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Review

Single-Phase Microgrid Power Quality Enhancement Strategies: A Comprehensive Review

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Abstract: Renewable distributed generators (RDGs) have made inroads in recent power systems owing to the environmental effect of traditional generators and their high consumption of electric energy. The widespread use of RDGs has been a recent trend in numerous nations. The integration complexity and the intermittent nature of RDGs can undermine the security and stability of microgrids (µGs). In order to guarantee the effectiveness, dependability, and quality of the electricity delivered, appropriate control methods are necessary. RDGs are being included in single-phase microgrids (1Ø-µGs) to generate energy closer to the user. The creation of low-voltage µGs allows for increased energy efficiency and improved electrical supply dependability. Nevertheless, the combined power pumped by DGs might create power quality (PQ) difficulties, especially during off-grid operations. The three biggest problems with PQ are reactive-power swapping, voltage and frequency (VαF) variations, and current and voltage (IαV) harmonic falsification associated with 1Ø-µGs; these conditions may affect the operation of µGs. The designed and implemented (primary–secondary control systems) in RDGs are the prevalent strategy discussed in the literature for mitigating these PQ difficulties. Furthermore, emerging grid innovations like the electrical spring offer viable alternatives that might reduce some problems through decentralized operation. Although several research studies have addressed PQ concerns in 3Ø-µGs, not all of these solutions are immediately applicable to their 1Ø equivalents. In this paper, the state of the art and a performance comparison of several PQ enhancement strategies of µGs is discussed. Additionally, the primary difficulties and several PQ approach tactics are highlighted. All vital features from high-quality published articles and new dimensions in this field are presented for mitigating PQ difficulties in 1Ø-µGs.

Keywords: frequency control; power quality; renewable distributed generators; voltage control; 1Ø-µGs

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1. Introduction

Single-phase microgrids (1Ø-µGs) have recently received significant consideration as an alternative solution to provide a reliable and sustainable power supply to remote and isolated communities [1–6]. These µGs are typically designed to operate autonomously from the main power grid, making them an ideal solution for areas with limited access to conventional grid infrastructure. However, power quality (PQ) issues have emerged as the primary challenge that undermines the efficiency and reliability of 1Ø-µGs. These issues occur due to the intermittent nature of renewable energy sources (RESs), voltage and frequency (VαF) fluctuations, and harmonic distortions (HDs) [7–12].

The PQ issues in 1Ø-µGs can be classified into three categories: voltage stability (VS), frequency stability (FS), and HD [13]. VS refers to the ability of the µGs to maintain a stable voltage level under varying load conditions [14,15]. It is a critical factor that influences the efficiency and reliability of a µG. Voltage instability can cause equipment damage, power interruptions, and system instability [16–18]. Similarly, FS refers to the ability of a μG to maintain a stable frequency level under varying load conditions. An underachieving FS can cause equipment damage and system instability. HD is another significant PQ issue in 1Ø-μGs. It refers to the distortion of sinusoidal waveforms due to the presence of stochastic/nonlinear loads, like electronic devices and converters. HD can cause equipment damage, electromagnetic interference, and system instability. Therefore, mitigating PQ issues is critical to ensuring the proper functioning of 1Ø-μGs [19–22].

Phasor measurement units (PMUs) offer time-synchronized signals from numerous μG positions; these signals are especially important when there is increased installation of DGs [23]. By monitoring the power system's variables with PMUs, a μG can promptly identify any grid instabilities. Only SCADA and EMS information were previously used to track the P–V and Q–V curves, but earlier studies created a model-free approach to detect the voltage amplitude. Based on [24], PQ can also be handled by PMUs. To examine any variations in V and F at the structure, real-time information from the PMU can be recorded for a set amount of time [24,25]. PMUs can gather V and F for the PQ analysis of information [24,25]. A minimization model is required to choose PMUs at tactical bus positions before conducting any investigation with PMUs [26–28]. In order to find the best location for the PMU, Ref. [28] presented recursive quadratic programming (RQP) with fewer limitations on equality than the design variables specified on an intimate set. According to the findings, RQP identifies the ideal PMU positions with the smallest number necessary for rendering the power system completely visible. A notable enhancement in the visibility over the estimation of redundancies produced by the RQP optimization approach, originally reported in [27], was demonstrated through numerical experiments on common benchmark power networks. Furthermore, study directions and applications of PMUs were presented in [25,26,29]. The setup and analysis of PQ using a PMU situated at a sensitive load were covered in Ref. [24]. The data from the PMU were assessed and identified anomalies in the V and F readings from the sensitive loads' PQ limitations.

Several mitigation strategies (energy storage systems (ESSs), VαF regulation, and active power (P) filtering) can be implemented to address PQ issues in 1Ø-μGs [30]. ESSs can be integrated into a μG to store excess power generated during peak hours and supply it during low-demand periods. This reduces the impact of power fluctuations on the VαF stability of the μG [31–34]. Voltage regulation (VR) techniques, such as tap-changing transformers, can be employed to maintain a stable voltage level under varying load conditions. VR techniques can effectively mitigate the voltage fluctuations in a μG [35,36]. Frequency regulation (FR) techniques, such as load shedding and using a dedicated frequency control system, can be employed to maintain a stable frequency level under varying load conditions. These techniques can effectively mitigate frequency instability in a μG [37]. Active power filters can be employed to reduce the HD caused by nonlinear loads. These filters act as a current source and inject a pay-off current into the system to offset harmonic distortions [38].

The decentralization of energy production is a contemporary phenomenon resulting from the widespread interaction of distributed generators (DGs). RESs and ESSs are typically part of low-voltage (LV) systems since they generate electricity closer to the user. The construction of 3Ø and 1Ø μGs that exploit energy utilization and enhance the resiliency of the community power grid has been made possible by the coordinated operation of generation and load. Nevertheless, problems are caused by the increase in converters inside the LV systems, causing numerous PQ problems during on-grid and off-grid operations [5,39,40]. In 1Ø-μGs, VαF variations, reactive power (Q) exchange, and voltage/current (V/I) HD are PQ concerns. Recent attention has been drawn to the PQ difficulties in off-grid operations since the consequences of these phenomena are amplified owing to the absence of grid rigidity [41–43].

The VαF deviations (ΔE and Δω, respectively) in to the droop control (DC) algorithm are required for demand-side management (DCM) [44,45]. The deviations' steady-state records are determined by a variety of variables, together with the DC gains, the impedance's load, and the injected P by the grid-following and -forming inverters linked to the µG. VαF variations are thus inevitable under regular events and are exacerbated by changes in loads. Additionally, the local voltage amplitudes regulate the DG units' Q production. The effects of unbalanced line impedances and inadequate DGs output impedances result in Q exchange between DGs [46], which lowers the maximum output P and increases the loss of power in the system [47].

In 1Ø-µGs, V/I harmonics are an essential PQ problem. HD increases power losses and may result in µG stability issues, especially in off-grid µGs. Due to poorly constructed control loops, DG units may introduce current harmonics. In addition, the harmonic I that DGs pump into the grid is known to rise with V distortion at the point of common coupling (POCC). Moreover, DGs create V-HD at the PCC as a result of harmonic currents needed by local nonlinear loads [46]. µGs with 1Ø may also use traditional passive/active filters for selective harmonic frequency adjustment [48–51]. Unfortunately, the mentioned filters raise the system's price and provide no further benefits to the µG except harmonic compensation. Moreover, these filters provide new resonant modes that might affect the µGs' stability by amplifying certain harmonic frequencies.

The hierarchical control architecture (HCA) also coordinates the activities of the grid-following and -forming units in 1Ø-µGs. The µG-HCA is separated into 3 sections, with diminishing frequencies as one moves up the hierarchy, as depicted in Figure 1 [52–58]. Typically, control algorithms that address particular PQ issues are implemented in one or a mix of these levels. Since the tertiary level is often not linked with the functioning of 1Ø-µGs, only the primary control (PC) and secondary control (SC) mechanisms for DGs are analyzed in this review.

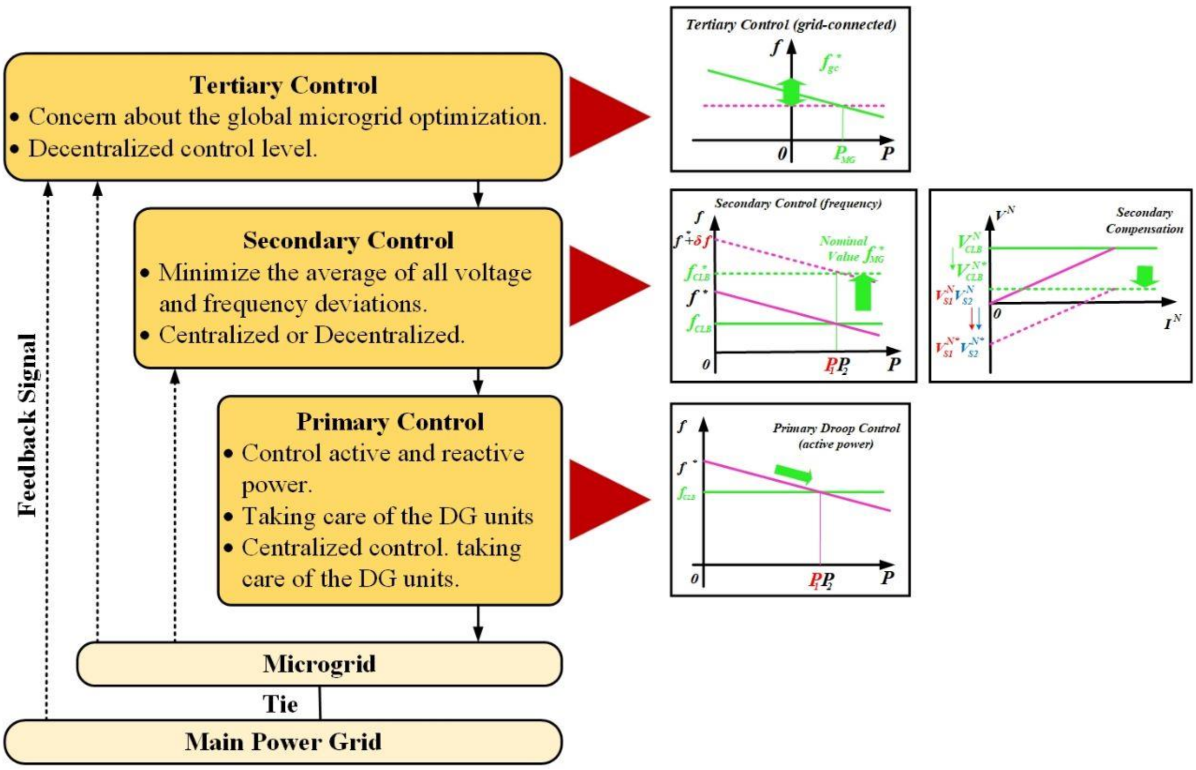

Figure 1. µG control and optimization use of 3 HCAs.

The primary DC and inside control loops (CLs) of the DGs comprise the first level. Using (*P*-*F*) and (*Q*–*V*), the DC method enables truly decentralized operation [26]. Traditional DC has been extensively discussed in [53,59–64]. The secondary level can be constructed as either a centralized HCA [65,66] or a distributed HCA [67,68] to optimize various operational characteristics of the µG. In the centralized architecture, SCLs are implemented in a central μG controller, whereas in the dispersed construction, the DG is involved in statistics to attain a shared aim. In contrast, power-based control (PBC) with a buckle-down accommodating strategy has been discussed [69–72] for addressing PQ problems in μGs. The PBC is situated between the classic DC and optimal control methods, which require comprehensive grid models. Nevertheless, the PBC method has primarily been explored for systems in 3Ø settings.

The 1Ø-μGs could benefit from an alternative solution provided by emerging grid technologies. Electric springs (ESs) were proposed as a substitute to traditional load voltage controllers (LVCs), which are fully described in [73–78]. Alternatively, in LV systems with RESs, ESs were coupled in series with nonessential loads to deliver V stabilization via essential loads [77]. In addition, ESs reduce the need for communication tools in DCM [77,79,80]. The configuration created by the ES and the nonessential load is usually denoted as a smart load (SL) [81–83]. In [84], the operating principle of ESs built on Hooke's law was presented. Simply put, through the absorption/supply of any excess/deficit of P in the local μG, the function of the ESs minimizes any V variations diagonally the crucial load. In [81], a comparison was made between the operation of several simultaneous ESs and a STATCOM. This comparison showed that a group of ESs manages VR better than a STATCOM with less Q. In [85], the authors demonstrated that one can reduce the size of the battery by integrating ESs into μGs. However, this is only possible if the ESs themselves lack ESS. Otherwise, the ESs could be used to decentralize battery rather than reduce ESS needs. Recent literature reviews of μG control and management algorithms can be found in [86–95]. Nevertheless, solutions designed for 3Ø-μGs are not always applicable to 1Ø-μGs. In this paper, we present an analysis of the current difficulties associated with PQ in 1Ø-μGs and propose mitigation strategies to address the problem. Hence, the following literature review focuses on methodologies and algorithms suitable for 1Ø-μG

The rest of this paper is organized as follows: Section 2 offers a quick overview of the PQ issues discussed in this work. Sections 3 and 4 discuss the HCA approaches for improving PQ. Section 5 discusses the emerging technology of ESs for improving PQ in 1Ø-μGs, while Section 6 compares and contrasts the various algorithms and methods. Future research directions are presented in Section 7. The conclusion of this review is presented in Section 8.

2. Difficulties with PQ in 1Ø-μGs

Multiple DGs with inverter interfaces that provide PαQ to nearby loads make up a μG. PQ issues with off-grid 1Ø-μGs are made worse by the grid's shortage of rigidity. Here, voltage/current HD, Q exchange, and VαF fluctuations are PQ issues. It is well known that electrical networks' current harmonics are primarily caused by power-electronic systems. Due to the nonlinear voltage dips caused by current harmonics in the distribution network, voltage HD is created at the equipment's PCC. The harmonics in VαI also interfere and increase losses [96,97].

The fragile equilibrium between production and demand is maintained by the DGs under control of the PαQ and VαF fluctuations; departures from nominal values are what cause fluctuations. VαF transitions happen when the dynamic balance changes as a result of changing loads. Depending on the DG's ability to react to load fluctuations, oscillations may result. Off-grid operations experience considerable frequency variations; whole loads can be powered by inertia-free, converter-driven machines. Furthermore, an excessive P fed by DGs may set in motion overvoltage, which needs to be regulated to ensure the adjoining critical loads are met [98,99].

The Q generated by the DG units during off-grid service does not help with power transfer, despite the fact that certain loads and the PCC's need for VR demand it. Q transmission among the converters is made possible by the differential converters' output voltages and load-dependent voltage fluctuations. In order to improve the operation of a μG, the Q produced by the DGs need to be reduced [100,101].

Typically, distribution systems function in radial mode, which involves radially connecting most of them. Others might have feeders that close the loops, but, generally, open switches maintain the loops open, and the loops only close when other components of the loops become open because of failures. This maintains this structure, and the system's safety features are built to work in a radial fashion. On the other hand, because of the DG connections at various sites, power flow within the μGs can be bidirectional. As a result, the μGs are not adequately protected by the standard protective measures [102–104].

The limited fault current capability of the converter devices within a μG is another issue. Except in situations when they are expressly engineered to generate a large fault current, the amount is often less than 50% of the rated current. When compared to utility DGs, the fault current provided by the μ sources is less in this situation. If enough μ sources have converter interfaces, switching from grid-tied to separate functioning would significantly reduce the amount of μG faults. As a result, the structure's overcurrent relays' sensitivity and functionality are impacted. If the relays are configured for larger fault currents in a grid-tied execution, the separate mode causes identical relays to work extremely slowly or not at all because of decreased fault currents. There are several different strategies for protecting μGs that have been developed and documented in the literature, such as adaptive protection, differential protection, distance protection, voltage-based protection, deployment of external systems, overcurrent, and symmetrical components [105–107].

3. HCA for 1Ø-μGs

The investigated μGs have also adopted a hierarchical architecture to increase the performance of droop control. These 1Ø-μGs networks can implement the following solutions to address power quality issues: elimination of Q exchange between DG units, regulation of VαF fluctuations, and alleviating VαI harmonics [108–116]. Various strategies are discussed in the next subsections to show the topic's significance.

3.1. PC Loops (PCLs)

Traditional DC performs poorly in 1Ø-μGs because these networks are mostly resistive. The physical PαQ appearance of DGs with an output filter inductor–capacitor (LC) is connected to these types of μGs [117]. This coupling results in a finding of the middle ground between VR and power-sharing precision [118]. Hence, the voltage (V) variations, frequency (F) oscillations, and Q issues of DGs are present in μGs. In [119–122], inverse/reverse droops for primarily resistive μGs were proposed. For resistive networks, the DC laws are stated as:

$$F = F^{*} - mQ \tag{1}$$

and

$$\mathrm{V} = V^{*} - nP \tag{2}$$

where m and n represent the DC gains.

