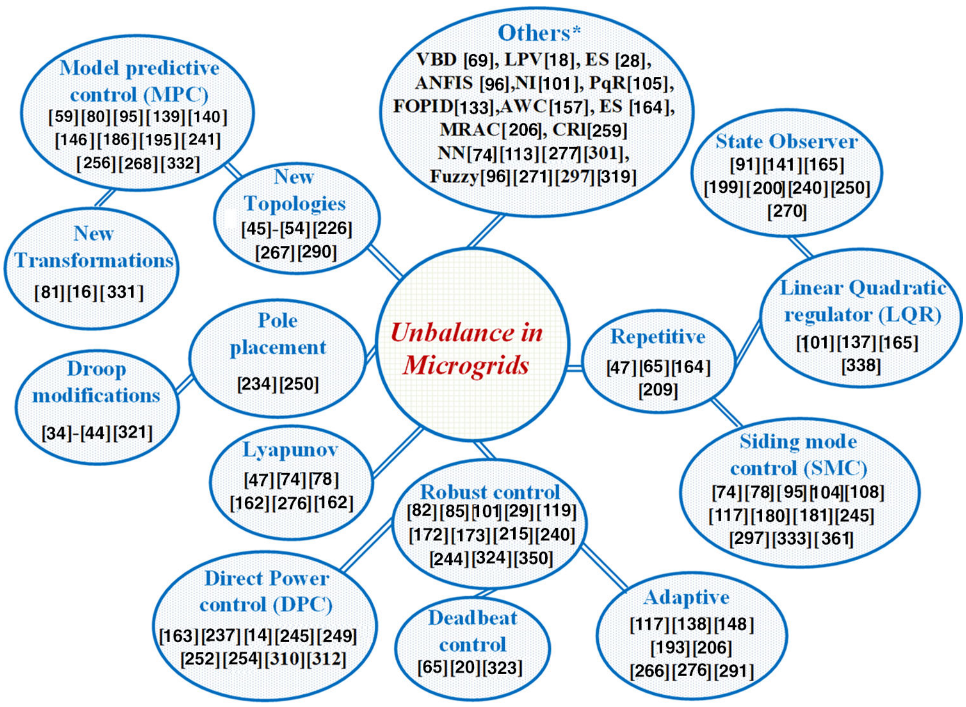
Ref.	Communication	Ref. frame	Controller	Filter	Voltage level	Power level	Expt. results
[302]	✗	STRF	PR + P	L	—	—	✗
[304]	✗	SRF	PI	L	230 V	4.7 kW	✓ HIL
[306]	✓	STRF	PR	L	230 V	—	✗
[313]	✗	DSRF	PI	LC	220 V	—	✗
[315]	✗	STRF	PR	LC	221 V	—	✗
[316]	✗	SRF	PI	LCL	250 V	—	✗
[318]	✗	STRF	PR	LCL	230 V	—	✗
[162]	✗	STRF	PR	L	$180V_{pk}$	—	✓
[320]	✗	DDSRF	PI	LCL	311 V	32 kVA	✓
[322]	✗	DDSRF	PI	LC	$220V_{pk}$	5 kW	✓
[324]	✗	STRF	proposed control	L	415 V	—	✓ HIL
[326]	✗	NARF	proposed control	L	380 V	2.5 kW	✓
[327]	✗	DDSRF	PI	L	$380V_{pk}$	5 kW	✓
[329]	✗	DDSRF	PI	L	480 V	—	✓
[16]	✗	New frame	proposed control	LC	—	—	✗
[332]	✗	STRF	proposed control	L	380 V	15 kW	✗
[334]	✗	STRF	PR	LCL	400 V	7.5 kVA	✓
[336]	✗	STRF	PR	CL	110 V	3 kW	✓
[338]	✗	DDSRF/STRF	proposed control	L	37 V	—	✓
[17]	✗	STRF	proposed control	LCL	380 V	25 kVA	✗
[341]	✗	DDSRF	PI	L	380 V	10 kVA	✓
[343]	✗	SRF	PI	—	575 V	1.5 MW	✗
[347]	✗	STRF	PR	LCL	220 V	—	✗
[350]	✗	STRF	SOGI	LC	400 V	400 kW	✗
[352]	✗	STRF	proposed control	L	155 V (l − n)	3.5 kVA	✗
[354]	✗	STRF	PR	—	380 V	18.81 kVA	✓
[356]	✗	SRF	—	L	—	—	✗
[358]	✗	—	—	—	11 kV	1 MW	✗
[360]	✗	SRF	proposed control	—	6.6 kV	2.5 MVA	✗
[362]	✗	STRF	PR	LC	208 V	7.5 kW	✓ HIL

