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# Review of Harmonic Mitigation Methods in Microgrid: From a Hierarchical Control Perspective

Behrooz Adineh, Reza Keypour, *Member, IEEE*, Pooya Davari, *Senior, IEEE*, and Frede Blaabjerg, *Fellow, IEEE*

**Abstract**—The Microgrid concept has been emerged into the power system to provide reliable, renewable and cheaper electricity for the rising global demand. When the microgrids are introduced, there will be several concerns such as active and reactive power sharing, load management, connecting to the main grid, voltage and current deviations, etc. Recently, with the fast deployment of distributed generation, methods to mitigate microgrid harmonics caused by nonlinear loads and power electronic devices have become one of the main focus areas. Consequently, many research works are devoted to this area introducing different harmonic mitigation methods suitable for the microgrids. Hence, the main goal of this paper is to clearly present a comprehensive review of harmonic mitigation methods from hierarchical control view-point. The control strategies proposed to mitigate harmonics are classified into three groups; Primary, secondary, and tertiary. Furthermore, this overview draws a sketch on the global trends in harmonic mitigation methods of an ac microgrid directly applicable to today's smart grid applications.

**Index Terms**—Harmonics mitigation, hierarchical control, microgrid control, power quality, power electronics, renewable energy.

## I. INTRODUCTION

NOWADAYS distributed generations (DGs) like solar systems, wind turbines, fuel cells and others have gained more attention due to their great benefits such as being renewable (i.e., reducing carbon foot print or substituting fossil-fuel), providing reliable electricity to areas lacking of electrical infrastructure [1], reducing environmental issues [2], improving overall system reliability, etc [3]–[10]. Integration of DGs along with linear and nonlinear loads is known as a microgrid [11]–[19]. Microgrids can be operated in two modes; islanded or grid-tied (grid connected) modes [20]–[22]. In the islanded mode, there is no connection between the microgrid and the main grid. Microgrid acts as a self-providing system, which generates power and provides its needs [23]. However, in the grid connected mode, a microgrid can send power to or receive power from the main grid [24]. With the penetration of microgrid, the hierarchical control concept is introduced [22], [25]–[28]. It should be noted that there are some literature explaining the nature of microgrids [29], [30] and the hierarchical control used to improve their reliability,

operation and efficiency [31], [32]. The hierarchical control of each microgrid can be categorized into three levels, as shown in Fig. 1. The first level is known as the primary level, which has to share active and reactive power properly among DGs, to keep voltage and frequency in a specified range and avoid circulating current between DGs. The main control system at this level is droop control (DrC) along with inner voltage and current controllers [33]. Inner controller structures are analyzed in [33]. The voltage and frequency deviations caused by the primary controller are compensated by the controllers used at the secondary level. The main roles of the tertiary controller are to share power in grid-tied mode and monitor the microgrid to operate optimally and economically. Although the use of these three level of controllers improves the reliability and efficiency of the microgrid in both modes, there are still some great concerns such as voltage and current harmonic distortions and also harmonic sharing problems between converters. Therefore, the authors proposed new control methods to overcome these issues [34]–[40].

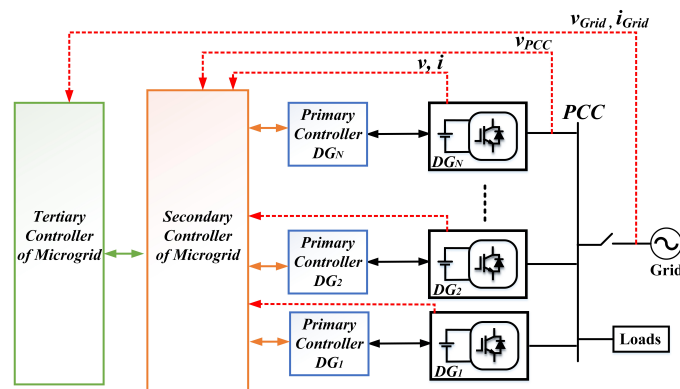


Fig. 1. Hierarchical control of microgrid

Switching, resonance, and nonlinear loads are the main reasons for that microgrids are polluting with voltage or current harmonics. First, the use of power electronic devices in DGs, which are crucial to generate and transfer ac powers to the loads is the first main reason of having harmonics in microgrids [9], [41]. These power converters generate voltage and current harmonics in DG's output due to their switching process, also control interaction and resonances. Resonance could come from the filter of a power converter, interaction of multiple converter filters or among filter capacitance and the line inductance. The voltage and current harmonics include high frequency harmonic components, which should be mitigated by using the new controllers in hierarchical control of

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the microgrid. On the other hand, the existence of nonlinear loads in the microgrid is another main reason for generating harmonics [42]. These nonlinear loads generate low frequency harmonic components at multiples of the microgrid frequency, which is usually 50 or 60 Hz [43].

With the high penetration of microgrids in the power system, voltage and current harmonics generated by the renewable energy sources using power converters in their structures are crucial to understand and investigate. The whole trend of microgrid research and, all experimental and simulation results are bound to make microgrids feasible, reliable and harmonic free systems with good power quality. There are some literature reviewed microgrid concepts, hierarchical control of microgrid and harmonic mitigation methods in a particular renewable energy source such as PV systems [36], [37], [43], [44], or harmonic mitigation methods only for single phase microgrids [45]. However, harmonic compensation methods in both single and three phase ac microgrids are not well addressed. It is necessary to have such a review to understand and compare the current state of the art of methods used to mitigate harmonic distortion in microgrids. Therefore, the main aim of this paper is to tackle this vital necessity of power electronic based systems, in order to clearly understand the control approaches proposed for harmonic mitigation in ac microgrids.