However, reverse DC gains also result in V/F fluctuations and high Q exchange between DGs. Moreover, the inverse droops prevent the straight linking of synchronous generators (SGs) to the μG. Following the installation of a supplementary L at the exit of the LC filter of the DGs, researchers [123,124] showed that standard droops may be employed in LV-Gs with acceptable performance after this. The large gains in traditional DC minimize the Q exchange between DGs, as proposed in [125–127]. The VαF oscillations are greatly exacerbated by high DC gain increases, particularly when the load is changed [117].

Selected harmonics compensation approaches incorporated in the DGs' PCLs have also been suggested as a means of reducing the VαI harmonic infusion by DGs in LV-μGs. In [128], an hth harmonic DC that dampens harmonic VsαIs was investigated. In essence, this technique raises the harmonic frequencies of the traditional DC. The level of complexity of the DC gain structure of the inverters is increased by the requirement to add several harmonic DCs according to the chosen harmonics.

Alternatively, linear harmonic controllers (HCs), proposed in [116,129–131], were utilized to alleviate VαI harmonics in μGs. The applied controllers were proportional resonant (PR) with low impedance at the harmonic F (HF) under consideration. Ref. [116] examined selective HC using PR controllers in 1Ø-μGs. The inner VαI loops are controlled by PR controllers with selective HC, as depicted in Figure 2. Each controller's transfer functions (TFs) are stated as follows:

$$G_{I,V}(s) = k_{pI,V} + \sum_{h=1,3,5,7} \frac{k_{iI,\ Vh}s}{s^2 + \omega_{cI,\ Vh}s + \omega_h^2} \tag{3}$$

where ($k_{pI,V}$, $k_{iI,\ Vh}$), $\omega_{cI,\ Vh}$, and ω_h are the proportional and resonant gains at the HF, which regulates the bandwidth at any HF, and the resonant F, respectively.

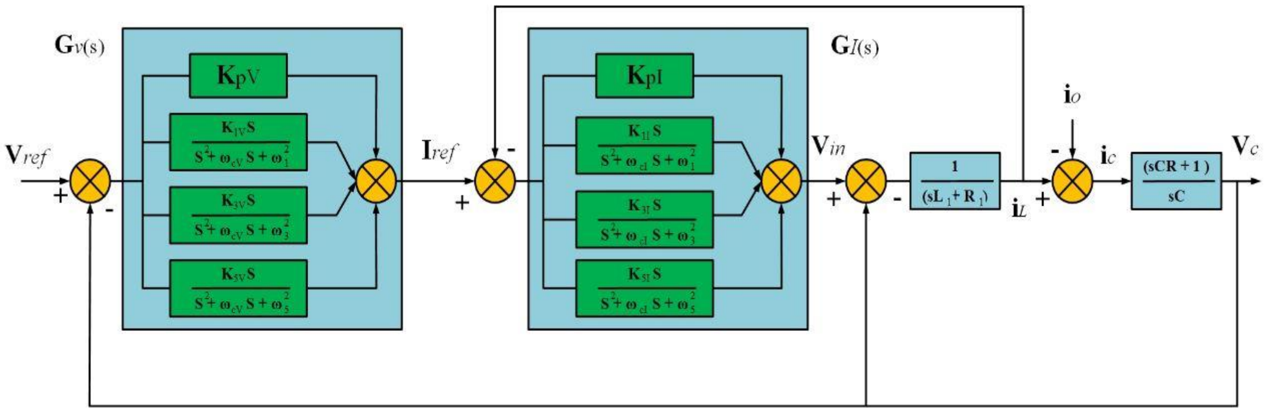

Figure 2. Internal CLs for a 1Ø−DG with PR controllers for VαI controls.

The low output impedance of the DGs as a result of the selective HC by the PR controllers reduces the VαI of the harmonics in μGs. Nevertheless, since external factors might affect the DGs' terminal impedance, PR controller functionality may suffer.

3.2. Virtual Impedance (VI) for PQ Enhancement

Other PC approaches suggested for improving the PQ of 1Ø-μGs are built on the impression of VI loops (VILs). VILs can be implemented in both 1Ø and 3Ø-μGs. R or L, RL, and RC are the emulated VI in [116,132–134]. As shown in Figure 3, the VIL is unified into the PCLs of the DGs. Multiplying the VI's Z_V by the output I (i_o) and additional to the desired V from the DC loop $\left(V_{ref}\right)$ to attain.

$$V_c = V_{ref} - i_o Z_V \tag{4}$$

where V_c is the wanted V output.

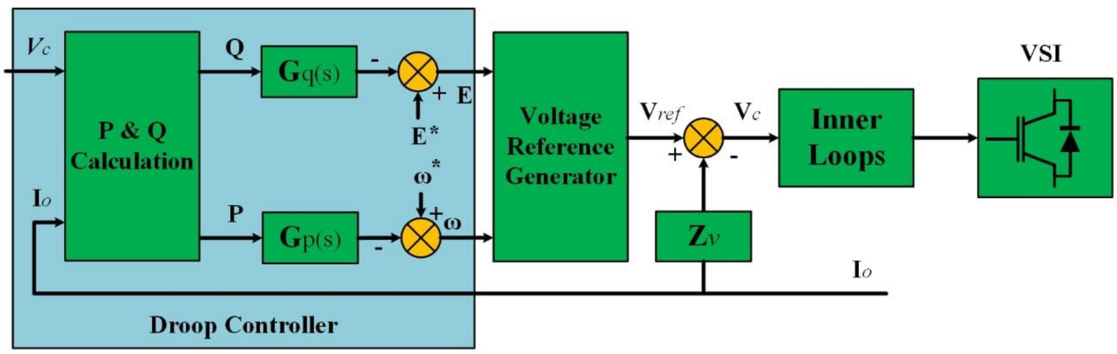

Figure 3. PCLs of a DG together with the VIL.

The R/L of VIL helps improve I allotment though minimizing steady-state VαF disparities. This suggests that the Q interchange between DGs has also been boosted. RL-VIL was proposed in [132–134], allowing for multiple output impedance options. This strategy was proposed to minimize the exchange of Q. Via a preservative, the virtual reactance, and a varying virtual resistance, the Q output was adjusted [134]. However, RL-VILs can diminish the efficacy of PR controllers by reducing resultant harmonic I and can increase V-HD, as reported in [116].

In [113,116,135], an RC-VIL that decreases the harmonic I by the DGs and the V-HD was suggested. As depicted in Figure 4, the C-VILs simulate a virtual C bank linked in series with the converter's terminals [136,137]. In this conceptual diagram, each C is a bandpass filter and a C impedance tuned to a separate HF. For compensation of the third, fifth, and seventh harmonics, the TF Zv(s) for the simulated C bank is expressed as:

$$Z_d(s) = R_V - \sum_{h=1,3,5,7} \frac{\omega_{ch}(k_{ph}s + k_{ih})}{s^2 + \omega_{ch}s + \omega_h^2} \tag{5}$$

where k_{ph} represents proportional gains, and k_{ih} represents integral gains.

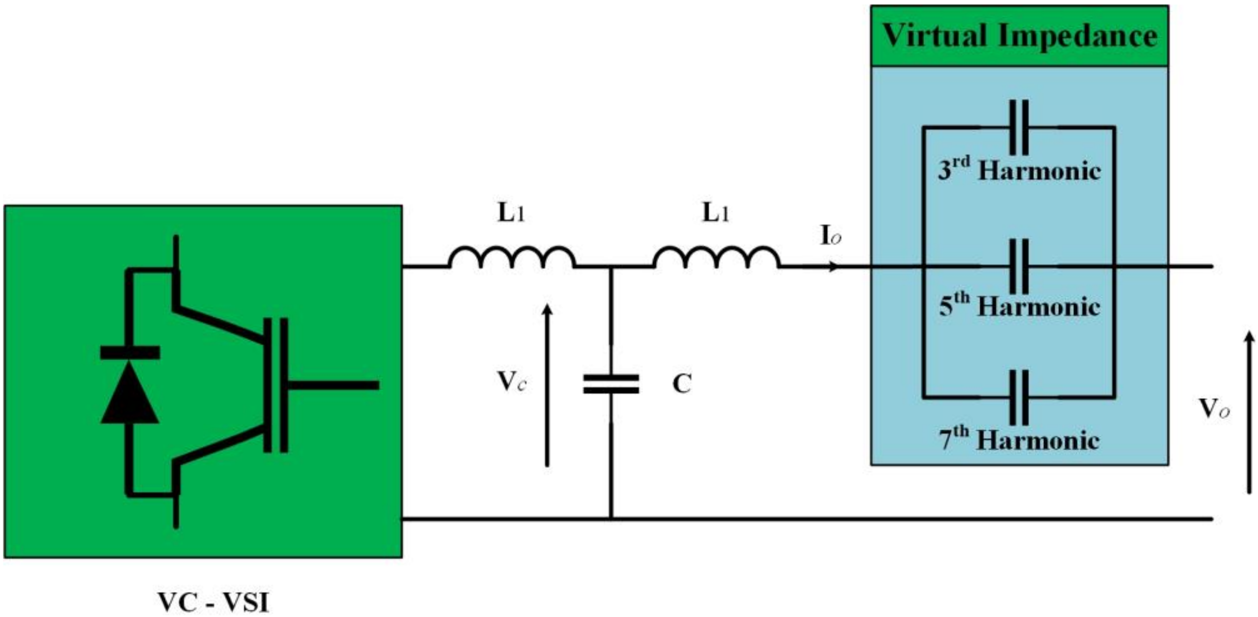

Figure 4. The proposed concept of C−VIL.

As shown in Figure 5, an adaptive negative virtual harmonic impedance (NVH-Z) loop to reduce I's harmonic in μGs was investigated [138]. A fast Fourier transform (FFT) function was applied to obtain the fundamental current and harmonic components I_o and I_h. The harmonic component and fundamental component were multiplied by Z_h, and Z_V, respectively. The Z_h value was adjusted by an algorithm for controlling harmonic droop, which is defined by the next equation [132,133]:

$$Z_h = b(H_o - H) \tag{6}$$

where b represents the $Z_h - H$ droop coefficient, H_o represents the harmonic variance capacity, and H represents the real harmonic produced power.

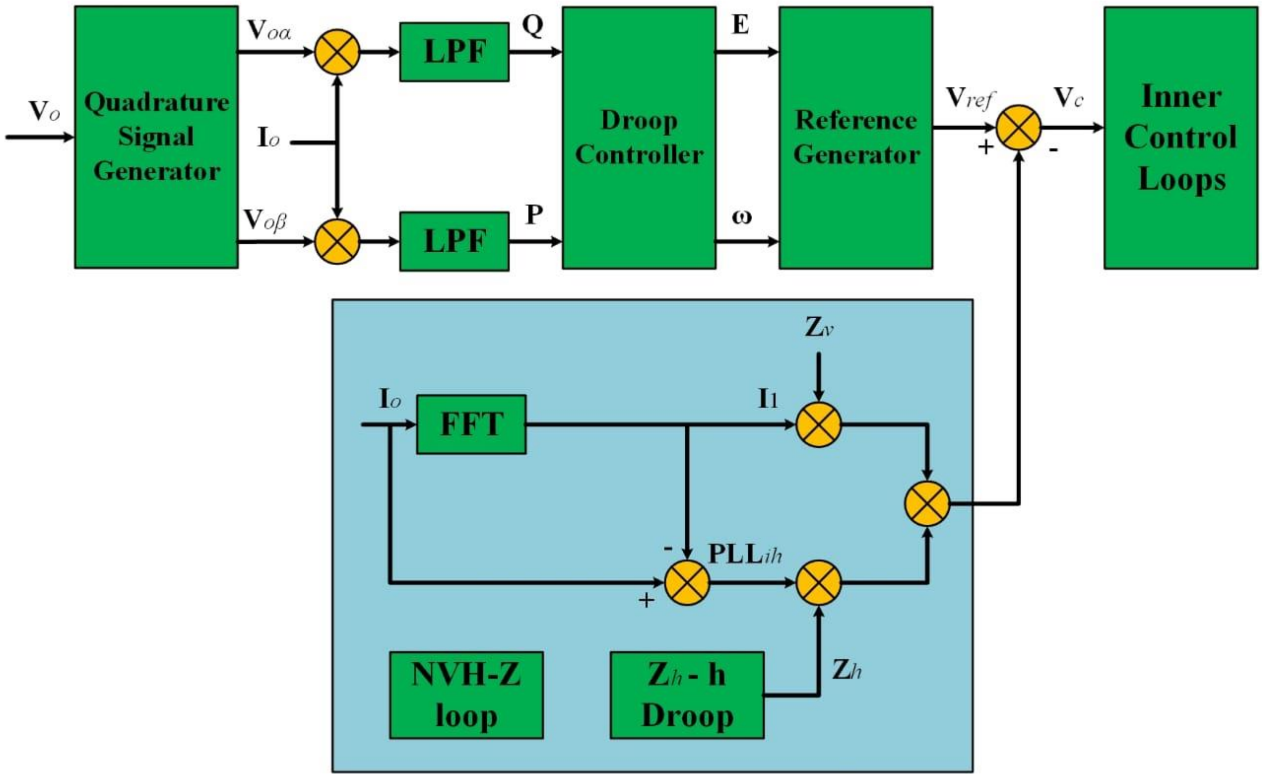

Figure 5. Adaptive NVH−,Z loop.

The resultant desired V is then fed into the VαI controllers.

4. Centralized and Distributed SCs

Since PCLs can only measure local variables, they cannot successfully enhance the PQ of µGs. Typically, VIs are designed with a known µG impedance [133]. However, in an off-grid µG, this impedance changes dynamically due to load switching. To achieve this advanced functionality, SC loops (SCLs) are required [118].

In [118,139], the authors proposed an HCA in which the µG central controller (µGCC) regulates the µG's VαF. The µGCC restores VαF by cascading the CLs of the DGs in the µG with PI control. Since SCLs are not essential to the operation of the µG and serve only to optimize its operation, only a low-bandwidth communication (LBC) connection is essential. However, because the Q is not accounted for in the choice of V compensation factors, these SCLs may increase the Q exchange flanked by DGs. In [140], Q sharing in islanded µGs using adaptive V-DC [141] and SCLs that eliminate Q exchange between DGs in 1Ø-µGs and simultaneously regulate VαF were examined. In [136,142], a Q-sharing block (SB) was added to the µGCC to eliminate the Q exchange between the inverters. As shown in Figure 6, the Q-SB was used with the VR loop. The µGCC determined the Q demand for each inverter, enabling per-unit Q sharing. In this instance, LBCs were applied to spread the pertinent work. In [140], additionally, the process took the limited quantity of power that could be obtained from the power source into consideration.

An adaptive DC loop (ADCL), which eliminates Q exchange among DGs and simultaneously controls VαF, was proposed in [141]. Figure 7 depicts the ADCL's block diagram. A central/fundamental controller of the µG determines the Q* for each DG. Then, the initial DC gain n is supplemented with a small departure from the integrated controller's DC gain. The magnitude of the output (E) is calculated using the suggested DC parameter n*. The ADCL's operating is comparable to that described in [136]. In the latter, SCLs were fed a V deviation that was additional to the PCLs; whereas in the former, DC parameters were adjusted to realize identical V deviation.

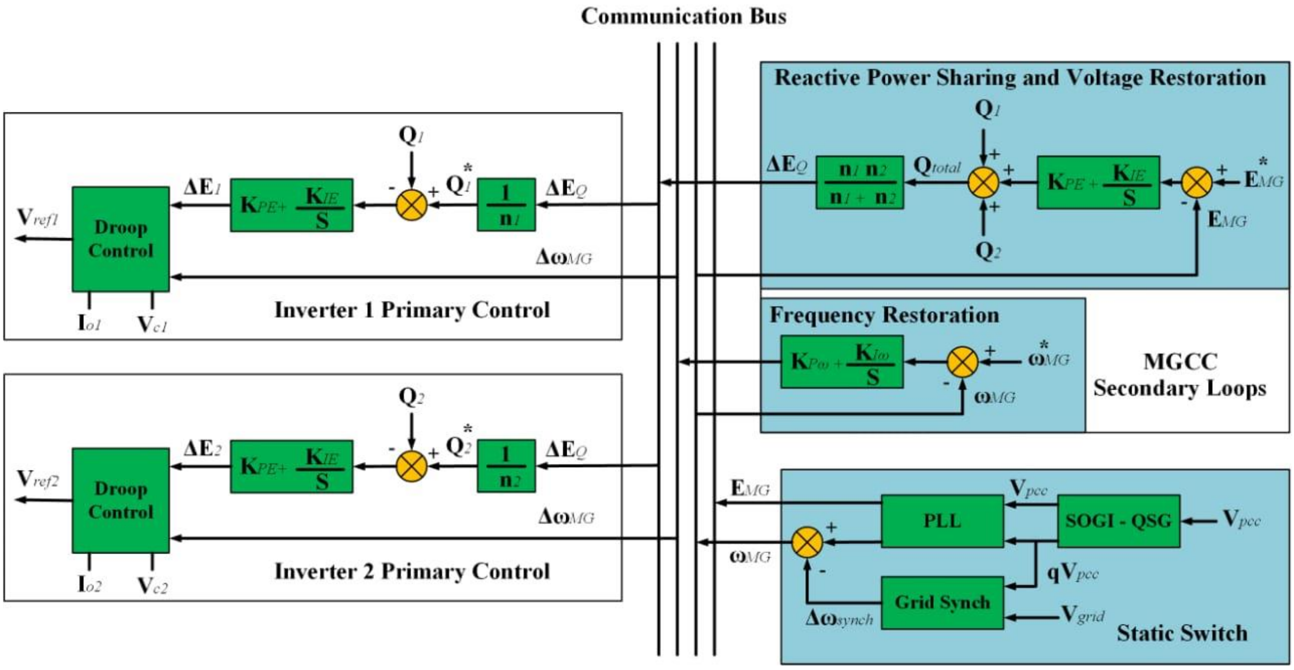

Figure 6. SCLs remove the Q conversation among the DGs while adaptable to the VαF of μGs.