oscillations and a hybrid controller for current-source grid-connected converters, while a detailed small-signal modelling framework is presented in [329] with sensitivity analyses to study the effects of parameters on the unbalanced fault characteristics. A simple control approach eliminating the need for extra hardware components and measurement of NS voltage and phase angle is discussed in [330], while Montanari and Gole [16] proposed a method to control the instantaneous power using an adaptive *mno* transformation using a modified IPT. Hwang and Lehn [331] discussed a technique to generate a space vector from a single real-valued signal and a controller for regulating the real and reactive powers with minimum voltage harmonics. A finite control set MPC is proposed in [332] to enhance the stability under unbalanced grid conditions which provides fast dynamic response and a robust feedback linearising control strategy based on SMC is presented in [333], which considers the dc side converter and compares the results with a PI-based control strategy. Considering the next-generation grid code requirements, Taul *et al*. [334] proposed a general current reference strategy for asymmetrical fault control through a direct explicit method to calculate power references and controller gains taking into account the power limits of the converter. The strategy discussed in [335] decouples unbalance and harmonic compensation in the phase sequences and the frequency domain for a grid-connected inverter and is designed to be sequence asymmetric to achieve compensation. A new topology and LVRT strategy for CSI-based DGs is discussed in [336], which analyses quantitatively the relationship between steady-state DC-link current and grid voltage and shows that LVRT cannot be realised in a conventional CSI. A smart controller for PV-based DGs that integrate the control for responding independently to low-grid voltages during faults, overvoltages and during low-loading and islanding is proposed in [337]. The performance comparison for three different current controllers based on symmetrical components and LQR have been presented in [338] for a NPC-based DG for wind systems in which the evaluation is done based on LVRT requirement fulfilment, grid-current balancing, maximum grid-current value control and oscillating power flow. Taul *et al*. [339] discussed the fundamental issue of grid-forming converter control under grid fault scenarios and present a fault-mode controller, which maintains the maximum converter limits. A novel signal extraction method named as virtual input signal-based IPT is proposed in [17], which is tested on a shunt APF for improving the performance under unbalanced power quality issues. A feed-forward transient compensation control strategy for doubly fed induction generators (DFIGs) for enhanced LVRT capability under unbalanced conditions is discussed in [340].

Shin *et al*. [341] proposed a new robust low-pass notch PLL-based FRT scheme and a universal voltage sag generator for the various grid codes with six parameters for the verification of LVRT performances. Another study for DFIGs using a frequency-domain modelling approach and a modified resonant controller is proposed to improve the system response during voltage sags in [342], while Amalorpavaraj *et al*. [343] proposed the use of a DVR with combined feed-forward and feedback control for FRT improvement of DFIG-based wind turbines. A flexible control strategy for the operation of PV grid-connected CHB inverters during unbalanced voltage sags is discussed in [344]. The various control schemes for FRT schemes under unbalanced grid conditions for DFIG-based DGs are discussed and reviewed in [345, 346]. A flexible scheme for LVRT eliminating the need for a PLL for GCIs under asymmetrical fault conditions is presented in [347]. A review of RCG strategies for PV-based DGs under grid faults is presented in [348]. An asymmetric LVRT strategy is proposed in [349] provides allowable margins for each phase voltage magnitude rather than controlling only the positive-sequence voltage which allows for a seamless transition over a fault. A robust control scheme for GCIs to compensate both positive sequence and NS powers under balanced and unbalanced grid conditions is discussed in [350].