The main core of this paper is to provide an overview on prior-art and state-of-the-art harmonic compensation methods in ac microgrids. State of art control schemes used in different literature are classified into three control levels; Primary, secondary, and tertiary. Since the first level in hierarchical control of microgrid has less complexity and can be used without communication links, many methods are proposed to mitigate and share harmonics at the primary level. The main approaches used at the primary level are modified droop controller (MDC), harmonic droop controller (HDC), virtual impedance (VI) loop, proportional-resonance (PR) controller, and repetitive controller (RC), as shown in Fig. 2. On the other hand, there are some papers proposing harmonic mitigation methods at the secondary or tertiary level, which both levels need communication links. In these methods, the central controller is able to compensate voltage or current harmonics using strategies such as optimization methods, neural networks, etc. The main strategies proposed in the literature are shown in Fig. 2.

The rest of this paper is as follows: the standards and limitations of harmonics in microgrid are addressed in section II. The harmonic detection and extraction methods are briefly discussed in section III. Section IV and V describe and explain the methods used at the primary and secondary levels of microgrid, respectively. Moreover, there is a subsection for comparing the control methods proposed at each level and explaining their future trends. The approaches used at the last level of the hierarchical control are well explained in section VI, and Section VII is the conclusion of this paper.

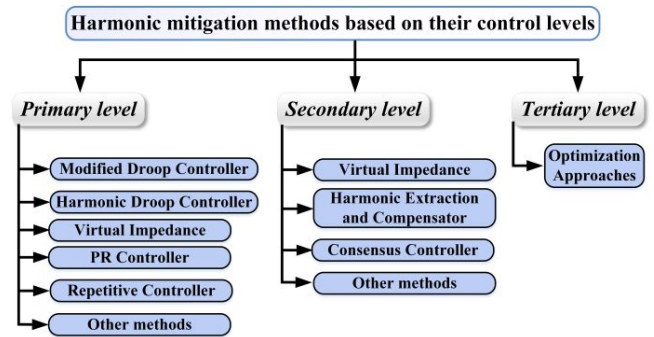


Fig. 2. Categorizing harmonic mitigation methods based on their control levels

## II. HARMONIC STANDARDS AND LIMITATIONS FOR MICROGRIDS

The main objectives of methods proposed in the literature in order to enhance power quality in microgrids are as follows [39], [43]:

- 1) Mitigation of point of common coupling (PCC) voltage harmonics;
- 2) Mitigation of local load harmonics;
- 3) Harmonic cancelation of DG line current;

Although most of the proposed methods are used to mitigate local harmonics in a microgrid including two inverters connected to the one bus named PCC or critical bus, it seems that it is necessary to extend the microgrid as a network and try to minimum harmonics in such a multi-bus microgrid like the ones in [46]. Therefore, there might be other objectives such as:

- 4) Mitigation of voltage and current harmonics in the critical bus of multi-bus microgrid;
- 5) Minimization of voltage and current harmonics of all buses in the multi-bus microgrid;
- 6) Current harmonics from individual equipment in microgrid.

It should be noted that all the proposed methods should meet the criteria suggested in the global power quality standards. For instance, the IEEE Standards board has two well-known and well-established standards that are useful for the grid with renewable energy sources integration [47], [48]. As displayed in Table I, it can be realized that the voltage harmonic distortion for an individual harmonic and total harmonic distortion (THD) limitations of PCC are decreased with the increase in the rated voltage of PCC.

TABLE I  
IEEE 519 STANDARD: VOLTAGE HARMONIC DISTORTION LIMITS

PCC rated voltage (kV)	Individual harmonic (%)	THD (%)
$V \leq 1$	5	8
$1 < V \leq 69$	3	5
$69 < V \leq 161$	1.5	2.5
$161 < V$	1	1.5

The tables used in [48] and [49] are describing the current harmonic distortion limits in the microgrid for different rated voltages.



### III. HARMONIC DETECTION METHODS (BRIEF REVIEW)

The main task of the harmonic detection method is to detect and extract the harmonic components of currents or voltages, which should be mitigated by the harmonic compensation methods. In other words, the features of harmonics such as amplitude, phase, etc. should be detected by using a reliable and accurate method from an input signal. Then, the harmonic distortion can be reduced by applying the proposed harmonic mitigation method, as shown in Fig. 3. Hence, the harmonic detection methods used in the microgrids are reviewed and classified into two groups, namely frequency-domain and time-domain groups, which are based on their mathematical algorithms in this section.

For the frequency-domain methods, the Fourier analysis is commonly used and rearranged to extract harmonic components from the input signals [50]. Currently, the main Fourier-based approaches are discrete Fourier transform (DFT), fast Fourier transform (FFT) [46], [51], and sliding discrete Fourier transform (SDFT) [52]. These methods need at least one cycle settling time, large memory storage and careful synchronization between fundamental and sampling frequency. They also have unreliable response in transient conditions. Therefore, the frequency domain methods could be more useful in monitoring and metering of harmonics. On the other hand, the time-domain approaches increase speed, require less calculations and would work better in real-time harmonic mitigation applications compared to the frequency ones [50], [53].

There are many published articles, which introduce and use time-domain harmonic detection methods to extract harmonics from the input signals. If the purpose of the harmonic extraction is to separate harmonics as a whole by excluding the fundamental component of the signal, the instantaneous power theory ( $pq$ ) based approaches can be used [54]–[56]. Although, these methods can extract harmonics by using high pass filters (HPF), their function and calculation would be affected if an unbalanced situation has occurred in the system. Furthermore, there are approaches, which are currently used more in microgrid applications and can extract harmonic components individually such as PR filters [57]–[59], second order generalized integrators (SOGI) [56], [60], delayed signal cancellation (DSC) [53], [61], [62], and moving average filters (MAF) [63], [64]. Some enhanced methods, based on the mentioned ones, are proposed in the literature for instance double SOGI (DSOGI) [65], [66], multi SOGI (MSOGI) [67], [68], cascaded DSC (CDSC) [62], [69], and MAF-DSC [70] to improve the performance and dynamic of such methods. It should be noted that all these methods widely use phase or frequency detection schemes such as phase/frequency lock loop (PLL/FLL) to track the fundamental frequency especially in unbalanced situations.