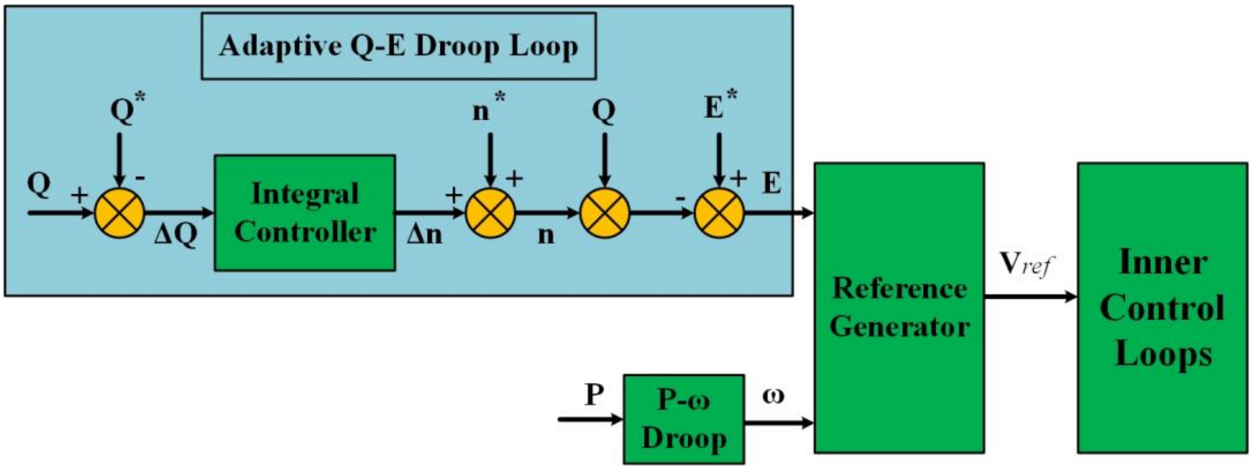

Figure 7. Adaptive (Q–E) DCL that minimizes the Q exchange among the DGs and adjusts the μG's PCC voltage.

In [46,133], the PCC's voltage HC was also taken into account. The authors in [46] proposed the HCA depicted in Figure 8, which reduces Q exchange and regulates VαF. The value and polarities of the voltage harmonics are extracted by a large number of second-order generalized integrators and diffused to the μGCC. To calculate the required harmonic correction by the DGs at the μGCC, a controller is employed for each harmonic.

The local DG then produces the compensating voltage, which is also managed by the PCLs. In [133], combining VIs with SCs was investigated. The researchers suggested that instead of a proportionate gain, the voltage harmonics are altered by VI in the DGs before being fed into the PCLs.

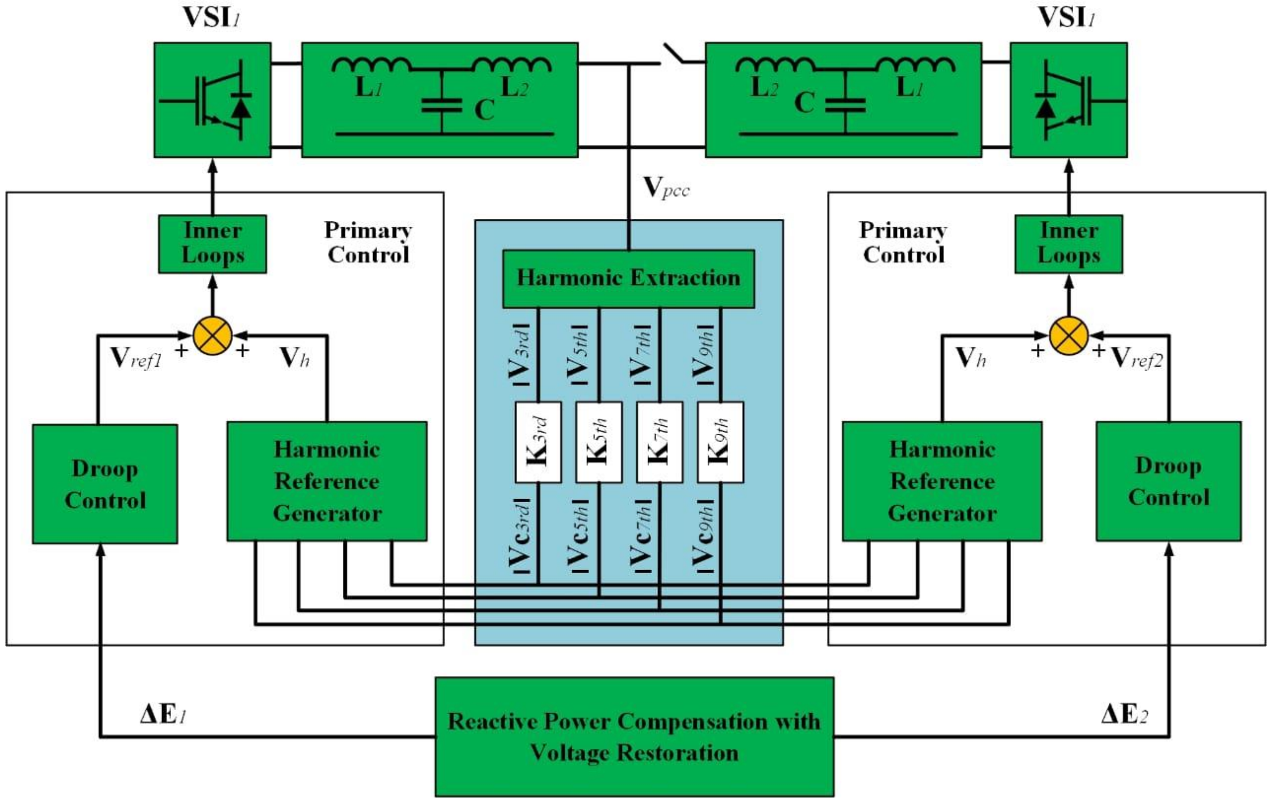

Figure 8. SCLs remove the Q exchange among the DGs even though adaptable to the VαF of µGs.

5. ESs in 1Ø-µGs

By virtue of their DSM capabilities and possible additional services, the ESs deployed in 1Ø-µGs may offer numerous benefits. Recent applications of ESs include VαF variations mitigation via DSM (PαQ) [79,82,143], power factor (PF) correction [144–146], and harmonic compensation [145]. Furthermore, the cooperative activity of several ESs was investigated in [147–149], because the parallel working of several SLs without coordination may find the balance in a µG's solidity.

5.1. Alleviating of VαF Variations

The primary ES configuration was covered in [150], and it has recently been referred to as ES-1 [151–153]. As illustrated in Figure 9a, ES-1 is linked in series with Z_{nc} and is made up of a half-/full-bridge 1Ø converter with a capacitor. The ES-1 in [143] operates in three different ways that are reliant on the accessibility and need for electrical P in the area. V_{pcc} is within the usual working range when the power production and load need are equal; hence, the ES-1 does not take part in DCM. It increases or decreases based on the relationship between power production and load request. An L/C voltage (V_{es}) is fed by ES-1 to keep the desired V_{pcc} via the control of V_{nc}. The ES-1's functioning causes the SL to provide restricted Q compensation, which controls the µG voltage, but it suffers from V_{es} and should be 90° leading/lagging i_{SL}.

The ES-1's PCL comprises two closed CLs that regulate the value and phase angle (PA) of v_{ES} [143]. Figure 10 illustrates the PCL's configuration of the ES-1. The value of $|v_{ES}|$ directly controls the Q output of the ES-1, whereas the PA ($\angle v_{ES}= q_{ES}$) between v_{ES} and i_{SL} controls the used P. For minimizing the ES-1 P's input/output, the 2CLs regulate the DC-link voltage. Ideally, it should not matter if some P flow is required to control the V's DC link (DCL). Additionally, the ES-1's Q compensation capabilities are constrained by the stored energy in the DCL capacitor.

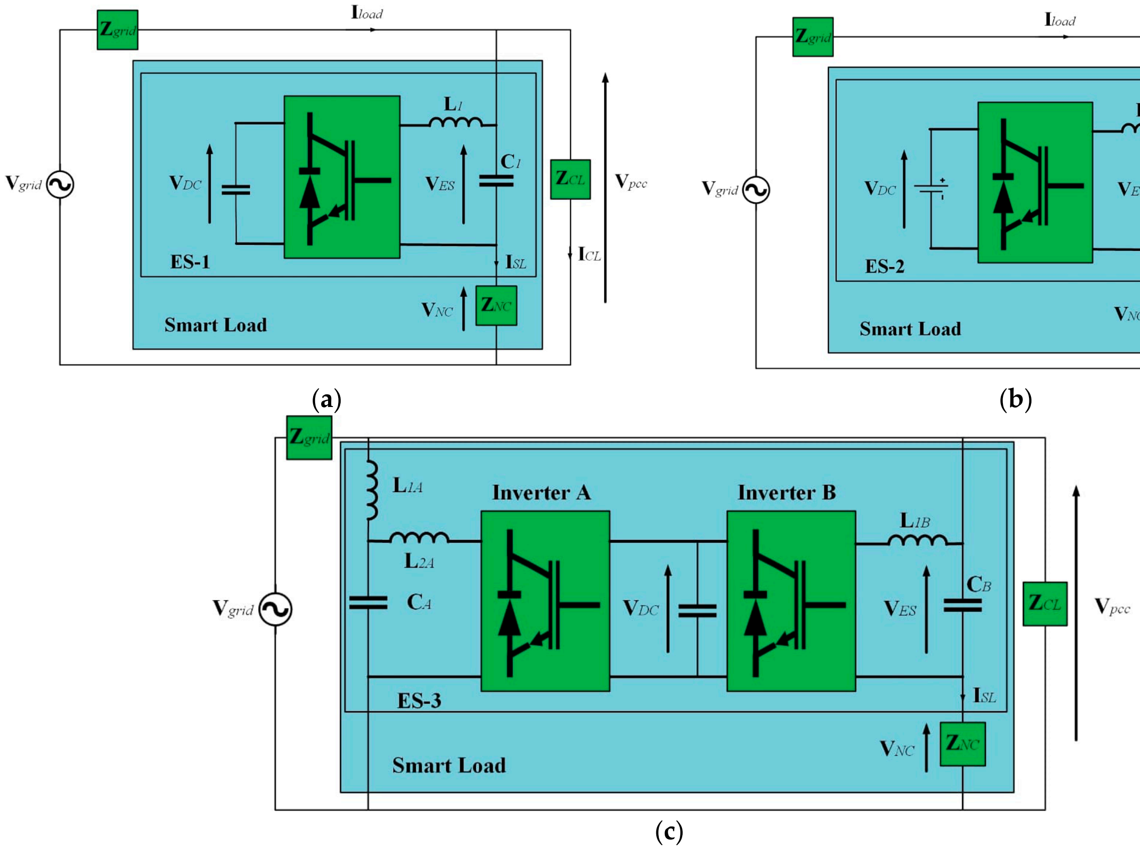

Figure 9. SL components: (**a**) ES−1 and Z_{NC}, (**b**) ES−2 and Z_{NC}, and (**c**) ES−3 and Z_{NC}.

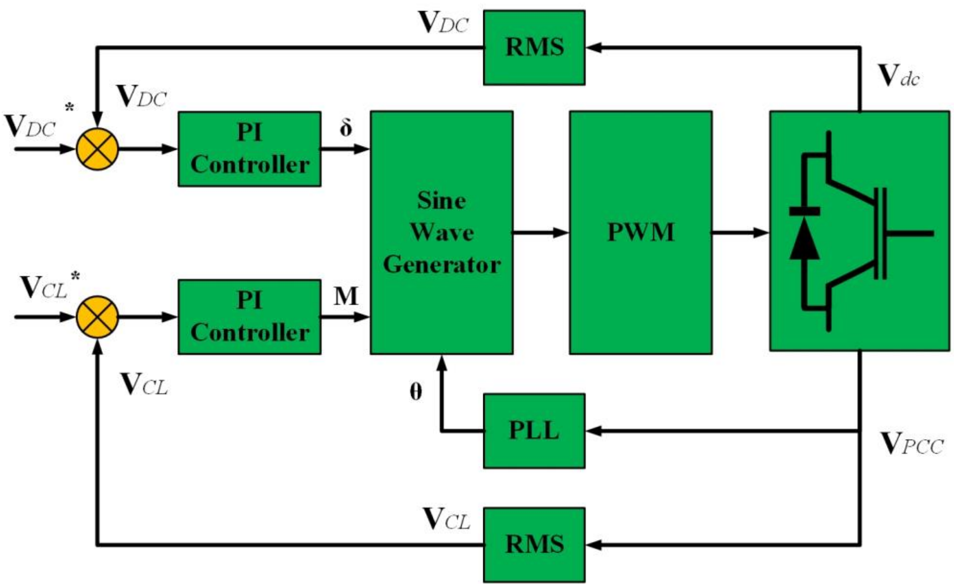

Figure 10. PCLs for VR and compensation of Q via ES-1.

For providing resident V support, ESs with DCM capabilities could also provide F regulation. Ref. [82] proposed an algorithm that enables an ES-1 to control the primary F. Figure 11 is a block diagram of this CL, which regulates the value and PA of the ES-1 v_{ES} based on ΔF. Consequently, the needed P consumed by the SL (P_{SL}) is calculated as:

$$P_{SL} = P_{SLo} + \Delta P_{SL} = P_{SLo} + m\Delta f \quad (7)$$

where ΔP_{SLo} is the SL's nominal P.

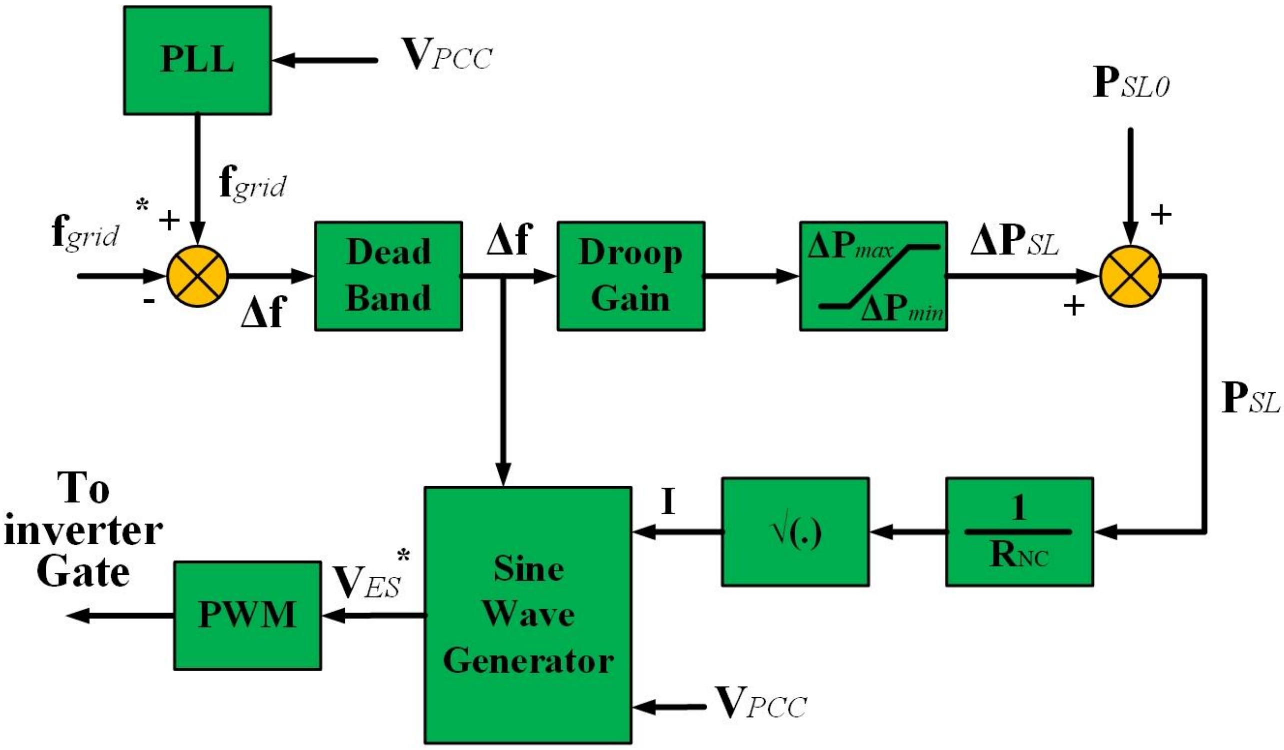

Figure 11. PCLs for FR by an ES−1.