Ref.	Communication	Ref. frame	Controller	Filter	Voltage level	Power level	Expt. results
[303]	✗	SRF	PI	LCL	416 V	—	✓
[305]	✗	—	—	—	—	—	✗
[307]	✗	SRF	PI + PR	LC	415 V	50 kW	✗
[314]	✗	STRF	PR	LC	120 V	—	✗
[295]	✗	SRF	PI	—	—	—	✓ HIL
[317]	✗	SRF	PI	L	250 V	3 kVA	✗
[319]	✗	SRF	PI	L	—	—	✗
[24]	✗	STRF	PR	L	415 V	35 kVA	✓
[321]	✗	DDSRF	PI	LC	$220V_{pk}$	—	✓
[323]	✗	STRF	deadbeat	L	$220V_{pk}$	10 kW	✓
[325]	✗	DDSRF	PI	LC	400 V	—	✗
[248]	✗	DDSRF	PI	L	100 V	—	✓
[328]	✗	SRF	MPI	LC	122 V	—	✓
[330]	✗	SRF	PI	L	20 kV	—	✓
[331]	✗	New frame	PI + SISVC	L	120 V	5 kVA	✓
[333]	✗	SRF	proposed control	L	$45V_{pk}$	—	✓
[335]	✗	STRF	PR	LCL	220 V	—	✓
[337]	✗	DDSRF/STRF	PR	LC	415 V	—	✓
[339]	✗	STRF	proposed control	LCL	400 V	7.35 kVA	✓
[340]	✗	SRF	PIR	—	230 V	7.5 hp	✓
[342]	✗	DDSRF/STRF	PIR	LCL	230 V	25 kW	✓
[344]	✗	SRF	SAW-proportional-resonant	L	430 V	9 kVA	✓
[349]	✗	STRF	—	—	690 V	1 MVA	✗
[351]	✗	DDSRF	PI + PR	LC	20 kV	1 MW	✓
[353]	✗	DDSRF	proposed control	—	220 V	1.5 kW	✓
[355]	✗	SRF	PI + PR	L	400 V	50 kVA	✓
[357]	✗	STRF	PR	LCL	230 V	7.5 kVA	✓
[359]	✗	STRF	PI + PR	—	27 kV	—	✗
[361]	✗	SRF	PI	LC	170 V	1 kW	✓
[363]	✗	STRF	multiple PR	LC	24.9 kV	—	✗

MPI, multiple frame PI; SISVC, single input space vector controller.



* VBD: Voltage based droop, LPV: Linear parameter varying, ES: Expert system, ANFIS: Adaptive neuro fuzzy inference systems, NI: Negative imaginary, PqR: Proportional quasi resonant, FOPID: Fractional order PID, AWC: Anti-wind up controller, ES: Expert system, MRAC: Model reference adaptive control, CRI: complex root locus, NN: Neural network

Fig. 6 *Various control strategies for tackling the issue of unbalance in MGs for both islanded and grid-connected modes*