Despite the advantages of the related methods such as their capability to be used for both single and three phase systems, do not need numerical filters, work well in unbalanced situations, and can extract positive-negative sequences, the proposed selective harmonic detection approaches have some drawbacks. The SOGI-based methods are prone to frequency

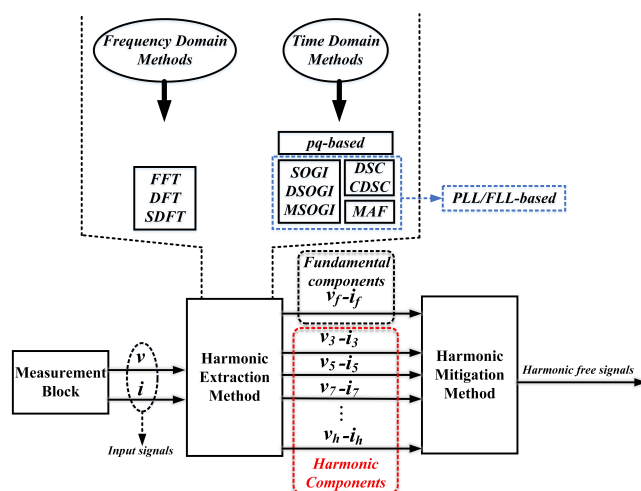


Fig. 3. Harmonic detection methods used in microgrids

fluctuation, they have slow response and give computational burden especially in MSOGI, and zero steady state error for the SOGI and DSOGI. The DSC-based methods suffer from discretization errors during the digital implementation and have a computational burden [62], [69]. Therefore, based on the pros and cons of the harmonic detection methods, a reliable and suitable method must be chosen and used in the different microgrid applications.

### IV. PROPOSED METHODS AT PRIMARY LEVEL

The main tasks of primary controller in a microgrid are voltage and frequency regulation, and active and reactive power control in both islanded and grid connected modes [22], [31]. Since this control level has the fastest response among the others and can be operated without any communication links, authors have preferred to propose their harmonic mitigation methods at this level. Conventional droop controller and inner voltage and current controllers are the most common and useful parts in a local primary controller, as shown in Fig. 4 [71]–[73]. In [54], [74]–[76], a modified droop controller is proposed to reduce THD of PCC. In this case, the main equations of the conventional droop controller are modified by using additional parameters. Moreover, some literature have proposed the harmonic droop controller along with the conventional or modified droop controller as in [77]–[84].

Some literature have reviewed the primary control strategies of microgrids as given in [3], [85]–[89]. In [90], some approaches using proportional-integral (PI), PR and nonlinear controllers for improving power quality of microgrids are discussed. However, the proposed harmonic mitigation methods used at the primary level are not well-reviewed in the literature. In this section, the methods proposed at the primary level of the microgrid are classified into five main groups, like shown in Fig. 2. The first two groups in Fig. 2 are modified and harmonic droop controllers, in which the main goal of these methods is to change the voltage reference entering the inner current and voltage controllers. Another common solution for improving power quality in microgrid is virtual impedance or admittance, in which the DG current is modified and then

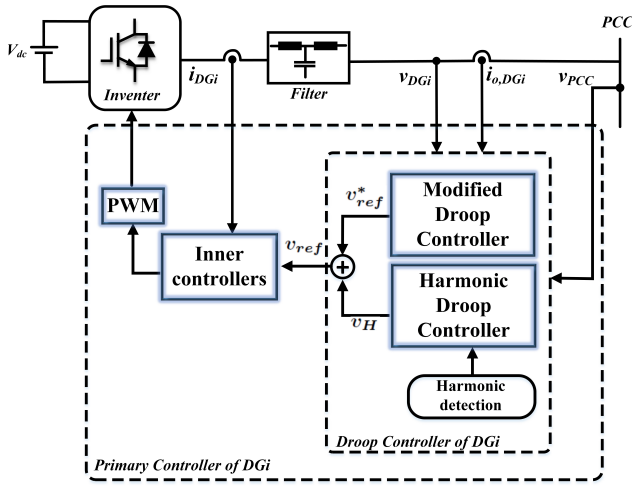


Fig. 4. Primary control structure of a microgrid

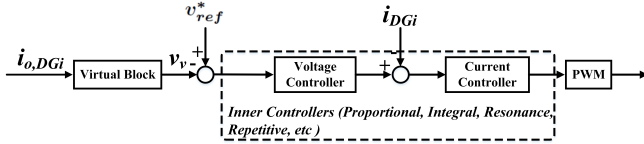


Fig. 5. Primary controllers including virtual impedance, voltage and current inner controllers

added to the DG voltage, as shown in Fig. 5. Other methods such as PR, repetitive, and so on controllers are often used in the current and voltage inner controllers to mitigate harmonic distortion, as shown in Fig. 5. In the following subsections, these methods are reviewed comprehensively and compared in the last subsection.

#### A. Modified Droop Controller (MDC)

Generally in the literature, the active power-frequency ( $P - f$ ) and reactive power-voltage ( $Q - V$ ) droop controllers are used to share power between DGs. The equations of droop controller is as follows:

$$\omega_i = \omega_i^* - m_i P_i, \quad E_i = E_i^* - n_i Q_i \quad (1)$$

where  $\omega_i^*$ ,  $E_i^*$ ,  $P_i$  and  $Q_i$  are the rated frequency, voltage amplitude, active and reactive power of  $i^{th}$  inverter in the microgrid, respectively. To mitigate voltage harmonic distortion at the primary level of the microgrids, the authors modified the droop controller or added harmonic droop controller to the conventional one, as it is shown in Fig. 4. These methods will be reviewed in the two next subsections.