The v_{ES} is dependent on I_{SL}, Δf, and v_{PCC}, as an ES-1 is only capable of exchanging Q. Fluctuations in V are limited to 10 percent as illustrated in IEEE1547 [1993]. Due to the limitations of the ES-1, however, P output managed via Q management is complicated [154].

5.2. Correction for PF

By adjusting for P/Q, an ES keeps the μG stable throughout variations in RES production/generation. Nevertheless, ESSs are necessary for sustaining P adjustment by ESs. ES-2 and ES-3 are two alternative ES structures that were designed in order to overcome around the P constraint of ES-1 [151,152]. As shown in Figure 9b, the battery bank in ES-2 takes the position of the DCL capacitor in ES-1. However, batteries have a number of known downsides, such as large expansion, a short lifespan, and a high price [155,156], which might restrict ES implementation in 1Ø-μGs. Figure 9c shows how ES-3 uses a 1Ø converter to substitute the batteries [157]. In general, converter B operates similarly to ES-2, while inverter A adjusts the DCL's V. ES-2's and ES-3's output's V (v_{PCC}) is adjusted at any angle, giving ES-2 6 more operating states than ES-1. By directing the ES-2's and ES-3's PαQ into a shared goal, PF adjustment is achieved.

PF compensation using ES-2 was proposed in [74], while strategies applicable to ES-3 were introduced in [158]. In [145], CLs in the dp reference frame to control the total incoming I i_{load}, as depicted in Figure 12, were designed. The i_{load} in Figure 9b comprises i_{sl} and i_{sl}. By individually adjusting the separated I components to produce an appropriate v_{ES}, PαQ compensation is carried out. In this instance, the limitation is that v_{pcc} is not directly regulated by v_{ES}. Since the i_{load} is being regulated, it presumes that all loads (critical/noncritical) are one load. In actual use, these two impedances may come from various equipment, and their combined I is measured outside of the SL.

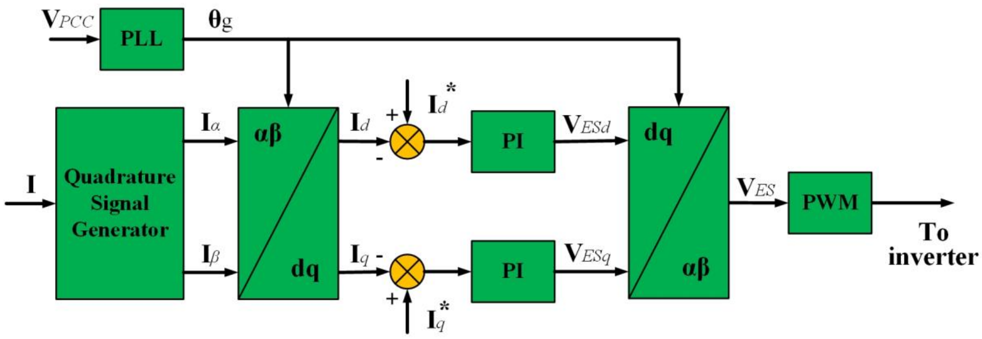

Figure 12. PCLs for ES−2's PF correction.

A dp frame-implemented input VαI control structure was presented in [74]. The PCL is depicted in Figure 13. PI controllers (PICs) regulate the components $v_{pcc,\ d}$, and $i_{in,q}$ in circuit 13, where the value is 13. In addition, the 1Ø phase−locked loop controls component $v_{s,\ q}$ to zero. In this instance, v_{pcc} is regulated in a straight line by v_{ES}, whereas i_{in} is regulated according to [145]. Ref. [159] proposed a δ-control method that models the local network using an observer to generate the desired v_{ES}. Figure 14 depicts the PF correction using the δ-control technique via ES-2. A PR controller helps to control v_{ES}, whereas an internal P controller control i_L. The viewer needs to know several parameters, including Z_{CL}, Z_{NC}, Z_{grid}, and voltages (V_{grid} and V_{pcc}). The SL is unable to determine these readings regionally, and they are not subject to change as a result of connecting or disconnecting loads.

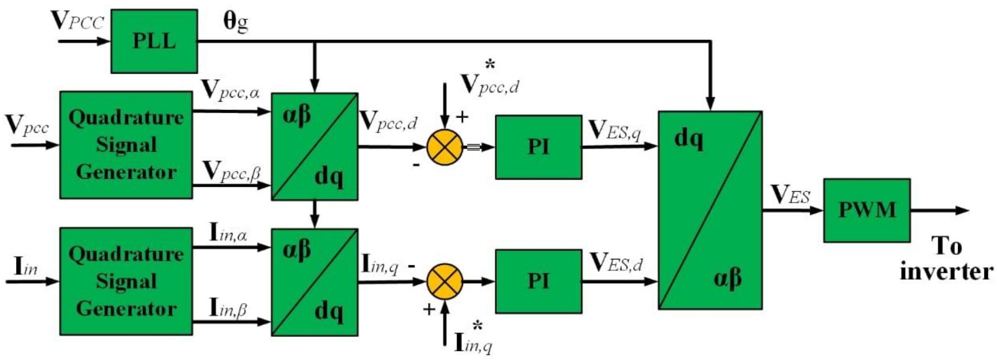

Figure 13. The VαI inputs control structure for PF adjustment with ES−2.

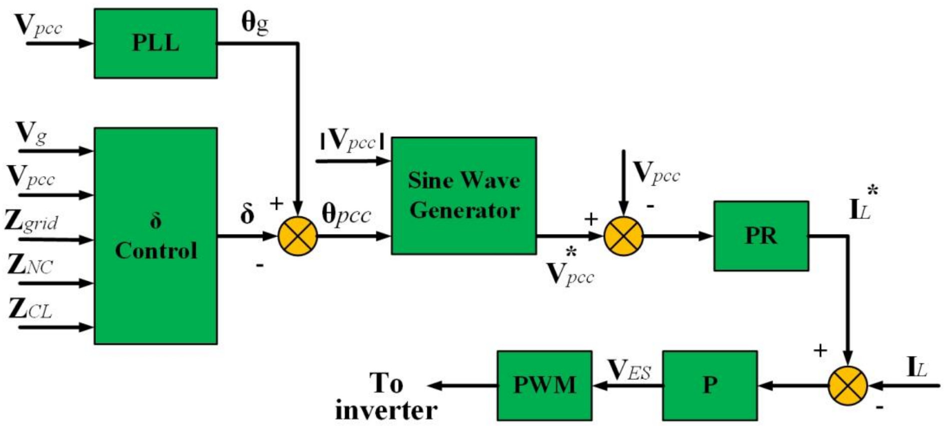

Figure 14. PF reimbursement control technique (δ) using ES−2.

Ref. [160] suggested a radial–chordal decomposition (RCD) algorithm for controlling the resultant ES−2. The strategy shown in Figure 15 hinges on regional variables that the

SL is able to measure. To perform PF adjustment with the ES−2, a v_{ES} vector must be calculated, which is not an easy task.

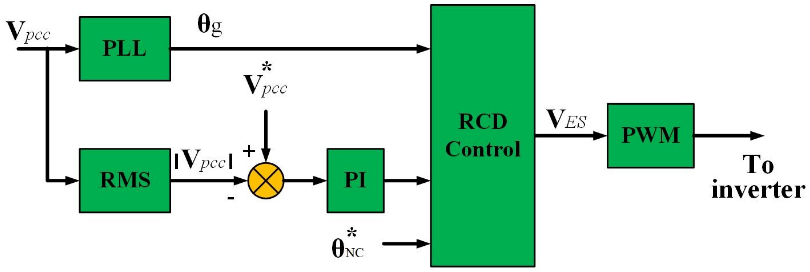

Figure 15. ES−2 uses the RCD technique to achieve PF adjustment.

Ref. [161] proposed a CL for ES-3 that adjusts the v_{pcc} and corrects the PF. As seen in Figure 16, converter A employs a PIC to regulate the DCL voltage (V_{DC}). The results of this loop are then used to create the reference v_{ES} for converter B by applying it to a mathematical representation of the SL. This CL's constraint is the unidentified equivalent R/X ratio of the system being used to weight the output of the PIC. This limits how the SL is deployed because an easy to set up capability is not available. In [158], an alternate solution dependent only on local parameters was introduced. Figure 17 depicts CLs in the dq frame to control v_{ES}. Converter B makes use of ES-2's capabilities, which uses a PIC to control $|v_{ES}|$ while maintaining a constant PA. Therefore, it is possible to obtain a sinusoidal V at the output of converter B ($v_{ES,B}$). By adapting the V_{DC} and $i_{in,A}$ with PICs in the dq frame, the CLs of converter A control the P sent to ES−3.

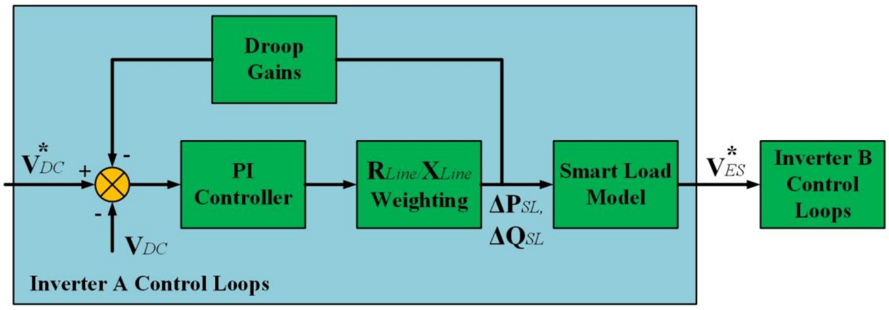

Figure 16. A CL is assigned to ES-3 for PF adjustment.

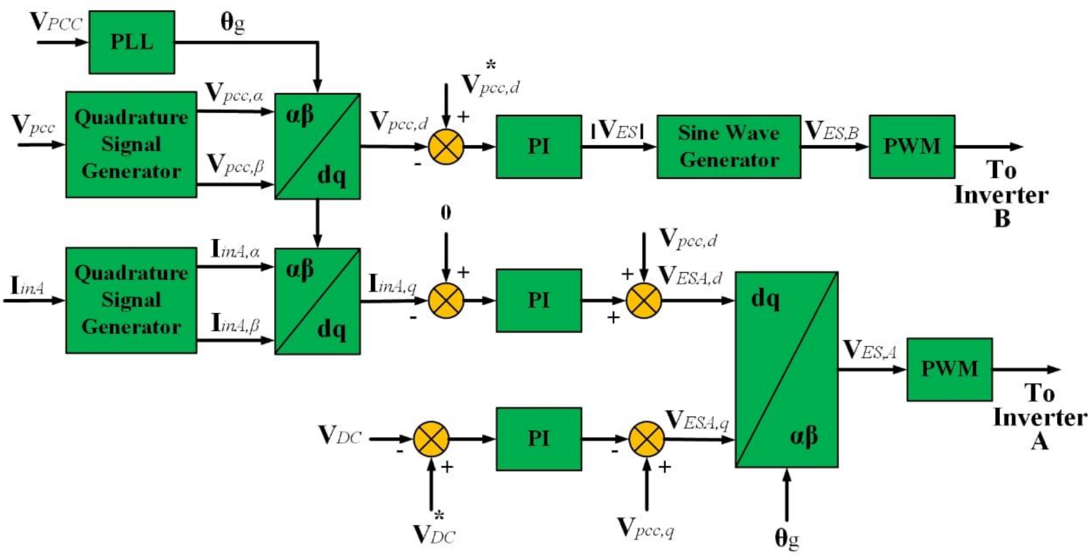

Figure 17. ES−2 uses the RCD technique for PF adjustment.

5.3. Harmonics Compensation (HC)

In [145], an HC process for ES-2 was introduced. As seen in Figure 12, the modified CLs are demonstrated in Figure 18. Using an FFT, the I harmonics are removed, and the CLs for each harmonic are introduced together. The method's effectiveness due to the measured/tested I harmonics phases was not taken into account during regulation. Also, the decreases in harmonics were not enumerated, so the algorithm/method's effectiveness is not objectively sound.

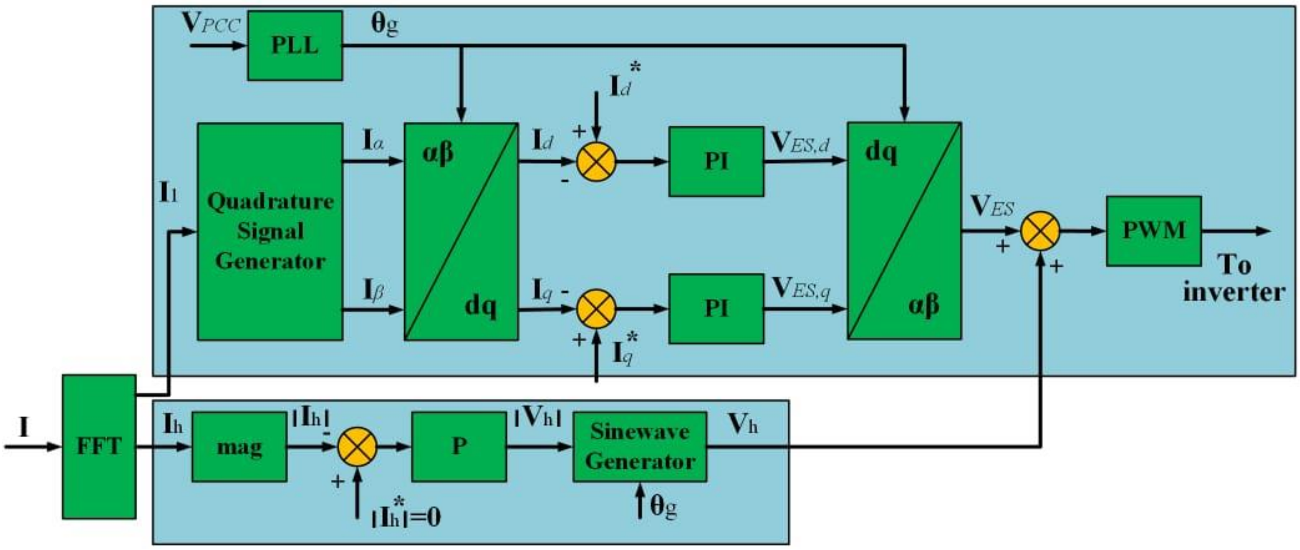

Figure 18. HC with ES-2.

5.4. Cooperative Operating of Several ESs

Ref. [145] examined how ES−1 and ES−2 operate simultaneously with not serious resistive loads. The two ESs serve complementary purposes: ES−1 adjusts the v_{pcc}, and ES-2 optimizes the PF through I management. This scenario shows how different ES types can cooperate because their individual purposes are diverse. Nevertheless, problems arise when several concurrent ESs autonomously handle the V, F, and/or PF at the POCC. When examining the VR in µGs, for example, all ESs within the µG are unable to use the same voltage reference. The I passes; subsequently, V drops at the line impedances cause the Vs in the LV circuits to differ [87].

A coordinated action amongst identical-type spread ESs was contemplated in [147]. In [148], a method for tuning ES-1′s PI gains to guarantee solidity when paralleling several ESs was described. To ascertain the PI gains to attain stability, a stability model was developed. Unfortunately, the range of benefits is solely applicable to the case study in question. Due to the necessity to tailor the gains for each unique circumstance, this technique fails to result in plug-and-play possibilities. Application of a V droop technique was used to manage the work of many distributed ES-1s, as first reported in [147].

$$V_{PCC} = V^*_{PCC} - KV_{ES} \quad (8)$$

where K is the V's DC parameter, V^*_{PCC} is the desired V's RMS, V_{ES} is the V's output, and V_{PCC} is the desired V obtained by the DC rule.