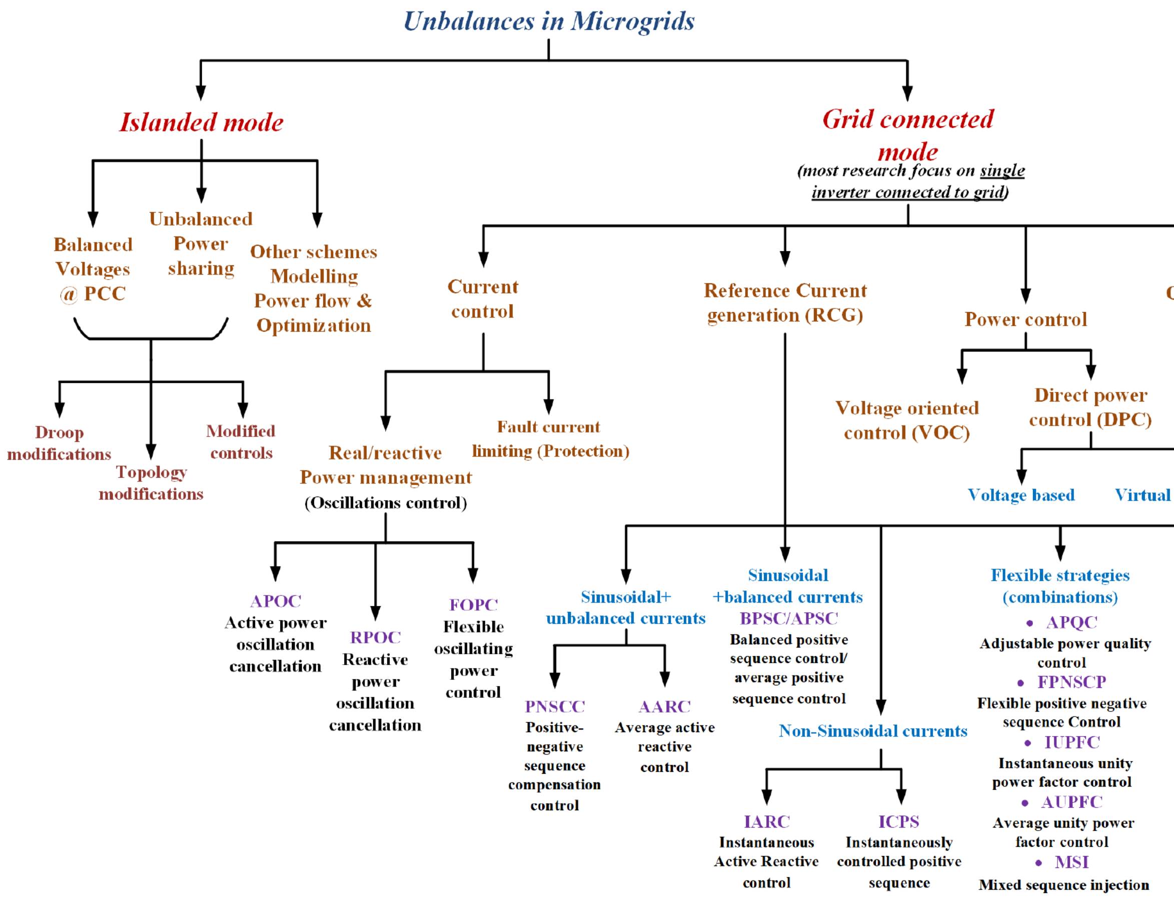


Fig. 7 *Unbalance management in MGs: a summary of objectives and strategies*

Mirhosseini *et al.* [351] discussed control of a large-scale grid-connected PV power plants operating under unbalanced grid voltage sags without the need for phase angle synchronisation, while a dissonant–resonant controller for negative-sequence voltage elimination for a grid-feeding converter is proposed in [352] and Zhang *et al.* [353] discussed a model predictive DPC for DFIG under unbalanced conditions. The modelling and experimental validation of another strategy for DFIG systems under distorted and balanced systems is discussed in [354]. Zarei *et al.* [355] proposed a control scheme to remove the third harmonic component in the output currents of grid-following inverters, under unbalanced grid conditions. Islam *et al.* [356] attempted to address short-term voltage instability in modern distributed networks under asymmetrical faults, while Ghahderijani *et al.* [357] proposed a voltage support control strategy to mitigate the voltage imbalance based on a minimum current approach. Oon *et al.* [358] aimed to establish the various possible inverter based distributed generator fault current characteristics, with compliance to the latest grid codes requirements and compares five reactive current injection techniques for their performance. Shabestary and Mohamed [359] discussed an autonomous coordination control scheme to achieve cooperative asymmetric low-voltage ride-through and grid support by multiple DG units. A new smooth variable structure filter in the DPC of inverters under unbalanced grid conditions is proposed in [360], which eliminates NS currents and also uses an adaptive SMC. The aspect of paper studies loss of synchronism of VSCs during grid faults is examined in [361] and a simple PLL based on the variable structure is proposed to improve the resynchronisation capability. Yazdani *et al.* [362] proposed a current limiting scheme for unbalanced grid conditions based on a virtual synchronous machine for power control, while Merritt *et al.* [363] proposed a unified control structure for grid connection and islanded mode operation for a VSC to maintain the PCC voltage balanced under unbalanced and non-linear loads. A strategy based on residential demand response for managing unbalances for a network with thermostatically controllable appliances is presented in [364], while Zhou *et al.* [365] proposed a distributed residential direct load control method that considers the operational constraints of three-phase unbalanced distribution networks. Two network reconfiguration approaches based on a look-up table-based algorithm and a Pareto-optimisation-based algorithm have been discussed in [366] for optimal reconfiguration in an unbalanced active distribution network.

4 Discussion

Fig. 7 pictorially summarises the state of the various objectives and categories for unbalance management in MGs. From the detailed literature survey presented in this study, related to the power quality issue of unbalance in MGs, the following points are instructive for the *islanded mode* of operation:

1. Most works deal with NS control ignoring the zero sequence components, while few studies have considered zero sequences for individual four-leg converters, more research is necessary for the parallel operation of these converters and the various issues therein such as zero-sequence circulating CC, neutral current compensation etc.
2. Most studies do not consider the full distributed energy resource system in the studies, i.e. the DC-link voltage is considered to be stiff. The complete system consisting of sources, storages, and their converters along with configuration (parallel or series connections) need to be factored in for the analysis.
3. There is scope for research on more effective controls for the issues such as current limitation and circulating current suppression and protection of the system.
4. The performances of the various control schemes under parameter variations especially the X/R ratios of the lines need to be analysed and investigated further.
5. Flexible control strategies for improving the power quality achieving multiple objectives such as harmonic, reactive power, and unbalanced mitigation simultaneously, should be researched upon.

6. The effect of unbalance on the DC link is the voltage ripple. Newer methods to eliminate this issue can be explored especially on the DC side itself, i.e. using the controllers of the interfacing DC–DC converters.
7. Attention needs to be focused on the architecture: four-wire MGs can be considered for effective unbalance mitigation for islanded MGs. Proper neutral conductor sizing and grounding need to be carried out for the same. Controls to curb the neutral to ground potential rise need to be devised.
8. The performance of the system under unbalanced conditions when DGs operating with different control structures are present in the system (combinations of different droop techniques as a heterogeneous combination) needs to be investigated, as researchers typically assume all the DGs in the system work with the same control scheme (homogeneous mix).