Modified droop controller (MDC), which is presented in Fig. 4 at the primary level of microgrid is used to modify the generated voltage reference. In [55], a modified voltage and frequency droop controller is introduced including a linear quadratic Gaussian scheme along with a Kalman estimation to mitigate voltage harmonic distortion in both islanded and grid connected microgrids using a LCL filter. In [75], a new droop characteristic, named as  $G - H$  droop, is added to the conventional droop given as:

$$G_i^* = G_0 - b_i (H_{0i} - H_i) \quad (2)$$

$G_i$  and  $b_i$  are harmonic conductance and harmonic droop coefficient of  $i^{th}$  DG, respectively.  $H_i$  is the calculated harmonic power as follows:

$$H = \sqrt{\tilde{p}^2 + \tilde{q}^2} \quad (3)$$

where  $\tilde{p}$  and  $\tilde{q}$  are the harmonic components of active and reactive power calculated in the droop scheme, respectively. Then the harmonic components at the PCC voltage extracted by low pass filters are multiplied to  $G_i^*$ . The voltage reference is generated after some calculations using output inductor of the inverter. In [54], a similar scheme as in [75] is performed for an islanded microgrid. Besides, negative sequences of voltage and current are used in  $Q^- - G$  droop controller. Moreover, the conventional droop controller is disabled and the proposed  $Q^- - G$  is just used to generate the current reference for the PWM inverter in the grid connected mode.

In [57], the conventional droop controller for the single phase inverters with resistive output impedances is modified. In the proposed method, the output voltage reference of the conventional droop controller is changed as follows:

$$v_{ref,new} = v_{ref} - k_i i_L + k_R (v_{ref} - v_o) \quad (4)$$

where  $v_{ref}$ ,  $k_i$ ,  $i_L$ ,  $k_R$ , and  $v_o$  are the reference voltage, current constant, inductor current, low pass filter constant in harmonic frequencies and output voltage, respectively. It is concluded that the main reason for affecting the voltage THD is the amplitude of the output impedance, and not the phase.

As shown in Table II, MDC based methods are somehow complex and sensitive to the microgrid parameter variations, which make them undesirable for practical purposes. Moreover, the only objective achieved in the literature is the compensation of voltage harmonics at PCC and other harmonic issues, as discussed in section II, have not yet been considered.

#### B. Harmonic Droop Controller (HDC)

Harmonic droop controller (HDC) is a harmonic mitigation method, which is used along with the conventional droop controller or MDC, as shown in Fig. 4. Harmonic extraction methods are playing a significant role in these methods and applied to separate harmonic components. The output voltage of the HDC is added to the voltage reference generated by the droop controller.

In [26], some harmonic cancellation methods along with the droop controller are introduced and investigated. In [77], the model of the grid connected inverter is explained at harmonic frequencies and a harmonic droop controller is introduced to add the right harmonic voltage reference to the droop controller for the sake of elimination of the harmonic components at the output voltage by minimizing the output impedance of the inverter. In [91], a selective harmonic suppression block is proposed along with the droop controller and virtual impedance to compensate THD of PCC voltage. In [92], a harmonic suppression controller including two low pass filters and two PI controllers for each harmonic component in addition to VI and conventional droop controller is introduced to modify the output of the inner current controller in order to reduce the selected harmonic components in an islanded microgrid.

As shown in Table II, the complexity level of the HDC based methods is not very low and these methods are sensitive to microgrid parameter variations. Moreover, the only objective achieved is the compensation of voltage harmonics at PCC and other harmonic issues, as discussed in section II, have not yet been considered.

### C. Virtual Impedance and Admittance (VIA)

The idea of using virtual impedance or/and admittance (VIA) loop in the primary control is recently developed to reduce power quality issues in microgrid by reshaping the output impedance. Although the first VIA methods are strongly sensitive to the microgrid impedances, adaptive VIA methods are suggested, which have a computational burden and they are more complex. Simple structure of the virtual block for voltage source converters is presented in Fig. 5. The output voltage of virtual impedance  $v_v$  is added to the output voltage reference of the droop controller  $v_{ref}^*$  to shape the virtual impedance control loop, and its equation is as follows:

$$v_{ref} = v_{ref}^* - v_v = v_{ref}^* - Z_v i_{o,DG} \quad (5)$$

where  $Z_v$  is the virtual output impedance of inverter. To reduce voltage harmonic distortion in microgrid using the virtual impedance loop, (5) is modified as follows:

$$v_{ref} = v_{ref}^* - v_v = v_{ref}^* - (Z_v + Z_h) i_{o,DG} \quad (6)$$

where  $Z_h$  is the virtual harmonic impedance, which can be resistive, capacitive, etc. If the virtual harmonic impedance parameters including virtual harmonic and filters gains are properly designed and adjusted, the harmonic compensation can be achieved.

In [93] and [94], VIs for both voltage and current source converters considering their functions are classified and also, some of papers are using VIs for harmonic current and voltage reduction are listed in [93]. In [94], a modified VI term is used in the local controller of DG to show that it is not too sensitive to the harmonics generated by the nonlinear loads in microgrid compared to the previous VI schemes. In [95], the output current of DG is decomposed to negative, positive and harmonic components and then compensated by using the virtual impedance scheme. In [96], the THD of the output voltage is reduced by using multiresonant controllers in the inner voltage loop and a virtual resistive loop with the need for local measurement. The reference voltage is as follows:

$$v_{ref} = v_{ref}^* - R_v i_o - \sum_{h=3,5,\dots}^{11} (R_h - R_v) i_{oh} \quad (7)$$

where  $R_v$ ,  $i_o$  and  $R_h$  are the virtual resistive term, output current of DG, and the resistive coefficient of each harmonic for  $h$  component of  $i_o$ , respectively.  $R_h$  should be chosen less than  $R_v$ .

A similar approach is proposed in [97], in which a new term as given in (8) is added to the voltage reference and virtual inductance to obtain a THD mitigation of the output voltage.

$$v_{ref} = v_{ref}^* - sL_v i_o - \sum_{h=3,5,\dots}^{11} R_h i_{oh} \quad (8)$$

where  $L_v$  is the virtual inductance term. In order to extract the fundamental and harmonic components of the output current, a band pass filter is used for each selected harmonic order [96], [97].