Multiple ESs can operate simultaneously without affecting the reliability of the µG, according to tests. In [135], the researchers proposed a two-level control technique (2LCT) to allow ESs to operate simultaneously. Figure 19 shows a block schematic of the 2LCT. Each ES−1 has a PCL architecture at the initial level, identical to that mentioned earlier [147], where G_V, Z_V, K, and (G_2, G_3) are the PR regulator, virtual impedance, V droop gain, and plant's TFs, which are represented as:

$$G_2 = \frac{1 + sXZ_o}{s^2 LZ_o + sLC + Z_o} \tag{9}$$

and

$$G_3 = \frac{1}{s^2 LZ_o + sLC + Z_o} \tag{10}$$

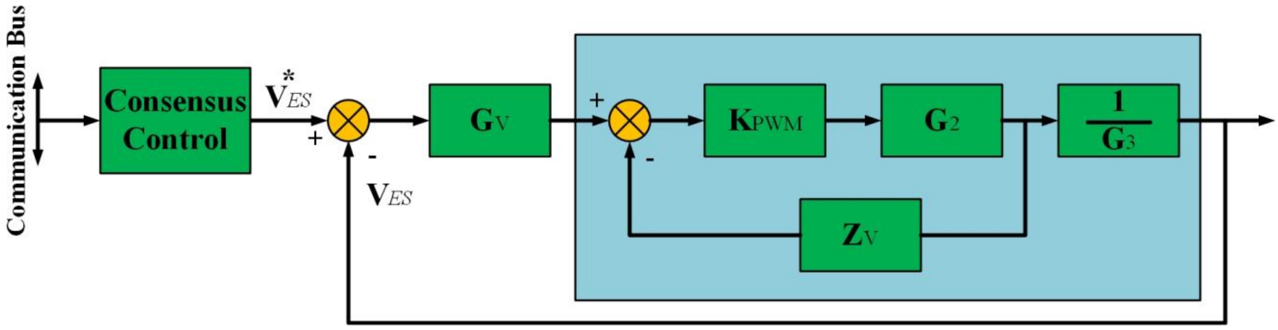

Figure 19. A 2LCT for several dispersed ESs.

The PCL's outside loop implements the DC legislation mentioned in (8). An extra virtual resistance is added to the CL in order to uniformly set the final impedance of each ES.

$$V_{ES}^{*} = V_{PCC} - R_V i_L \tag{11}$$

where V_{ES}^{*}, R_V, i_L, are the intended V's output, virtual resistance, and ES's inductor current, respectively.

Nevertheless, it is unclear from the analysis in [162] what effect R_V has on the SL's resultant impedance and the reactive compensated transfer. To achieve the desired V, a higher level that employs agreement control was subsequently created.

6. Discussion of the Approaches under Consideration

The above sections discussed the various methods and procedures that could be applied to address the PQ problems in 1Ø−µGs. Tables 1–3 summarize the characteristics and restrictions of the techniques outlined in the earlier parts of this paper. The capability of the strategy/system to lower/eliminate V/F changes, the Q between DGs, and VαI–HDs when applied to 1Ø−µGs are the bases for the comparisons.

Table 1. Strengths and restrictions of PCL approaches.

Method	Advantages	Limitations
Conventional DC [163–166]	• Easily implemented. • Resembles the functionality of SGs.	• VαF fluctuations. • A trade-off between VR and Q-sharing precision. • There is still Q interaction between DGs. • No harmonic I/V regulation (NH I/VR).
Traditional DC with additional GS inductor [57,123,124]	• Easy to implement. • Imitates how SGs work. • Enhances isolation between both DGs' PαQ signals.	• High VαF fluctuations. • A trade-off between VR and precise Q sharing. • The Q exchange (QE) between DGs is not disregarded. • NH I/VR.

Table 1. *Cont.*

Method	Advantages	Limitations
Inverse/reverse droops [121,167,168]	• Easy to use.	• High VαF fluctuations. • There is no way to directly interact with SGs. • The P exchange among DGs. • NH I/VR.
Large traditional droop parameters [110,125,169,170]	• Easy to implement. • Reduces the Q exchange between the DGs.	• Meaningfully increases VαF oscillations. • NH I/VR.
*h*th harmonic DC [171–173]	• Provides selective harmonic compensation. • Leeway of DC to higher harmonic Fs. • Lessens VαI harmonics.	• Oscillations of VαF. • There is still a Q exchange between DGs. • Complicated DG-CLs. • It is difficult to tune harmonic droop.
PR controllers [131,174–176]	• Limits Q exchange within DGs. • Provides selective harmonic compensation. • Suppresses both IαV harmonics.	• VαF instabilities. • Performance is affected by the impedance characteristics of the electrical network. • Lowers the I harmonic flowing through the DGs (but does not eliminate it).
R/L or RL virtual impedance [132,133,177–181]	• Easily designed and implemented. • Enhances the I share. • Minimizes Q transfer within DGs.	• VαF oscillations cannot be suppressed. • The Q transfer among DGs is not eradicated. • Rises the V at the POCC. • Predominantly beneficial for specified µG impedance.
RC virtual impedance [46,124,182,183]	• Simple to implement • Enhances I harmonic exchange. • Minimizes Q transfer within DGs. • Improves V-HD at the POCC.	• VαF variations are inevitable. • The Q transfer within DGs is not completely reduced. • This method is primarily successful for known µG impedances.
NVH-Z [138]	• Improves I fundamental and harmonic share. • Diminishes the Q transfer flanked by the DGs.	• VαF variations are inescapable. • The Q transfer between DGs is not abolished. • Regularly active for an identified µG impedance.

Table 2. Properties and limitations of the SCL techniques.

Method	Advantages	Limitations
VαF restoration loops (RLs) [139,184,185]	• Low-bandwidth noncritical communication (LBNC) • Eradicates VαF variations.	• Potentially increases the Q transfer between the DGs. • NH I/VR.
VαF RLs together with Q control [46,140,141,186,187]	• LBNC. • Eliminates VαF fluctuations • Eliminates Q exchange between the DGs.	• NH I/VR.
VαF RLs including Q control and V- HC [46,133,188]	• LBNC. • Eliminates VαF variations. • Eliminates Q transfer between DGs. • Risk mitigation of the THD of VαI.	• Tuning of SCLs for harmonic recompense is difficult. • Synchronization of harmonic injection is a serious element.

Table 3. Emerging grid technology strengths and limitations.

Method	Advantages	Limitations
ES-1 [82,143,189]	• No ESS. • Mitigates V oscillations via Q compensation.	• Only provides Q reimbursement. • Cannot discourse F's fluctuations. • NH I/VR. • The complexity of multiparallel ES-1 SL coordination.
ES-2 [74,145,190]	• Alleviates VαF instabilities.	• Requires ESS. • No harmonic I/V regulation. • It requires complicated coordination of numerous concurrent ES-3 SLs.
ES-3 [157,158,161,191]	• No ESS. • Mitigates VαF instabilities.	• No harmonic I/V regulation. • It is difficult to coordinate several concurrent ES-3 SLs.

Among the most well-established of the approaches presented in this work are primary DC techniques built on traditional DC. Despite the performance issues these methods have, the technology has developed enough to be used in practical scenarios. The most important compromise is between VR and Q-transfer precision in DGs. To reduce or eliminate the Q exchange across DGs, Q regulation must also be adopted. The PCLs of the DGs' VI methods are subject to identical criticisms. Inadequate optimization of such techniques can reduce their efficiency because the grid's impedance is frequently undetermined. The use of such strategies is particularly beneficial if the features of the regional network are specified.

In the literature, centralized and distributed techniques are distinguished as SC techniques. The methods used in traditional electricity generation are expanded upon by centralized methods, although both implement the same functionality. While the DGs in a μG are distributed over a greater geographic region, traditional electricity production is often placed close together in power plants. The main benefit of centralized SC is convenience because decisions are taken directly and sent regionally to the DGs in charge of providing energy to the μG. The reliability of the SCLs is dependent on the functionality of the central controller; therefore, this is a drawback. Decentralized SCLs provide more dependability at the cost of more sophisticated network structures and control method design. Despite the fact that decentralized methods have a lot of potential for practical μG executions, centralized control is now the most practical choice.

ES-based SLs are a developing grid solution that could offer dispersed PQ adjustment. The Q compensation needed to control local voltages can be provided by ES-1. But, because no ESSs exists, such gadgets are not very useful when there are significant local RESs. Improved abilities and potential PQ improvement functions are offered by ES-2 and ES-3. Before implementing such equipment, it is also necessary to look into how ESs may be integrated into actual loads like air conditioning.

7. Future Research Directions

There will be a variety of problems in future systems as a result of the implementation of μGs in contemporary power systems. The examined studies that were described here address a few concerns. However, further research is needed on a few of the previously listed issues. As a result, the following proposals are made for further work in μG control, operation, and management and mitigating PQ issues.

- Additional features, including the PQ index and equipment longevity, can be thought of as objectives in the context of μG management. The load control strategies ought to be examined more thoroughly than before on the control side.

- The increased use of μGs in recent systems creates a host of new problems, such as connections between μGs, multi μGs, multi agents, decentralized and centralized control procedures, and many others.
- Considering the advancement of technology, it is critical to understand how new machinery, particularly μGs, will affect power systems.
- Response to demand and load management in DGs have become crucial issues. With the growth in RESs and sophisticated metering systems in current decades, this topic may now be more important than ever.
- New solvers can be used to simplify and expedite the solving process because heuristic methods have improved.
- Proper uncertainty modeling can make the network functioning resistant to change. The uncertainties in μGs have been addressed in a number of studies, although a comprehensive approach needs to be offered, particularly if multiple uncertain factors exist simultaneously.
- Future systems will also need to address smartening. Every day, more and more systems will use information and communication technologies. So, it is important to take into account the connections between cyber and physical systems and their issues.
- Recent power systems are more open to incorporating μGs thanks to the use of innovative nonlinear and adaptive control techniques.

8. Conclusions

This study presented an overview of 1Ø−μGs PQ issues and potential solutions. VαF oscillations happen throughout off-grid mode as a result of the inherent limits of conventional DC. Some concerning additional issues are the Q exchange between DGs and HD. The HCA that is used to address PQ matters was also thoroughly analyzed and reported. The vast majority of available techniques involve changing the DG units' primary CLs, which may include implementing droop gains like inverse/reverse droops (have limited applications because they cannot be directly connected to synchronous generators) or large droop gains (greatly increase VαF deviations as well as the flow of Q across inverters).

The performance restrictions of additional primary control techniques based on the idea of VI were also mentioned. Investigations have also been conducted into SCLs-based techniques for reducing PQ problems. These comprised the abolition of VαF variations, the abolition of the transfer of Q between DG units, and a reduction in HD. When aiming for identical objectives, it was found that secondary control approaches significantly outperform primary control methods in terms of effectiveness and performance.

Additionally, a review of the newly developed grid technology for ESs was given. ESs are capable of offering extra auxiliary services in addition to controlling voltage in weak grids. Further studies at the PCC have concentrated on reducing VαF variations and boosting PF. The DC input capacitor must be substituted by a battery or another converter (ES−2 and ES−3) in order for this capability to be possible. The reduction in the current HD was also described, but the supplementary services offered by such types of equipment are still in the early stages; thus, there is still space for major progress.

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Abbreviations

1Ø-µGs	Single-phase microgrids
PQ	Power quality
RESs	Renewable energy sources
VαF	Voltage and frequency
HDs	Harmonic distortions
FS	Frequency stability
VS	Voltage stability
ESSs	Energy storage systems
VR	Voltage regulation
FR	Frequency regulation
DGs	Distributed generators
LV	Low voltage
Q	Reactive power
V\I	Voltage/current
DC	Droop control
POCC	Point of common coupling
HCA	Hierarchical control architecture
PC	Primary control
SC	Secondary control
PBC	Power-based control
LVCs	Load voltage controllers
SL	Smart load
PαQ	Active and reactive power
HCs	Harmonic controllers
TFs	Transfer functions
LBC	Low bandwidth communications
SB	Sharing block
ADCL	Adaptive DC loop
µGCC	µG central controller
PF	Power factor
PA	Phase angle
DCL	DC link
PICs	PI controllers
RCD	Radial–chordal decomposition
V_{DC}	DCL voltage
HC	Harmonics compensation
2LCTs	Two-level control techniques
LBNC	Low-bandwidth non-critical communication
RLs	Restoration loops

References

1. Saha, D.; Bazmohammadi, N.; Vasquez, J.C.; Guerrero, J.M. Multiple Microgrids: A Review of Architectures and Operation and Control Strategies. *Energies* **2023**, *16*, 600. [CrossRef]
2. Quintana-Barcia, P.; Dragicevic, T.; Garcia, J.; Ribas, J.; Guerrero, J.M. A Distributed Control Strategy for Islanded Single-Phase Microgrids with Hybrid Energy Storage Systems Based on Power Line Signaling. *Energies* **2018**, *12*, 85. [CrossRef]
3. Fazal, S.; Haque, E.; Arif, M.T.; Gargoom, A.; Oo, A.M.T. Grid integration impacts and control strategies for renewable based microgrid. *Sustain. Energy Technol. Assess.* **2023**, *56*, 103069. [CrossRef]
4. Ardjoun, S.A.E.M.; Denaï, M.; Chafouk, H. A Robust Control Approach for Frequency Support Capability of Grid-Tie Photovoltaic Systems. *J. Sol. Energy Eng.* **2022**, *145*, 021009. [CrossRef]