For the *grid-connected mode* of operation

1. Most studies consider only a single inverter connected to the grid and investigate the current/ power control as per the grid codes and protection (current limiting aspects). Multiple parallel GCIs and MG level unbalance management in the grid-connected mode have hardly been investigated. The control schemes need to focus on the sharing of the unbalance compensation goals among multiple units in the grid-connected mode.
2. An update of the standards about unbalance faults needs to be carried out. To date, only the German grid code has the specifications for DG control under asymmetrical grid conditions.
3. Efforts focusing on improved models of the DGs and systems under unbalanced conditions are needed for efficient imbalance/fault analysis to propose better controls and predict fault responses and performances.
4. The available literature already reports the susceptibility of various control strategies to parameter variations such as the grid impedance, X/R ratios of lines etc. This needs to be thoroughly analysed and methods to mitigate them need to be worked upon.
5. More work needs to be carried out for multi-area MGs and especially in hybrid AC/DC MGs. The sharing of the unbalance mitigation efforts (and power quality enhancement tasks) in a decentralised way between the controllers of the AC side converters, the interlinking converters, and the DC side converters is an aspect that needs to be researched upon.
6. Further research on effective current limitations and system-level protection schemes is needed.
7. Control schemes ensuring fast recovery after faults, which also ensure stable post fault operation needs to be worked upon.
8. More robust FRT schemes need to be worked upon, as existing FRT schemes do not consider distorted waveforms which may pose challenges in the detection of the fault inception and clearance instances that are required for proper changing of the control mode for imbalance management.
9. Newer strategies for the proper synchronisations with the unbalanced grid, seamless re-connections with grid after faults need to be explored.
10. The crucial operating aspects such as black start capability, seamless mode transition under unbalanced grid conditions need to be addressed.
11. The new concepts such as electric spring and soft normally open point need to be explored for their capability to mitigate unbalanced conditions.
12. Self-healing control strategies, reconfiguration and optimal scheduling and management, repair and resource scheduling of the system during and after faults and sequential service restoration are crucial aspects that need further work.
13. Coordinated control with other power quality improvement apparatus already existent in the system needs to be worked upon. Furthermore, optimal control strategies for improving the power quality achieving multiple objectives such as harmonic, reactive power and unbalanced mitigation simultaneously should be researched upon.
14. Further work on optimal power/load flow and dispatch algorithms and their RT implementation under unbalanced conditions and fluctuating renewable generation need to be carried out.
15. Efforts need to be directed towards the unbalanced sharing and the control and operational challenges there in between synchronous machines, VSGs, and inverter-based DGs under unbalanced conditions.
16. As mentioned for the islanded operation mode case, studies need to focus on the zero sequence components flow and control for the grid-connected system too and the issues such as neutral-ground potential rise need to be analysed thoroughly.

In general, the works do not consider the variability in the generation and most use only the true definition (VUF/current unbalance factor) for the unbalance quantification without considering the phase angle shift, which occurs under unbalanced conditions. The issue of unbalance mitigation should also be viewed through a systemic level and not just the control aspect. These are some vital aspects that need to be considered in future efforts.

5 Conclusions

Ensuring good power quality is an important aspect in the context of active distribution and MGs today. Most works proposed in the literature on MGs assume balanced conditions. However, with the increasing penetration of renewables and single-phase roof-top solar installations, the unbalance introduced in the system increases. The management of the system under unbalanced conditions is an important area, which has gained a lot of attention recently. The major issues due to unbalances in the islanded mode are overloading of the DGs due to overcurrents in the phases, unbalanced voltages at the PCC, high-circulating currents, disproportionate power-sharing among DGs and power oscillations, while in the grid-connected mode, the fast detection of faults, proper synchronisation, fault ride-through control, proper resynchronisation with the grid in the case of disconnection during fault and stable ramping up of the power after fault recovery, DG power and over current limiting are the main challenges. This study has presented a comprehensive, critical and exhaustive survey of the various approaches which have been researched upon in this area in the context of the islanded and grid-connected modes of operation of MGs and individual inverter control under unbalanced conditions. Further future directions for research have been outlined categorically for the MG operating modes. Various control algorithms and topology modifications have been categorised and the work would prove to be beneficial for engineers, utility operators, designers, researchers, manufacturers, and practitioners in the field.

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