In [98], the virtual variable harmonic impedance loop is used at the harmonic frequencies to regulate the output voltage of islanded microgrid. In [60], a different virtual impedance scheme, which can be used as a resistive, inductive or complex impedances, with SOGI is used to obtain less output voltage distortion caused by nonlinear loads. In [99], a wireless controller with three loops is proposed to share nonlinear loads and compensate the THD of the load voltage. However, there will be current peaks and hot-swap issues in the proposed droop controller method. In [100], a virtual complex impedance loop is combined with the droop controller to obtain current sharing between DGs and output voltage harmonic minimization. The complex virtual impedance, including resistive and inductive terms and the used low pass filter, is given as follows:

$$Z_v = R_v + \frac{\omega_c}{s + \omega_c} sL_v \quad (9)$$

where  $R_v$ ,  $L_v$  and  $\omega_c$  are virtual resistance and inductance, and cut off frequency of the low pass filter, respectively.

In [56], a virtual resistor loop is proposed to damp multi resonances in a single phase grid connected microgrid. In [101], it is shown that the use of capacitive VI would mitigate the harmonic distortion of an islanded microgrid by extracting the negative and positive sequence components of the output current. In [58] and [102], a virtual capacitance scheme is proposed to compensate selective harmonic components (3, 5, 7, 9) in an islanded microgrid. The total virtual impedance is as follows:

$$Z_v = R_v - \sum_{h=3,5,7,9} \frac{\omega_{ch} (k_{ph}s + k_{ih})}{s^2 + \omega_{ch}s + \omega_h} \quad (10)$$

where  $\omega_{ch}$ ,  $k_{ph}$ ,  $k_{ih}$  and  $\omega_h$  are bandwidth, proportional gain, integral gain and frequency of each harmonic component, respectively. Although simulation results showed good improvement in mitigating voltage harmonic distortion in inverters with LCL filters, there are many parameters to be chosen for each harmonic component. Furthermore, the way to adjust these parameters is not clear.

In [103], virtual admittance and capacitance schemes are proposed to mitigate the harmonics of the output current and voltage in a single phase microgrid, respectively. The virtual impedance is the same as (10) and the virtual admittance is as follows:

$$Y_v = \sum_{h=3}^{13} C_n \frac{\omega_n s (\omega_n s^2 + \omega_h^2 s)}{(s^2 + \omega_n s + \omega_h)^2} \quad (11)$$

where  $C_n$ ,  $\omega_n$  and  $\omega_h$  are gain of each harmonic component, fundamental and harmonic frequencies, respectively. Although the compensation of the harmonic current is achieved using virtual admittance, the grid frequency variation is not considered since  $Y_v$  is dependent on the grid frequency.

In [104], a capacitive VI loop was proposed in order to decrease the voltage harmonics at the PCC in a single phase

microgrid. In [51], negative sequences of virtual harmonic impedance are used only at harmonic frequencies to reduce the harmonic voltage of the load side in an islanded microgrid. In [65], an enhanced VI approach is proposed to reduce THD of PCC voltage in an islanded microgrid by adding two new generated signals into the voltage reference. In [66], voltage harmonic distortion compensation is achieved by using an adaptive virtual impedance (VIA) scheme in addition to the harmonic cancellation block using a proposed self tuning filter for harmonic extraction to reduce the number of Phase Locked Loop (PLL) blocks. In [68], the modified virtual impedance and admittance are introduced to mitigate selective harmonic components in voltage and current source inverters, respectively. In [105], a variable virtual harmonic impedance scheme is combined with the conventional droop controller and the positive and negative harmonic components of the output voltage are reduced in a grid tied converter using PR controllers. In [106], a virtual impedance scheme is proposed to compensate negative and positive sequence of both third and fifth harmonic components in both islanded and grid connected microgrids.

As discussed above, it is revealed that the negative, positive, and harmonic extraction methods are needed to improve the performance of VIA methods for compensating harmonic distortion in microgrids. Therefore, the proposed VIA methods would be more complex. As shown in Table II, although improved VI based approaches can be independent of the microgrid parameters, the procedure to design and adjust the parameters of these control methods would be very complex.

#### D. Proportional Resonant Controller

One of the common controllers used in the inner current and voltage controllers of the microgrid is PR controller, which is including proportional (P) and resonant controllers to be used for harmonic mitigation purposes. Since PR controllers are applied in the stationary frame ( $\alpha$  and  $\beta$ ), synchronization problems in three phase microgrids and steady state errors in single phase ones can be neglected. Therefore, PR controllers can be used in both single and three phase systems to mitigate selected harmonics. However, using one resonant controller for each harmonic component would increase the complexity and it would make the steady state response slow. The main transfer function of the PR controller is as follows:

$$G_t = k_P + G_R + G_R^h = k_P + \frac{k_i s}{s^2 + \omega_n^2} + \sum_h \frac{k_{ih} s}{s^2 + (\omega_n h)^2} \quad (12)$$

where  $G_R$  and  $G_R^h$  are the transfer function of an ideal resonant controller and harmonic compensator (HC) of this controllers, respectively.  $k_P$ ,  $k_i$ ,  $k_{ih}$  and  $h$  are the gains of proportional, integral and HC controllers, and the harmonic order, respectively.  $k_p$  is adjusted as for a PI controller, and generally determines the microgrid dynamics. To avoid stability issues related to an infinite gain at the frequency of  $\omega_n$  in (12), a non-ideal PR controller and HC can be used as

follows:

$$G_R = \frac{k_i \omega_c s}{s^2 + 2\omega_c s + \omega_n^2}, \quad G_R^h = \sum_h \frac{k_{ih} \omega_c s}{s^2 + 2\omega_c s + (\omega_n h)^2} \quad (13)$$

where  $\omega_c$  is the cut-off frequency of the non-ideal PR controller. If the HC parameters including  $k_{ih}$  and  $\omega_c$  are properly tuned, the selective harmonic compensation can be achieved.