5. Mahmoud, M.M. Improved current control loops in wind side converter with the support of wild horse optimizer for enhancing the dynamic performance of PMSG-based wind generation system. *Int. J. Model. Simul.* **2022**, 1–15. [CrossRef]
6. Darshi, R.; Shamaghdari, S.; Jalali, A.; Arasteh, H. Decentralized Reinforcement Learning Approach for Microgrid Energy Management in Stochastic Environment. *Int. Trans. Electr. Energy Syst.* **2023**, *2023*, 1–15. [CrossRef]
7. Raza, S.A.; Jiang, J. Mathematical Foundations for Balancing Single-Phase Residential Microgrids Connected to a Three-Phase Distribution System. *IEEE Access* **2022**, *10*, 5292–5303. [CrossRef]
8. Ashtiani, N.A.; Khajehoddin, S.A.; Karimi-Ghartemani, M. Modeling and Stability Analysis of Single-Phase Microgrids Controlled in Stationary Frame. *IEEE Trans. Power Electron.* **2022**, *37*, 7759–7774. [CrossRef]
9. Mahmoud, M.M.; Ratib, M.K.; Aly, M.M.; Abdel-Rahim, A.-M.M. Wind-driven permanent magnet synchronous generators connected to a power grid: Existing perspective and future aspects. *Wind. Eng.* **2021**, *46*, 189–199. [CrossRef]
10. Mahmoud, M.M.; Aly, M.M.; Abdel-Rahim, A.-M.M. Enhancing the dynamic performance of a wind-driven PMSG implementing different optimization techniques. *SN Appl. Sci.* **2020**, *2*, 684. [CrossRef]
11. Ardjoun, S.A.E.M.; Abid, M. Fuzzy sliding mode control applied to a doubly fed induction generator for wind turbines. *Turk. J. Electr. Eng. Comput. Sci.* **2015**, *23*, 1673–1686. [CrossRef]
12. Mahmoud, M.M.; Ratib, M.K.; Aly, M.M.; Moamen, A.; Rahim, M.A. Effect of Grid Faults on Dominant Wind Generators for Electric Power System Integration: A Comparison and Assessment. *Energy Syst. Res.* **2021**, *4*, 70–78.
13. Mahmoud, M.M.; Atia, B.S.; Esmail, Y.M.; Ardjoun, S.A.E.M.; Anwer, N.; Omar, A.I.; Alsaif, F.; Alsulamy, S.; Mohamed, S.A. Application of Whale Optimization Algorithm Based FOPI Controllers for STATCOM and UPQC to Mitigate Harmonics and Voltage Instability in Modern Distribution Power Grids. *Axioms* **2023**, *12*, 420. [CrossRef]
14. Liu, G.; Ollis, T.B.; Ferraril, M.F.; Sundararajan, A.; Chen, Y.; Olama, M.M.; Tomsovic, K. RETRACTED ARTICLE: Distributed energy management for networked microgrids in a three-phase unbalanced distribution network. *Front. Energy* **2022**, 1–16. [CrossRef]
15. Mahmoud, M.M.; Hemeida, A.M.; Senjy, T.; Ewais, A.M. Fault Ride-Through Capability Enhancement for Grid-Connected Permanent Magnet Synchronous Generator Driven by Wind Turbines. In Proceedings of the 2019 IEEE Conference on Power Electronics and Renewable Energy (CPERE), Aswan, Egypt, 23–25 October 2019; pp. 567–572. [CrossRef]
16. Mahmoud, M.M.; Esmail, Y.M.; Atia, B.S.; Kamel, O.M.; AboRas, K.M.; Bajaj, M.; Bukhari, S.S.H.; Wapet, D.E.M. Voltage Quality Enhancement of Low-Voltage Smart Distribution System Using Robust and Optimized DVR Controllers: Application of the Harris Hawks Algorithm. *Int. Trans. Electr. Energy Syst.* **2022**, *2022*, 18. [CrossRef]
17. Ardjoun, S.A.E.M.; Denai, M.; Abid, M. A robust power control strategy to enhance LVRT capability of grid-connected DFIG-based wind energy systems. *Wind. Energy* **2019**, *22*, 834–847. [CrossRef]
18. Mohamed, M.; Basiony, S.; Mohamed, K.; Mohamed, A.; Abdallah, E.; Abdel-Moamen, A.-R. Investigations on OTC-MPPT Strategy and FRT Capability for PMSG Wind System with the Support of Optimized Wind Side Controller Based on GWO Technique. *Energy Syst. Res.* **2021**, *4*, 79–91. [CrossRef]
19. Giraldo, J.S.; Castrillon, J.A.; Lopez, J.C.; Rider, M.J.; Castro, C.A. Microgrids Energy Management Using Robust Convex Programming. *IEEE Trans. Smart Grid* **2018**, *10*, 4520–4530. [CrossRef]
20. Xu, Z.; Yang, P.; Zeng, Z.; Peng, J.; Zhao, Z. Black Start Strategy for PV-ESS Multi-Microgrids with Three-Phase/Single-Phase Architecture. *Energies* **2016**, *9*, 372. [CrossRef]
21. Mahmoud, M.M.; Aly, M.M.; Salama, H.S.; Abdel-Rahim, A.-M.M. A combination of an OTC based MPPT and fuzzy logic current control for a wind-driven PMSG under variability of wind speed. *Energy Syst.* **2021**, *13*, 1075–1098. [CrossRef]
22. Mahmoud, M.M.; Aly, M.M.; Salama, H.S.; Abdel-Rahim, A.-M.M. An internal parallel capacitor control strategy for DC-link voltage stabilization of PMSG-based wind turbine under various fault conditions. *Wind. Eng.* **2021**, *46*, 983–992. [CrossRef]
23. Biswal, C.; Sahu, B.K.; Mishra, M.; Rout, P.K. Real-Time Grid Monitoring and Protection: A Comprehensive Survey on the Advantages of Phasor Measurement Units. *Energies* **2023**, *16*, 4054. [CrossRef]
24. Pappu, S.; Rahnama, A.; Tovar, M.; Bayne, S.; Little, B.; Friend, S.; Borhani, M. Power Quality Analysis of a Sensitive Load Using a Phasor Measurement Unit. In Proceedings of the 2012 IEEE Green Technologies Conference, Tulsa, OK, USA, 19–20 April 2012; pp. 1–6. [CrossRef]
25. de Melo, I.D.; Pereira, J.L.R.; Duque, C.A.; Antunes, M.P.; Silva, L.R.M.; de Souza, M.A. Power Quality Monitoring using Synchronized Phasor Measurements: An approach based on hardware-in-the-loop simulations. In Proceedings of the 2019 IEEE Milan PowerTech, Milan, Italy, 23–27 June 2019; pp. 1–6. [CrossRef]
26. Ahmed, M.M.; Amjad, M.; Qureshi, M.A.; Imran, K.; Haider, Z.M.; Khan, M.O. A Critical Review of State-of-the-Art Optimal PMU Placement Techniques. *Energies* **2022**, *15*, 2125. [CrossRef]
27. Theodorakatos, N.P.; Lytras, M.; Babu, R. A Generalized Pattern Search Algorithm Methodology for solving an Under-Determined System of Equality Constraints to achieve Power System Observability using Synchrophasors. *J. Phys. Conf. Ser.* **2021**, *2090*, 012125. [CrossRef]
28. Theodorakatos, N.P.; Lytras, M.; Babu, R. Towards Smart Energy Grids: A Box-Constrained Nonlinear Underdetermined Model for Power System Observability Using Recursive Quadratic Programming. *Energies* **2020**, *13*, 1724. [CrossRef]
29. Paramo, G.; Bretas, A.; Meyn, S. Research Trends and Applications of PMUs. *Energies* **2022**, *15*, 5329. [CrossRef]
30. Brandao, D.I.; Araujo, L.; Caldognetto, T.; Pomilio, J.A. Coordinated control of three- and single-phase inverters coexisting in low-voltage microgrids. *Appl. Energy* **2018**, *228*, 2050–2060. [CrossRef]

31. Kandari, R.; Neeraj, N.; Micallef, A. Review on Recent Strategies for Integrating Energy Storage Systems in Microgrids. *Energies* **2022**, *16*, 317. [CrossRef]
32. Ishaq, S.; Khan, I.; Rahman, S.; Hussain, T.; Iqbal, A.; Elavarasan, R.M. A review on recent developments in control and optimization of micro grids. *Energy Rep.* **2022**, *8*, 4085–4103. [CrossRef]
33. Mahmoud, M.M.; Ratib, M.K.; Aly, M.M.; Abdel–Rahim, A.-M.M. Application of Whale Optimization Technique for Evaluating the Performance of Wind-Driven PMSG Under Harsh Operating Events. *Process. Integr. Optim. Sustain.* **2022**, *6*, 447–470. [CrossRef]
34. Mohamed, S.A.; Anwer, N.; Mahmoud, M.M. Solving optimal power flow problem for IEEE-30 bus system using a developed particle swarm optimization method: Towards fuel cost minimization. *Int. J. Model. Simul.* **2023**, 1–14. [CrossRef]
35. Jones, E.S.; Jewell, N.; Liao, Y.; Ionel, D.M. Optimal Capacitor Placement and Rating for Large-Scale Utility Power Distribution Systems Employing Load-Tap-Changing Transformer Control. *IEEE Access* **2023**, *11*, 19324–19338. [CrossRef]
36. Mahmoud, M.M.; Aly, M.M.; Salama, H.S.; Abdel-Rahim, A.-M.M. Dynamic evaluation of optimization techniques–based proportional–integral controller for wind-driven permanent magnet synchronous generator. *Wind. Eng.* **2020**, *45*, 696–709. [CrossRef]
37. Dreidy, M.; Mokhlis, H.; Mekhilef, S. Inertia response and frequency control techniques for renewable energy sources: A review. *Renew. Sustain. Energy Rev.* **2017**, *69*, 144–155. [CrossRef]
38. Buła, D.; Grabowski, D.; Maciążek, M. A Review on Optimization of Active Power Filter Placement and Sizing Methods. *Energies* **2022**, *15*, 1175. [CrossRef]
39. Rafiq, M.; Naz, S.; Martins, J.M.; Mata, M.N.; Mata, P.N.; Maqbool, S. A Study on Emerging Management Practices of Renewable Energy Companies after the Outbreak of Covid-19: Using an Interpretive Structural Modeling (ISM) Approach. *Sustainability* **2021**, *13*, 3420. [CrossRef]
40. Casalicchio, V.; Manzolini, G.; Prina, M.G.; Moser, D. Renewable Energy Communities: Business Models of Multi-family Housing Buildings. In *Green Energy and Technology*; Springer: Berlin/Heidelberg, Germany, 2021; pp. 261–276. [CrossRef]
41. Garcia-Torres, F.; Vazquez, S.; Moreno-Garcia, I.M.; Gil-De-Castro, A.; Roncero-Sanchez, P.; Moreno-Munoz, A. Microgrids Power Quality Enhancement Using Model Predictive Control. *Electronics* **2021**, *10*, 328. [CrossRef]
42. Lingampalli, B.R.; Kotamraju, S.R.; Kumar, M.K.; Reddy, C.R.; Pushkarna, M.; Bajaj, M.; Kotb, H.; Alphonse, S. Integrated Microgrid Islanding Detection with Phase Angle Difference for Reduced Nondetection Zone. *Int. J. Energy Res.* **2023**, *2023*, 1–17. [CrossRef]
43. Mahmoud, M.M.; Salama, H.S.; Aly, M.M.; Abdel-Rahim, A.-M.M. Design and implementation of FLC system for fault ride-through capability enhancement in PMSG-wind systems. *Wind. Eng.* **2020**, *45*, 1361–1373. [CrossRef]
44. Mahmoud, M.M.; Ratib, M.K.; Raglend, I.J.; Swaminathan, J.; Aly, M.M.; Abdel-Rahim, A.-M.M. Application of Grey Wolf Optimization for PMSG-Based WECS under Different Operating Conditions: Performance Assessment. In Proceedings of the2021 Innovations in Power and Advanced Computing Technologies (i-PACT), Kuala Lumpur, Malaysia, 27–29 November 2021. [CrossRef]
45. Ewais, A.M.; Elnoby, A.M.; Mohamed, T.H.; Mahmoud, M.M.; Qudaih, Y.; Hassan, A.M. Adaptive frequency control in smart microgrid using controlled loads supported by real-time implementation. *PLoS ONE* **2023**, *18*, e0283561. [CrossRef]
46. Micallef, A.; Apap, M.; Spiteri-Staines, C.; Guerrero, J.M.; Vasquez, J.C. Reactive Power Sharing and Voltage Harmonic Distortion Compensation of Droop Controlled Single Phase Islanded Microgrids. *IEEE Trans. Smart Grid* **2014**, *5*, 1149–1158. [CrossRef]
47. Vasquez, J.C.; Guerrero, J.M.; Luna, A.; Rodriguez, P.; Teodorescu, R. Adaptive Droop Control Applied to Voltage-Source Inverters Operating in Grid-Connected and Islanded Modes. *IEEE Trans. Ind. Electron.* **2009**, *56*, 4088–4096. [CrossRef]
48. Alavi, S.A.; Mehran, K.; Hao, Y.; Rahimian, A.; Mirsaeedi, H.; Vahidinasab, V. A Distributed Event-Triggered Control Strategy for DC Microgrids Based on Publish-Subscribe Model Over Industrial Wireless Sensor Networks. *IEEE Trans. Smart Grid* **2018**, *10*, 4323–4337. [CrossRef]
49. Mahmoud, M.M.; Atia, B.S.; Abdelaziz, A.Y.; Aldin, N.A.N. Dynamic Performance Assessment of PMSG and DFIG-Based WECS with the Support of Manta Ray Foraging Optimizer Considering MPPT, Pitch Control, and FRT Capability Issues. *Processe* **2022**, *12*, 2723. [CrossRef]
50. Guerrero, J.M.; Loh, P.C.; Lee, T.-L.; Chandorkar, M. Advanced Control Architectures for Intelligent Microgrids—Part II: Power Quality, Energy Storage, and AC/DC Microgrids. *IEEE Trans. Ind. Electron.* **2012**, *60*, 1263–1270. [CrossRef]
51. Ghafouri, A. Microgrid modeling for contribution to the frequency control of power system. *Wind. Eng.* **2021**, *46*, 767–779. [CrossRef]
52. Ahmethodzic, L.; Music, M. Comprehensive review of trends in microgrid control. *Renew. Energy Focus* **2021**, *38*, 84–96. [CrossRef]
53. Bidram, A.; Davoudi, A. Hierarchical Structure of Microgrids Control System. *IEEE Trans. Smart Grid* **2012**, *3*, 1963–1976. [CrossRef]
54. Yamashita, D.Y.; Vechiu, I.; Gaubert, J.-P. A review of hierarchical control for building microgrids. *Renew. Sustain. Energy Rev.* **2019**, *118*, 109523. [CrossRef]
55. Bazmohammadi, N.; Anvari-Moghaddam, A.; Tahsiri, A.; Madary, A.; Vasquez, J.C.; Guerrero, J.M. Stochastic Predictive Energy Management of Multi-Microgrid Systems. *Appl. Sci.* **2020**, *10*, 4833. [CrossRef]

56. Mahmoud, M.M.; Hemeida, A.M.; Abdel-Rahim, A.-M.M. Behavior of PMSG Wind Turbines with Active Crowbar Protection Under Faults. In Proceedings of the 2019 Innovations in Power and Advanced Computing Technologies (i-PACT), Vellore, India, 22–23 March 2019; Volume 1, pp. 1–6. [CrossRef]
57. Vasquez, J.C.; Guerrero, J.M.; Savaghebi, M.; Eloy-Garcia, J.; Teodorescu, R. Modeling, Analysis, and Design of Stationary-Reference-Frame Droop-Controlled Parallel Three-Phase Voltage Source Inverters. *IEEE Trans. Ind. Electron.* **2012**, *60*, 1271–1280. [CrossRef]
58. Shafiee, Q.; Stefanović, Č.; Dragicevic, T.; Popovski, P.; Vasquez, J.C.; Guerrero, J.M. Robust Networked Control Scheme for Distributed Secondary Control of Islanded Microgrids. *IEEE Trans. Ind. Electron.* **2014**, *61*, 5363–5374. [CrossRef]
59. Alsafran, A.S.; Daniels, M.W. Comparative Study of Droop Control Methods for AC Islanded Microgrids. In Proceedings of the 2020 IEEE Green Technologies Conference (GreenTech), Oklahoma City, OK, USA, 1–3 April 2020; pp. 26–30. [CrossRef]
60. Zadehbagheri, M.; Kiani, M.J.; Sutikno, T.; Moghadam, R.A. Design of a new backstepping controller for control of microgrid sources inverter. *Int. J. Electr. Comput. Eng. (IJECE)* **2022**, *12*, 4469–4482. [CrossRef]
61. Maqbool, H.; Yousaf, A.; Asif, R.M.; Rehman, A.U.; Eldin, E.T.; Shafiq, M.; Hamam, H. An Optimized Fuzzy Based Control Solution for Frequency Oscillation Reduction in Electric Grids. *Energies* **2022**, *15*, 6981. [CrossRef]
62. Mahmoud, M.M.; Atia, B.S.; Esmail, Y.M.; Bajaj, M.; Wapet, D.E.M.; Ratib, M.K.; Hossain, B.; AboRas, K.M.; Abdel-Rahim, A.-M.M. Evaluation and Comparison of Different Methods for Improving Fault Ride-Through Capability in Grid-Tied Permanent Magnet Synchronous Wind Generators. *Int. Trans. Electr. Energy Syst.* **2023**, *2023*, 1–22. [CrossRef]
63. Lu, J.; Savaghebi, M.; Zhang, B.; Hou, X.; Sun, Y.; Guerrero, J.M. Distributed Dynamic Event-Triggered Control for Accurate Active and Harmonic Power Sharing in Modular On-Line UPS Systems. *IEEE Trans. Ind. Electron.* **2021**, *69*, 13045–13055. [CrossRef]
64. Bevrani, H.; Shokoohi, S. An Intelligent Droop Control for Simultaneous Voltage and Frequency Regulation in Islanded Microgrids. *IEEE Trans. Smart Grid* **2013**, *4*, 1505–1513. [CrossRef]
65. Savaghebi, M.; Jalilian, A.; Vasquez, J.C.; Guerrero, J.M. Secondary control scheme for voltage unbalance compensation in an islanded droop-controlled microgrid. *IEEE Trans. Smart Grid* **2012**, *3*, 797–807. [CrossRef]
66. Han, Y.; Shen, P.; Zhao, X.; Guerrero, J.M. An Enhanced Power Sharing Scheme for Voltage Unbalance and Harmonics Compensation in an Islanded AC Microgrid. *IEEE Trans. Energy Convers.* **2016**, *31*, 1037–1050. [CrossRef]
67. Alsafran, A.S. A Feasibility Study of Implementing IEEE 1547 and IEEE 2030 Standards for Microgrid in the Kingdom of Saudi Arabia. *Energies* **2023**, *16*, 1777. [CrossRef]
68. Shafiee, Q.; Guerrero, J.M.; Vasquez, J.C. Distributed Secondary Control for Islanded Microgrids—A Novel Approach. *IEEE Trans. Power Electron.* **2014**, *29*, 1018–1031. [CrossRef]
69. Yu, C.; Zhou, H.; Lu, X. Frequency control of droop-based low-voltage microgrids with cobweb network topologies. *IET Gener. Transm. Distrib.* **2020**, *14*, 4310–4320. [CrossRef]
70. Köbrich, D.; Marín, L.G.; Muñoz-Carpintero, D.; Ahumada, C.; Sáez, D.; Sumner, M.; Jiménez-Estévez, G. A robust distributed energy management system for the coordinated operation of rural multi-microgrids. *Int. J. Energy Res.* **2022**, *46*, 19775–19795. [CrossRef]
71. Aldin, N.A.N.; Abdellatif, W.S.E.; Elbarbary, Z.M.S.; Omar, A.I.; Mahmoud, M.M. Robust Speed Controller for PMSG Wind System Based on Harris Hawks Optimization via Wind Speed Estimation: A Real Case Study. *IEEE Access* **2023**, *11*, 5929–5943. [CrossRef]
72. Sheykhi, N.; Salami, A.; Guerrero, J.M.; Agundis-Tinajero, G.D.; Faghihi, T. A comprehensive review on telecommunication challenges of microgrids secondary control. *Int. J. Electr. Power Energy Syst.* **2022**, *140*, 108081. [CrossRef]
73. Solanke, S.S.; Jadoun, V.K.; Jayalakshmi, N.S.; Kanwar, N.; Shrivastava, A. A Recapitulation of Electric Spring for Demand Side Management & Power Quality Mitigation. *IOP Conf. Series Mater. Sci. Eng.* **2022**, *1228*, 012028. [CrossRef]
74. Soni, J.; Panda, S.K. Electric Spring for Voltage and Power Stability and Power Factor Correction. *IEEE Trans. Ind. Appl.* **2017**, *53*, 3871–3879. [CrossRef]
75. Kamel, O.M.; Diab, A.A.Z.; Mahmoud, M.M.; Al-Sumaiti, A.S.; Sultan, H.M. Performance Enhancement of an Islanded Microgrid with the Support of Electrical Vehicle and STATCOM Systems. *Energies* **2023**, *16*, 1577. [CrossRef]
76. Ratib, M.K.; Alkhalaf, S.; Senjyu, T.; Rashwan, A.; Mahmoud, M.M.; Hemeida, A.M.; Osheba, D. Applications of hybrid model predictive control with computational burden reduction for electric drives fed by 3-phase inverter. *Ain Shams Eng. J.* **2022**, *4*, 102028. [CrossRef]
77. Hui, S.Y.; Lee, C.K.; Wu, F.F. Electric Springs—A New Smart Grid Technology. *IEEE Trans. Smart Grid* **2012**, *3*, 1552–1561. [CrossRef]
78. Madiba, T.; Bansal, R.; Mbungu, N.; Bettayeb, M.; Naidoo, R.; Siti, M. Under-frequency load shedding of microgrid systems: A review. *Int. J. Model. Simul.* **2021**, *42*, 653–679. [CrossRef]
79. Chaudhuri, N.R.; Lee, C.K.; Chaudhuri, B.; Hui, S.Y.R. Dynamic Modeling of Electric Springs. *IEEE Trans. Smart Grid* **2014**, *5*, 2450–2458. [CrossRef]
80. Kollipara, K.D.; Kumar, J.V.; Prasanthi, R.; Sura, S.R.; Patnaik, M.S.P.K.; Sankar, R.S.R. Energy Efficient Photovoltaic-Electric Spring for Real and Reactive Power Control in Demand-Side Management. *Front. Energy Res.* **2022**, *10*, 762931. [CrossRef]
81. Luo, X.; Akhtar, Z.; Lee, C.K.; Chaudhuri, B.; Tan, S.-C.; Hui, S.Y.R. Distributed Voltage Control with Electric Springs: Comparison with STATCOM. *IEEE Trans. Smart Grid* **2014**, *6*, 209–219. [CrossRef]

82. Akhtar, Z.; Chaudhuri, B.; Hui, S.Y.R. Primary Frequency Control Contribution from Smart Loads Using Reactive Compensation. *IEEE Trans. Smart Grid* **2015**, *6*, 2356–2365. [CrossRef]
83. Boudjemai, H.; Ardjoun, S.A.E.M.; Chafouk, H.; Denai, M.; Elbarbary, Z.M.S.; Omar, A.I.; Mahmoud, M.M. Application of a Novel Synergetic Control for Optimal Power Extraction of a Small-Scale Wind Generation System with Variable Loads and Wind Speeds. *Symmetry* **2023**, *15*, 369. [CrossRef]
84. Lee, C.K.; Chaudhuri, B.; Hui, S.Y. Hardware and Control Implementation of Electric Springs for Stabilizing Future Smart Grid with Intermittent Renewable Energy Sources. *IEEE J. Emerg. Sel. Top. Power Electron.* **2013**, *1*, 18–27. [CrossRef]
85. Lee, C.K.; Hui, S.Y.R. Reduction of Energy Storage Requirements in Future Smart Grid Using Electric Springs. *IEEE Trans. Smart Grid* **2013**, *4*, 1282–1288. [CrossRef]
86. Vandoorn, T.L.; Vasquez, J.C.; De Kooning, J.; Guerrero, J.M.; Vandevelde, L. Microgrids: Hierarchical Control and an Overview of the Control and Reserve Management Strategies. *IEEE Ind. Electron. Mag.* **2013**, *7*, 42–55. [CrossRef]
87. Han, Y.; Li, H.; Shen, P.; Coelho, E.A.A.; Guerrero, J.M. Review of Active and Reactive Power Sharing Strategies in Hierarchical Controlled Microgrids. *IEEE Trans. Power Electron.* **2017**, *32*, 2427–2451. [CrossRef]
88. Zuo, K.; Wu, L. A review of decentralized and distributed control approaches for islanded microgrids: Novel designs, current trends, and emerging challenges. *Electr. J.* **2022**, *35*, 107138. [CrossRef]
89. Ullah, S.; Khan, L.; Sami, I.; Ro, J.-S. Voltage/Frequency Regulation with Optimal Load Dispatch in Microgrids Using SMC Based Distributed Cooperative Control. *IEEE Access* **2022**, *10*, 64873–64889. [CrossRef]
90. Elmetwaly, A.H.; Younis, R.A.; Abdelsalam, A.A.; Omar, A.I.; Mahmoud, M.M.; Alsaif, F.; El-Shahat, A.; Saad, M.A. Modeling, Simulation, and Experimental Validation of a Novel MPPT for Hybrid Renewable Sources Integrated with UPQC: An Application of Jellyfish Search Optimizer. *Sustainability* **2023**, *15*, 5209. [CrossRef]
91. Sundarajoo, S.; Soomro, D.M. Under voltage load shedding and penetration of renewable energy sources in distribution systems: A review. *Int. J. Model. Simul.* **2022**, 1–19. [CrossRef]
92. El Zerk, A.; Ouassaid, M. Real-Time Fuzzy Logic Based Energy Management System for Microgrid Using Hardware in the Loop. *Energies* **2023**, *16*, 2244. [CrossRef]
93. Mutarraf, M.U.; Guan, Y.; Terriche, Y.; Su, C.-L.; Nasir, M.; Vasquez, J.C.; Guerrero, J.M. Adaptive Power Management of Hierarchical Controlled Hybrid Shipboard Microgrids. *IEEE Access* **2022**, *10*, 21397–21411. [CrossRef]
94. Khan, M.Z.; Ahmed, E.M.; Habib, S.; Ali, Z.M. Multi-objective Optimization Technique for Droop Controlled Distributed Generators in AC Islanded Microgrid. *Electr. Power Syst. Res.* **2022**, *213*, 108671. [CrossRef]
95. Brandao, D.I.; Araujo, L.S.; Alonso, A.M.S.; dos Reis, G.L.; Liberado, E.V.; Marafao, F.P. Coordinated Control of Distributed Three- and Single-Phase Inverters Connected to Three-Phase Three-Wire Microgrids. *IEEE J. Emerg. Sel. Top. Power Electron.* **2019**, *8*, 3861–3877. [CrossRef]
96. Zheng, D.; Zhang, W.; Alemu, S.N.; Wang, P.; Bitew, G.T.; Wei, D.; Yue, J. Protection of microgrids. In *Microgrid Protection and Control*; Elsevier: Amsterdam, Netherlands, 2021; pp. 121–168. [CrossRef]
97. Veronica, A.J.; Kumar, N.S. Control strategies for frequency regulation in microgrids: A review. *Wind. Eng.* **2019**, *45*, 107–122. [CrossRef]
98. Memon, A.A.; Laaksonen, H.; Kauhaniemi, K. Microgrid Protection with Conventional and Adaptive Protection Schemes. In *Microgrids: Advances in Operation, Control, and Protection*; Springer: Berlin/Heidelberg, Germany, 2021; pp. 523–579. [CrossRef]
99. Azeroual, M.; Boujoudar, Y.; EL Iysaouy, L.; Aljarbouh, A.; Fayaz, M.; Qureshi, M.S.; Rabbi, F.; EL Markhi, H. Energy management and control system for microgrid based wind-PV-battery using multi-agent systems. *Wind. Eng.* **2022**, *46*, 1247–1263. [CrossRef]
100. Hosseinzadeh, N.; Aziz, A.; Mahmud, A.; Gargoom, A.; Rabbani, M. Voltage Stability of Power Systems with Renewable-Energy Inverter-Based Generators: A Review. *Electronics* **2021**, *10*, 115. [CrossRef]
101. Aazami, R.; Heydari, O.; Tavoosi, J.; Shirkhani, M.; Mohammadzadeh, A.; Mosavi, A. Optimal Control of an Energy-Storage System in a Microgrid for Reducing Wind-Power Fluctuations. *Sustainability* **2022**, *14*, 6183. [CrossRef]
102. Kamel, R.M.; Chaouachi, A.; Nagasaka, K. Comparison the Performances of Three Earthing Systems for Micro-Grid Protection during the Grid Connected Mode. *Smart Grid Renew. Energy* **2011**, *2*, 206–215. [CrossRef]
103. Malekpour, A.R.; Niknam, T.; Pahwa, A.; Fard, A.K. Multi-Objective Stochastic Distribution Feeder Reconfiguration in Systems with Wind Power Generators and Fuel Cells Using the Point Estimate Method. *IEEE Trans. Power Syst.* **2012**, *28*, 1483–1492. [CrossRef]
104. Qin, D.; Chen, Y.; Zhang, Z.; Enslin, J. A Hierarchical Microgrid Protection Scheme using Hybrid Breakers. In Proceedings of the2021 IEEE 12th International Symposium on Power Electronics for Distributed Generation Systems, Chicago, IL, USA, 28 June 2021–1 July 2021; pp. 1–6. [CrossRef]
105. Senarathna, S.; Hemapala, K.T.M.U. Review of adaptive protection methods for microgrids. *AIMS Energy* **2019**, *7*, 557–578. [CrossRef]
106. Hatata, A.Y.; Essa, M.A.; Sedhom, B.E. Adaptive Protection Scheme for FREEDM Microgrid Based on Convolutional Neural Network and Gorilla Troops Optimization Technique. *IEEE Access* **2022**, *10*, 55583–55601. [CrossRef]
107. Pavankumar, Y.; Debnath, S.; Paul, S. Microgrid fault detection technique using phase change of Positive sequence current. *Int. J. Model. Simul.* **2022**, *43*, 171–184. [CrossRef]

108. Guerrero, J.; Berbel, N.; de Vicuna, L.G.; Matas, J.; Miret, J.; Castilla, M. Droop Control Method for the Parallel Operation of Online Uninterruptible Power Systems using Resistive Output Impedance. In Proceedings of the Twenty-First Annual IEEE Applied Power Electronics Conference and Exposition, Dallas, TX, USA, 19–23 March 2006.
109. Nabatirad, M.; Razzaghi, R.; Bahrani, B. Decentralized Voltage Regulation and Energy Management of Integrated DC Microgrids Into AC Power Systems. *IEEE J. Emerg. Sel. Top. Power Electron.* **2020**, *9*, 1269–1279. [CrossRef]
110. Majumder, R.; Chaudhuri, B.; Ghosh, A.; Majumder, R.; Ledwich, G.; Zare, F. Improvement of Stability and Load Sharing in an Autonomous Microgrid Using Supplementary Droop Control Loop. *IEEE Trans. Power Syst.* **2010**, *25*, 796–808. [CrossRef]
111. Guerrero, J.M.; Hang, L.; Uceda, J. Control of Distributed Uninterruptible Power Supply Systems. *IEEE Trans. Ind. Electron.* **2008**, *55*, 2845–2859. [CrossRef]
112. Hartmann, B.; Táczi, I.; Talamon, A.; Vokony, I. Island mode operation in intelligent microgrid—Extensive analysis of a case study. *Int. Trans. Electr. Energy Syst.* **2021**, *31*, e12950. [CrossRef]
113. Alsafran, A.S.; Daniels, M.W. Consensus Control for Reactive Power Sharing Using an Adaptive Virtual Impedance Approach. *Energies* **2020**, *13*, 2026. [CrossRef]
114. Zhang, J.; Wang, X.; Ma, L. A finite-time distributed cooperative control approach for microgrids. *CSEE J. Power Energy Syst.* **2020**, *8*, 1194–1206. [CrossRef]
115. Albatran, S.; Al-Shorman, H. Reactive power correction using virtual synchronous generator technique for droop controlled voltage source inverters in islanded microgrid. *Energy Syst.* **2021**, *14*, 391–417. [CrossRef]
116. Micallef, A.; Apap, M.; Spiteri-Staines, C.; Guerrero, J.M. Mitigation of Harmonics in Grid-Connected and Islanded Microgrids Via Virtual Admittances and Impedances. *IEEE Trans. Smart Grid* **2017**, *8*, 651–661. [CrossRef]
117. Petersen, B.; Bindner, H.; Poulsen, B.; You, S. Smart transmission grid: Vision and framework. *IEEE Trans. Smart Grid* **2017**, *4*, 168–177. [CrossRef]
118. Guerrero, J.M.; Vasquez, J.C.; Matas, J.; de Vicuna, L.G.; Castilla, M. Hierarchical Control of Droop-Controlled AC and DC Microgrids—A General Approach Toward Standardization. *IEEE Trans. Ind. Electron.* **2011**, *58*, 158–172. [CrossRef]
119. Zhao, M.; Wang, X.; Mo, J. Workload and energy management of geo-distributed datacenters considering demand response programs. *Sustain. Energy Technol. Assessments* **2023**, *55*, 102851. [CrossRef]
120. Soultanis, N.L.; Hatziargyriou, N.D. Control issues of inverters in the formation of L. V. micro-grids. In Proceedings of the 2007 IEEE Power Engineering Society General Meeting, Tampa, FL, USA, 24–28 June 2007; pp. 1–7. [CrossRef]
121. Wang, B.; Lin, Q.; Wen, B.; Burgos, R. Gird-Forming Distributed Generation Inverter Control for A Smooth Transition from Grid-Connected to Islanded Operation Mode in Microgrids. In Proceedings of the2022 IEEE Energy Conversion Congress and Exposition (ECCE), Detroit, MI, USA, 9–13 October 2022; pp. 1–8. [CrossRef]
122. Wang, J. Design Power Control Strategies of Grid-Forming Inverters for Microgrid Application. In Proceedings of the 2021 IEEE Energy Conversion Congress and Exposition, ECCE 2021—Proceedings, Virtual, 10–14 October 2021; pp. 1079–1086. [CrossRef]
123. Vasquez, J.C.; Mastromauro, R.A.; Guerrero, J.M.; Liserre, M. Voltage Support Provided by a Droop-Controlled Multifunctional Inverter. *IEEE Trans. Ind. Electron.* **2009**, *56*, 4510–4519. [CrossRef]
124. Islam, M.; Nadarajah, M.; Hossain, J. Multifunctional control of single-phase transformerless PV inverter connected to a distribution network. In Proceedings of the 2016 Australasian Universities Power Engineering Conference (AUPEC), Brisbane, QLD, Australia, 25–28 September 2016; pp. 1–6. [CrossRef]
125. Mohamed, Y.A.-R.I.; El-Saadany, E.F. Adaptive Decentralized Droop Controller to Preserve Power Sharing Stability of Paralleled Inverters in Distributed Generation Microgrids. *IEEE Trans. Power Electron.* **2008**, *23*, 2806–2816. [CrossRef]
126. Firdaus, A.; Mishra, S. Mitigation of Power and Frequency Instability to Improve Load Sharing Among Distributed Inverters in Microgrid Systems. *IEEE Syst. J.* **2019**, *14*, 1024–1033. [CrossRef]
127. Haddadi, A.; Shojaei, A.; Boulet, B. Enabling high droop gain for improvement of reactive power sharing accuracy in an electronically-interfaced autonomous microgrid. In Proceedings of the 2011 IEEE Energy Conversion Congress and Exposition: Energy Conversion Innovation for a Clean Energy Future, ECCE 2011, Phoenix, AZ, USA, 17–22 September2011; pp. 673–679. [CrossRef]
128. Zhong, Q.-C. Robust Droop Controller for Accurate Proportional Load Sharing Among Inverters Operated in Parallel. *IEEE Trans. Ind. Electron.* **2011**, *60*, 1281–1290. [CrossRef]
129. Prabaharan, N.; Jerin, A.R.A.; Najafi, E.; Palanisamy, K. An overview of control techniques and technical challenge for inverters in micro grid. *Hybrid-Renew. Energy Syst. Microgrids* **2018**, 97–107. [CrossRef]
130. Meral, M.E.; Çelík, D. A comprehensive survey on control strategies of distributed generation power systems under normal and abnormal conditions. *Annu. Rev. Control* **2018**, *47*, 112–132. [CrossRef]
131. Castilla, M.; Miret, J.; Matas, J.; de Vicuna, L.G.; Guerrero, J.M. Control Design Guidelines for Single-Phase Grid-Connected Photovoltaic Inverters with Damped Resonant Harmonic Compensators. *IEEE Trans. Ind. Electron.* **2009**, *56*, 4492–4501. [CrossRef]
132. Micallef, A.; Apap, M.; Staines, C.S.; Zapata, J.M.G. Secondary control for reactive power sharing and voltage amplitude restoration in droop-controlled islanded microgrids. In Proceedings of the 2012 3rd IEEE International Symposium on Power Electronics for Distributed Generation Systems, PEDG 2012, Aalborg, Denmark, 25–28 June 2012; pp. 492–498. [CrossRef]
133. He, J.; Li, Y.W.; Guerrero, J.M.; Blaabjerg, F.; Vasquez, J.C. An Islanding Microgrid Power Sharing Approach Using Enhanced Virtual Impedance Control Scheme. *IEEE Trans. Power Electron.* **2013**, *28*, 5272–5282. [CrossRef]