In [59], the authors introduced and investigated the features of PR controllers in the single and three phase grid tied converters. In [107], a multivariable-PI-resonant voltage controller is presented for regulating the output voltage. In [108] and [109], a PR controller and harmonic compensator are proposed together in the inner current loop to reduce the selected harmonics of DG current. Furthermore, a comparison between PR, PR and HC, and PI controllers are done for a single phase PV full bridge inverter. The PR and HC transfer functions are as given (12).

Next, in [110], the authors suggested applying PR and HC controllers in three phase grid connected microgrid using PLL in order to estimate the frequency needed for an adaptive current controller. Furthermore, the harmonic spectrum of grid current in the presence of the PI, PR, and DeadBeat (DB) controllers are shown in [33]. The results showed that the DB controller has better behavior in grid connected microgrid to reduce harmonic distortion. In [111], a PI-PR current controller is proposed and investigated to reduce both positive and negative sequence of harmonics in the rotating frame. The use of this method is not discussed for grid connected microgrids. In [112], a multifunctional controller based on multi PR and harmonic impedance controllers is proposed to mitigate harmonic distortion and voltage unbalance in a grid connected microgrid. In addition, a virtual negative sequence impedance is implemented on the controller to suppress negative sequence of the unbalanced load currents. In [113], a PI-PR controller along with a low pass filter in series with the modified virtual impedance loop is proposed to improve the voltage THD of an islanded microgrid.

As shown in Table II, the PR controllers can be used in combination with other mitigation methods such as VI, MDC, HDC, and HC to improve the performance of such controllers and microgrid.

#### E. Repetitive Controller

Another controller structure used in the inner controllers of the primary controller is the repetitive controller. In [118], a compensator based on the repetitive and deadbeat control is proposed to reduce the THD of voltage in an islanded microgrid, in which a discrete time mathematical model of the proposed controller is presented and used. Moreover, a comparison between PI and RC is done and it is observed that although the RC has a longer settling time, it is much more effective than the PI controller to reduce voltage THD [119]. In [120], a repetitive controller based on a finite-impulse response digital filter is proposed to reduce selected harmonics and THD of the PCC in the single phase grid connected PV system. In [114]–[117], the use of  $H^\infty$  repetitive controllers in current and voltage loops is investigated in order to mitigate

TABLE II  
COMPARING HARMONIC MITIGATION METHODS USED AT THE PRIMARY LEVEL

References	Method	Complexity	Sensitive to system parameters	Harmonic mitigation goals
[54], [55], [57], [75]	MDC	Moderate	✓	THD <sub>v</sub> at PCC
[77], [91], [92]	HDC	Moderate	✓	THD <sub>v</sub> at PCC
[51], [95], [99], [102], [104]	VI	Low	✓	THD <sub>v</sub> and THD <sub>i</sub> at PCC
[103]	VIA	Moderate	-	THD <sub>v</sub> at PCC
[60]	VI-SOGI	Moderate	✓	THD <sub>v</sub> at PCC
[100]	VI-MDC	Moderate	✓	THD <sub>v</sub> at PCC
[106]	VI-HDC	High	✓	THD <sub>v</sub> at PCC
[58], [66], [68], [94], [96], [97], [101], [105], [112]	VI-PR	Moderate	✓	THD <sub>v</sub> at PCC
[98], [111]	AVI-PR	High	-	THD <sub>v</sub> at PCC
[65]	AVI-DSOGI	High	-	THD <sub>v</sub> at PCC
[56]	VI-DB	Low	✓	THD <sub>v</sub> and THD <sub>i</sub> at PCC
[33], [107]	PR-PI	High	✓	THD <sub>v</sub> at PCC
[108]–[110]	PR-PI-HC	Moderate	✓	THD <sub>v</sub> at PCC
[114]–[121]	RC	Moderate	✓	THD <sub>v</sub> at PCC

MDC: Modified Droop Controller, HDC: Harmonic Droop Controller, VI: Virtual Impedance, VIA: Virtual Impedance and Admittance, DB: Dead Beat, AVI: Adaptive Virtual Impedance, HC: Harmonic Compensator, RC: Repetitive Controller, PR: Proportional Resonance, PI: Proportional Integral, SOGI: Second Order Generalized Integrator, DSOGI: Double SOGI, THD<sub>v</sub>: Voltage THD, THD<sub>i</sub>: Current THD

harmonic distortion. However, the application of the proposed methods in the presence of multi inverters (more than one inverter) is not clear and therefore their effects on the active and reactive power sharing of the inverters in microgrids are not considered. A simulation comparison is done in [121] for PI, PR, DB and  $H^\infty$  controllers in the presence of unbalanced and nonlinear loads.

#### F. Other Methods

In [122], hysteresis current control technique is proposed as a closed loop at the primary level of the microgrid to reduce THD of grid current. In [123], a digital controller based on the robust servomechanism theory for three phase inverters is developed to gain low THD output voltage under different load situations. Three harmonic mitigation methods were proposed in [124] in order to change the current reference in the inner current loop for improving power quality in a single phase inverter connected to the grid. In [125] and [126], an adaptive hybrid voltage and current controlled scheme is presented to reduce voltage THD of PCC in both grid connected and islanded mode of the single phase microgrid without using PLL. In [127], the voltage of PCC and load current are passed through a sinusoidal signal integrator filter and then reactive power is calculated and current reference is generated to compensate harmonic currents in a single phase grid connected microgrid. In [128], two control strategies based on changing the current loop, which add a current to the load to the inner current loop, are proposed to improve the grid current and voltage of PCC in grid connected and islanded mode of a single phase microgrid, respectively. In [129], a linear harmonic compensator in series with a tracker regulator, which consists of PI controllers is introduced for a single phase grid tied PV inverter. In [130], a new droop controller scheme based on a model predictive control approach is introduced

and the proposed cascaded controller is used in the inner controller in order to improve power quality in an islanded CIGRE benchmark microgrid using five DGs. In [131], a method consisting of two blocks, which are the harmonic estimation and compensation blocks, is proposed to reduce THD of PCC voltage and DG current by using PI controllers and PLL. In [78], there are two inverters, which have different responsibilities in an islanded microgrid. The first one is used to share power between loads and the second one is utilized to compensate voltage harmonic distortion. In [132], in order to improve power quality of PCC in an islanded microgrid, the voltage feedback is changed from capacitor voltage to output voltage along with PR controllers, which are reshaping the harmonic impedance, and virtual admittance, and it is reducing the size of output impedance.

#### G. Comparison and Trends of Harmonic Minimization Methods in Primary Level

Table II summarizes and compares the harmonic mitigation methods, which are comprehensively reviewed in the previous subsections, used at the primary level of ac microgrids. As shown in Table II, the authors preferred to use virtual impedance, virtual impedance and admittance, and adaptive virtual impedance based controllers along with the other common controllers such as droop, and inner controllers used at the primary level to reduce voltage harmonic distortion. However, in order to effectively mitigate harmonic distortion in a microgrid by using the proposed approaches, the microgrid controller design would be complex and will have computational burden. Other methods such as RC and PR controllers are used in voltage and/or current inner controllers to achieve the harmonic mitigation goals. Even though the design procedure of such methods is not very complex, they are often very sensitive to the microgrid parameters and affected the



active and reactive power sharing between the DGs. Modifying the droop controllers or implementing HDC in a microgrid are other proposed methods to overcome the power quality issues. However, these methods are also sensitive to system parameters. Therefore, future trends for improving the power quality issues might be as follows:

- 1) Try to apply the proposed methods in the multi-bus microgrid and mitigate voltage harmonic distortion of the critical bus,
- 2) Try to apply and verify the proposed methods in the multi-bus microgrid and mitigate voltage harmonic distortion at all buses of such microgrid,
- 3) It should be noticed that the current harmonic distortion is a crucial issue in the microgrid as well as voltage harmonic distortion, which must be mitigated by the proposed methods and have not yet been seen very well in the literature,
- 4) It is revealed that it is necessary to propose a robust, reliable and fast harmonic mitigation method, which is not affecting the performance of DGs in the microgrid such as active and reactive power sharing, voltage and frequency responses, and so on. Moreover, the behavior of such method should be investigated and improved in different microgrid situations e.g. plug and play situation, transients between islanding and grid connecting modes.

## V. METHODS PROPOSED IN SECONDARY LEVEL

This section will review mitigation methods at secondary and tertiary control of a microgrid, like illustrated in Fig. 1. The red lines in Fig. 1 are showing for the low bandwidth communication links between DGs and the main grid, and secondary and tertiary levels.

Two main schemes, which can be found in literature using the secondary control level for harmonic mitigation are shown in Fig. 6 [133]. The first one is named a centralized approach, which is using all the online information from the DG units and loads in the microgrid to make the best decision and send the required information to the DG unit local controllers, as shown in Fig. 6(a). Another one, which is called decentralized or distributed approach is suggested for grid connected microgrids with multi-different DG units [7], [134], like shown in Fig. 6(b). In this approach, online or offline information of microgrid is sent to the central controller, which is responsible for harmonic mitigation of DG units locally and in the whole microgrid. At the secondary control level of microgrid, there is a microgrid central controller (MGCC) in order to transfer information via communication links between DGs and MGCC itself [135]–[138].

In [139], there are a low-bandwidth central controller and distributed high-bandwidth local controllers to mitigate harmonic distortion for parallel inverters in an islanded microgrid. The proposed method is applied to a set of three 10-kVA inverters in a microgrid. The experimental results showed that harmonic rejection can be achieved by only using a low bandwidth central controller in DGs instead of using one inverter with a full bandwidth controller. In [140], the THD

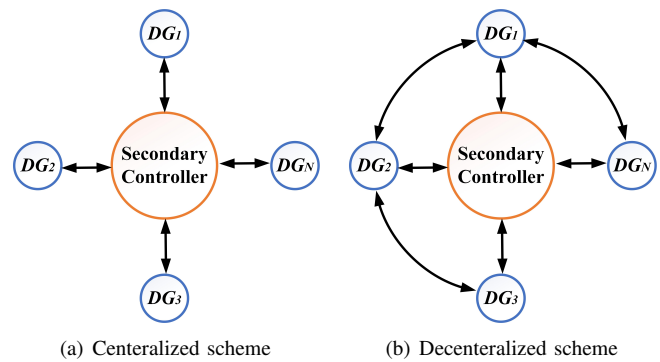


Fig. 6. Two control schemes for secondary controller in microgrid

reduction is achieved by introducing the virtual admittance in a central controller. The PCC voltage is measured and sent to a central controller, and then, the needed virtual admittance and current reference used in the local controllers of each DG are calculated in the central controller. The proposed virtual admittance based controller can be applied in both current and voltage control modes of the voltage source inverters. In [141], the selected harmonics are mitigated in an islanded microgrid in the presence of multiple distributed capacitors by using a central controller, which receives the sensitive bus voltage as an input and sends a current signal as an output to add into the current loops of DGs. A Park transformation aided signal modulation/demodulation approach is presented to overcome the bandwidth limitations of the communication links. In the proposed approach, the harmonic frequency signals measured on the central controller using SOGI-PLL method are transformed from time domain to constant vectors in rotating reference frames. Then, these information are transformed back to harmonic frequency signals on the local controller of each DG. Moreover, the voltage harmonics extracted in the central controller are compared with the distortion limits for the selected harmonic voltages ( $h = 5, 7, 11, 13$ ), and then a PI controller is used to regulate the produced error [141].