134. Zhu, Y.; Fan, Q.; Liu, B.; Wang, T. An Enhanced Virtual Impedance Optimization Method for Reactive Power Sharing in Microgrids. *IEEE Trans. Power Electron.* **2018**, *33*, 10390–10402. [CrossRef]
135. Micallef, A.; Apap, M.; Spiteri-Staines, C.; Guerrero, J.M. Performance comparison for virtual impedance techniques used in droop controlled islanded microgrids. In Proceedings of the 2016 International Symposium on Power Electronics, Electrical Drives, Automation and Motion, SPEEDAM 2016, Capri, Italy, 22–24 June 2016; pp. 695–700. [CrossRef]
136. Micallef, A.; Apap, M.; Spiteri-Staines, C.; Guerrero, J.M. Single-Phase Microgrid with Seamless Transition Capabilities Between Modes of Operation. *IEEE Trans. Smart Grid* **2015**, *6*, 2736–2745. [CrossRef]
137. Marzoni, M.A.; Sadeghzadeh, S.M. Control of single-phase photovoltaic H6 inverter in grid-connected and stand-alone modes of operation. *Int. J. Power Electron.* **2022**, *16*, 80. [CrossRef]
138. Sreekumar, P.; Khadkikar, V. A New Virtual Harmonic Impedance Scheme for Harmonic Power Sharing in an Islanded Microgrid. *IEEE Trans. Power Deliv.* **2015**, *31*, 936–945. [CrossRef]
139. Guerrero, J.M.; Chandorkar, M.; Lee, T.-L.; Loh, P.C. Advanced Control Architectures for Intelligent Microgrids—Part I: Decentralized and Hierarchical Control. *IEEE Trans. Ind. Electron.* **2013**, *60*, 1254–1262. [CrossRef]
140. Milczarek, A.; Malinowski, M.; Guerrero, J.M. Reactive Power Management in Islanded Microgrid—Proportional Power Sharing in Hierarchical Droop Control. *IEEE Trans. Smart Grid* **2015**, *6*, 1631–1638. [CrossRef]
141. Mahmood, H.; Michaelson, D.; Jiang, J. Reactive Power Sharing in Islanded Microgrids Using Adaptive Voltage Droop Control. *IEEE Trans. Smart Grid* **2015**, *6*, 3052–3060. [CrossRef]
142. Alsafran, A.S. Effectiveness of Communication Topology Design on Rate of Convergence of the Reactive Power Sharing in off-grid Microgrids. In Proceedings of the 2021 6th International Conference on Smart and Sustainable Technologies (SpliTech), Bol and Split, Croatia, 8–11 September 2021. [CrossRef]
143. Chen, X.; Hou, Y.; Tan, S.-C.; Lee, C.-K.; Hui, S.Y.R. Mitigating Voltage and Frequency Fluctuation in Microgrids Using Electric Springs. *IEEE Trans. Smart Grid* **2014**, *6*, 508–515. [CrossRef]
144. Avancini, D.B.; Rodrigues, J.J.P.C.; Rabêlo, R.A.L.; Das, A.K.; Kozlov, S.; Solic, P. A new IoT-based smart energy meter for smart grids. *Int. J. Energy Res.* **2020**, *45*, 189–202. [CrossRef]
145. Yan, S.; Tan, S.-C.; Lee, C.-K.; Chaudhuri, B.; Hui, S.Y.R. Use of Smart Loads for Power Quality Improvement. *IEEE J. Emerg. Sel. Top. Power Electron.* **2016**, *5*, 504–512. [CrossRef]
146. Ankita; Jarial, R. Improved Electric spring control for Power Factor Correction Using Fuzzy PI Controller. In Proceedings of the 2022 2nd International Conference on Emerging Frontiers in Electrical and Electronic Technologies (ICEFEET), Patna, India, 24–25 June 2022; pp. 1–6. [CrossRef]
147. Lee, C.K.; Chaudhuri, N.R.; Chaudhuri, B.; Hui, S.R. Droop control of distributed electric springs for stabilizing future power grid. In Proceedings of the 2015 IEEE Power & Energy Society General Meeting, Denver, CO, USA, 26–30 July 2015; p. 1. [CrossRef]
148. Yang, Y.; Ho, S.-S.; Tan, S.-C.; Hui, S.-Y.R. Small-Signal Model and Stability of Electric Springs in Power Grids. *IEEE Trans. Smart Grid* **2016**, *9*, 857–865. [CrossRef]
149. Zheng, Y.; Hill, D.J.; Meng, K.; Hui, S.Y.R. Critical Bus Voltage Support in Distribution Systems with Electric Springs and Responsibility Sharing. *IEEE Trans. Power Syst.* **2016**, *32*, 3584–3593. [CrossRef]
150. Wang, Q.; Deng, F.; Cheng, M.; Buja, G. The State of the Art of Topologies for Electric Springs. *Energies* **2018**, *11*, 1724. [CrossRef]
151. Solanki, M.D.; Joshi, S.K. Review of Electric Spring: A new smart grid device for efficient demand dispatch and active and reactive power control. In Proceedings of the 2016 Clemson University Power Systems Conference (PSC), Clemson, SC, USA, 8–11 March 2016; pp. 1–8. [CrossRef]
152. Rokde, J.; Thosar, D.A. Review of Various Application of Electric Spring. *SSRN Electron. J.* **2022**. [CrossRef]
153. Tapia-Tinoco, G.; Garcia-Perez, A.; Granados-Lieberman, D.; Camarena-Martinez, D.; Valtierra-Rodriguez, M. Hardware structures, control strategies, and applications of electric springs: A state-of-the-art review. *IET Gener. Transm. Distrib.* **2020**, *14*, 5349–5363. [CrossRef]
154. Alsafran, A. Literature Review of Power Sharing Control Strategies in Islanded AC Microgrids with Nonlinear Loads. In Proceedings of the 2018 IEEE PES Innovative Smart Grid Technologies Conference Europe (ISGT-Europe), Sarajevo, Bosnia and Herzegovina, 21–25 October 2018; pp. 1–6. [CrossRef]
155. Yang, H.; Li, T.; Long, Y.; Chen, C.L.P.; Xiao, Y. Distributed Virtual Inertia Implementation of Multiple Electric Springs Based on Model Predictive Control in DC Microgrids. *IEEE Trans. Ind. Electron.* **2021**, *69*, 13439–13450. [CrossRef]
156. Quijano, D.A.; Vahid-Ghavidel, M.; Javadi, M.S.; Padilha-Feltrin, A.; Catalao, J.P.S. A Price-Based Strategy to Coordinate Electric Springs for Demand Side Management in Microgrids. *IEEE Trans. Smart Grid* **2022**, *14*, 400–412. [CrossRef]
157. Wang, Q.; Cheng, M.; Buja, G. Integration of Electric Springs and Multi-Port Transformers—A New Solution for AC Microgrids with Renewable Energy Sources. *Energies* **2017**, *10*, 193. [CrossRef]
158. Yan, S.; Lee, C.-K.; Yang, T.; Mok, K.-T.; Tan, S.-C.; Chaudhuri, B.; Hui, S.Y.R. Extending the Operating Range of Electric Spring Using Back-To-Back Converter: Hardware Implementation and Control. *IEEE Trans. Power Electron.* **2016**, *32*, 5171–5179. [CrossRef]
159. Wang, Q.; Cheng, M.; Chen, Z.; Wang, Z. Steady-State Analysis of Electric Springs with a Novel δ Control. *IEEE Trans. Power Electron.* **2015**, *30*, 7159–7169. [CrossRef]
160. Mok, K.-T.; Tan, S.-C.; Hui, S.Y.R. Decoupled Power Angle and Voltage Control of Electric Springs. *IEEE Trans. Power Electron.* **2015**, *31*, 1216–1229. [CrossRef]

161. Akhtar, Z.; Chaudhuri, B.; Hui, S.Y.R. Smart Loads for Voltage Control in Distribution Networks. *IEEE Trans. Smart Grid* **2015**, *8*, 1–10. [CrossRef]
162. Chen, X.; Hou, Y.; Hui, S.Y.R. Distributed Control of Multiple Electric Springs for Voltage Control in Microgrid. *IEEE Trans. Smart Grid* **2016**, *8*, 1350–1359. [CrossRef]
163. Lu, F.; Liu, H. An Accurate Power Flow Method for Microgrids with Conventional Droop Control. *Energies* **2022**, *15*, 5841. [CrossRef]
164. Buraimoh, E.; Aluko, A.O.; Oni, O.E.; Davidson, I.E. Decentralized Virtual Impedance- Conventional Droop Control for Power Sharing for Inverter-Based Distributed Energy Resources of a Microgrid. *Energies* **2022**, *15*, 4439. [CrossRef]
165. Wang, X.; Zhang, J.; Zheng, M.; Ma, L. A distributed reactive power sharing approach in microgrid with improved droop control. *CSEE J. Power Energy Syst.* **2020**, *7*, 1238–1246. [CrossRef]
166. Boyle, J.; Littler, T.; Muyeen, S.; Foley, A.M. An alternative frequency-droop scheme for wind turbines that provide primary frequency regulation via rotor speed control. *Int. J. Electr. Power Energy Syst.* **2021**, *133*, 107219. [CrossRef]
167. Chowdhury, S.; Crossley, P. Islanding protection of active distribution networks with renewable distributed generators: A comprehensive survey. *Electr. Power Syst. Res.* **2009**, *79*, 984–992. [CrossRef]
168. Jahn, J.; Engler, A. Inductive decoupling of low-voltage sub-networks. In Proceedings of the 2007 9th International Conference on Electrical Power Quality and Utilisation, Barcelona, Spain, 9–11 October 2007; pp. 1–6. [CrossRef]
169. Feng, F.; Fang, J. Weak Grid-Induced Stability Problems and Solutions of Distributed Static Compensators with Voltage Droop Support. *Electronics* **2022**, *11*, 1385. [CrossRef]
170. Binu, K.U.; Mija, S.J.; Cheriyan, E.P. Nonlinear analysis and estimation of the domain of attraction for a droop controlled microgrid system. *Electr. Power Syst. Res.* **2022**, *204*, 107712. [CrossRef]
171. Alghamdi, S.; Sindi, H.F.; Al-Durra, A.; Alhussainy, A.A.; Rawa, M.; Kotb, H.; AboRas, K.M. Reduction in Voltage Harmonics of Parallel Inverters Based on Robust Droop Controller in Islanded Microgrid. *Mathematics* **2022**, *11*, 172. [CrossRef]
172. Zhong, Q.-C. Harmonic Droop Controller to Reduce the Voltage Harmonics of Inverters. *IEEE Trans. Ind. Electron.* **2012**, *60*, 936–945. [CrossRef]
173. Zhong, Q.-C.; Hornik, T. Harmonic Droop Controller to Improve Voltage Quality. In *Control of Power Inverters in Renewable Energy and Smart Grid Integration*; Wiley Online Library: New York, NY, USA, 2012; pp. 347–358. [CrossRef]
174. Mammadov, A.D.; Dincel, E.; Söylemez, M.T. Analytical design of discrete PI–PR controllers via dominant pole assignment. *ISA Trans.* **2021**, *123*, 312–322. [CrossRef]
175. Rezaei, M.H.; Akhbari, M. Power decoupling capability with PR controller for Micro-Inverter applications. *Int. J. Electr. Power Energy Syst.* **2021**, *136*, 107607. [CrossRef]
176. Kar, P.K.; Priyadarshi, A.; Karanki, S.B. Control Strategy for Single-Phase Grid-Interfaced Modified Multilevel Inverter Topology for Distributed Power Generation. *IEEE Syst. J.* **2021**, *16*, 1627–1636. [CrossRef]
177. Cardoso, L.S.; Rocha, T.D.O.A.; Ribeiro, R.L.A.; Pinheiro, J.R.; Neto, J.R.D. Improvements on Power Flow Control of Voltage-Source-Based Grid-Supporting Converter by Using Virtual Impedance Concept. In Proceedings of the 2019 IEEE PES Innovative Smart Grid Technologies Conference-Latin America (ISGT Latin America), Gramado, Brazil, 15–18 September 2019; pp. 1–6. [CrossRef]
178. Kim, J.; Guerrero, J.M.; Rodriguez, P.; Teodorescu, R.; Nam, K. Mode Adaptive Droop Control with Virtual Output Impedances for an Inverter-Based Flexible AC Microgrid. *IEEE Trans. Power Electron.* **2011**, *26*, 689–701. [CrossRef]
179. Cheng, L.; Liu, Z.; Liu, J.; Tu, Y. An RL-Type Active Damper for Stabilizing Wide Band Oscillations in Grid-Tied Inverter Systems. In Proceedings of the ECCE 2020—IEEE Energy Conversion Congress and Exposition, Detroit, MI, USA, 11–15 October 2020; pp. 1686–1693. [CrossRef]
180. Azghandi, M.A.; Barakati, S.M. Virtual RL Damping and Harmonic Suppression for Current-Source Inverter-Based Photovoltaic Systems. In Proceedings of the 2019 10th International Power Electronics, Drive Systems and Technologies Conference, PEDSTC 2019, Shiraz, Iran, 12–14 February 2019; pp. 572–576. [CrossRef]
181. Jonke, P.; Makoschitz, M.; Ertl, H. Dreiphasiger Netzsimulator mit virtueller Ausgangsimpedanz. *e i Elektrotechnik und Informationstechnik* **2022**, *140*, 110–122. [CrossRef]
182. Liu, Y.; Zhou, X.; Yu, H.; Hong, L.; Xia, H.; Yin, H.; Chen, Y.; Zhou, L.; Wu, W. Sequence Impedance Modeling and Stability Assessment for Load Converters in Weak Grids. *IEEE Trans. Ind. Electron.* **2020**, *68*, 4056–4067. [CrossRef]
183. Eskandari, M.; Savkin, A.V. A Critical Aspect of Dynamic Stability in Autonomous Microgrids: Interaction of Droop Controllers Through the Power Network. *IEEE Trans. Ind. Inform.* **2021**, *18*, 3159–3170. [CrossRef]
184. Hou, S.; Chen, J.; Chen, G. Distributed control strategy for voltage and frequency restoration and accurate reactive power-sharing for islanded microgrid. *Energy Rep.* **2023**, *9*, 742–751. [CrossRef]
185. Bilgundi, S.K.; Sachin, R.; Pradeepa, H.; Nagesh, H.B.; Kumar, M.V.L. Grid power quality enhancement using an ANFIS optimized PI controller for DG. *Prot. Control Mod. Power Syst.* **2022**, *7*, 1–14. [CrossRef]
186. Todorovic, I.; Isakov, I.; Reljic, D.; Jerkan, D.G.; Dujic, D. Mitigation of Voltage and Frequency Excursions in Low-Inertia Microgrids. *IEEE Access* **2023**, *11*, 9351–9367. [CrossRef]
187. Alam, S.; Al-Ismail, F.S.; Abido, M.A. Power management and state of charge restoration of direct current microgrid with improved voltage-shifting controller. *J. Energy Storage* **2021**, *44*, 103253. [CrossRef]

188. Zhao, C.; Sun, W.; Wang, J.; Fang, Z. Distributed robust secondary voltage control for islanded microgrid with nonuniform time delays. *Electr. Eng.* **2021**, *103*, 2625–2635. [CrossRef]
189. Wilson, D.G.; Robinett, R.D.; Bacelli, G.; Abdelkhalik, O.; Coe, R.G. Extending Complex Conjugate Control to Nonlinear Wave Energy Converters. *J. Mar. Sci. Eng.* **2020**, *8*, 84. [CrossRef]
190. Chinnici, G.; Selvaggi, R.; D'amico, M.; Pecorino, B. Assessment of the potential energy supply and biomethane from the anaerobic digestion of agro-food feedstocks in Sicily. *Renew. Sustain. Energy Rev.* **2018**, *82*, 6–13. [CrossRef]
191. Abohamer, M.; Awrejcewicz, J.; Amer, T. Modeling of the vibration and stability of a dynamical system coupled with an energy harvesting device. *Alex. Eng. J.* **2023**, *63*, 377–397. [CrossRef]