In [142], one PI and one harmonic compensator in addition to virtual impedance scheme for each selected harmonic are presented in primary and secondary controllers in order to compensate for the harmonic distortion in an islanded microgrid. Furthermore, the positive and negative sequences of fundamental and harmonic components of output current are elicited in the virtual impedance scheme to produce the voltage reference as an output of the central controller. The voltages of the PCC are measured to extract the fundamental component and harmonic positive/negative sequences in  $dq$  frame by using PLL and second order LPFs. Then, these messages are sent to the central controllers to generate compensation references. Moreover, in the local controller of DG, the harmonic positive/negative sequences and fundamental component of the output current are extracted to calculate the harmonic distortion indices. These indices are then compared with the harmonic distortion limitations and multiplied to the compensation references received from the central controller.



Finally, the voltage reference of each DG can be as follows:

$$v_{ref} = v_{ref}^* + v_c - v_v \quad (14)$$

where  $v_{ref}^*$ ,  $v_c$ , and  $v_v$  are the voltage reference generated by the droop controller, the output voltage of compensation effort controller of each DG, and the output voltage of virtual impedance loop, which is based on (6). This voltage reference is then passed through the PR controller of both inner current and voltage controllers, which is based on (13) to generate PWM signals. The proposed method is complex and there are many parameters, which must be tuned properly. In [52], a modified inner controller based on the information from the central controller is proposed to compensate selected harmonics in a single phase islanded microgrid by using an enhanced virtual impedance controller. The PLL based SDFT approach is used in both central and local controllers to extract voltage harmonic and fundamental components. Then, the proposed virtual impedance method is used to reduce THD of the PCC. The voltage reference of each DG, which is generally based on (5) would be as follows:

$$\begin{aligned} v_{ref} &= v_{ref}^* - v_{vf} - v_{vh} \\ &= v_{ref}^* - (R_{vf} \cdot i_{of\alpha} - \omega L_{vf} \cdot i_{of\beta}) \\ &\quad - \left( \sum_h G_{Rh} \cdot v_{oh\alpha} - \sum_h G_{Ih} \cdot v_{oh\beta} \right) \end{aligned} \quad (15)$$

where  $R_{vf}$  and  $L_{vf}$  are the virtual resistance and inductance at  $h^{th}$  harmonic order.  $i_{of\alpha}$  is the fundamental component of DG output current, and  $i_{of\beta}$  is achieved by delaying  $i_{of\alpha}$  for quarter-fundamental cycle.  $G_{Rh}$  and  $G_{Ih}$  are the real and imaginary gains, respectively.  $v_{oh\alpha}$  and  $v_{oh\beta}$  are the voltage harmonic components of PCC in  $\alpha\beta$  frame. The PR controller based on (13) and a P controller are used in the voltage and current controllers in order to improve the voltage harmonic compensation. However, the experimental results on decreasing voltage THD are not meeting the standard limitations. In [61], it is suggested to use a local harmonic compensator along with the harmonic distortion calculation in the secondary controller to cancel out the selected harmonic components. A similar approach as in [142] is used in the measurement block and secondary controller to generate the compensation reference. In the local controller, the DSC-SOGI based virtual impedance is used to detect and extract harmonic and fundamental components of DG output currents. Then, the harmonic power  $H_p$  is calculated as follows:

$$H_p = v^* \sqrt{(i_{o,\alpha\beta 5}^-)^2 + (i_{o,\alpha\beta 7}^+)^2 + (i_{o,\alpha\beta 11}^-)^2 + (i_{o,\alpha\beta 13}^+)^2} \quad (16)$$

where  $v^*$  and  $i_{o,\alpha\beta h}^\pm$  are rated voltage, and harmonic sequences of output current, respectively. After that, the compensation reference of the primary controller  $k_{cr,prim}$  is calculated as follows:

$$k_{cr,prim} = k_H H_p \sum_h v_{o\alpha\beta,h}^\pm \quad (17)$$

where  $k_H$  and  $\sum_h v_{o\alpha\beta,h}^\pm$  are the constant value for ensuring the stability of microgrid, and the total harmonics voltage,

respectively. Finally, the modified voltage reference of DG can be obtained as follows:

$$v_{ref} = v_{ref}^* + k_{cr,sec} - k_{cr,prim} \quad (18)$$

where  $k_{cr,sec}$  and  $k_{cr,prim}$  are the compensation reference voltage of the secondary and primary levels of the microgrid. The inner controllers are designed similar to [52]. In [143], a harmonic droop controller along with the virtual impedance loop based on a consensus protocol is suggested to change the voltage reference entering the inner controllers and enhance the power quality of the microgrid. The modified voltage reference is as follows:

$$v_{ref} = v_{ref}^* + v_H = v_{ref}^* + (v_{hd} - v_h) \quad (19)$$

where,  $v_{hd}$  and  $v_h$  are the output of both consensus algorithm and harmonic power regulator, and harmonic droop controller, respectively.

In [144], the measured grid current and PCC voltage are used to elicit the fundamental and harmonic components in the central controller along with the selective virtual impedance in the primary level in order to achieve selective harmonic compensation in a single phase grid connected microgrid. The proposed harmonic compensation method is similar to the one in [142]. In [145], a three level controller including primary, secondary, and tertiary levels is proposed to compensate voltage THD, harmonic component distortion and voltage unbalance in a multi-bus microgrid. In the suggested controller, the secondary level is responsible to reduce voltage distortion in the critical bus of an islanded microgrid. The compensation efforts of each DG is calculated at the primary level by using the information received from the secondary level, which is the compensation reference, and from the tertiary level, which is decision variables produced in an intelligent algorithm. The output of this compensation effort block is added to the voltage references generated by the droop controller and conventional virtual impedance, and then, the voltage signal is passed through two PR controllers which are implemented in the inner controllers. In [146], a two level controller is proposed to reduce selected harmonic components in an islanded microgrid. At the secondary side, the harmonic components are extracted through SOGI-FLL and then compensated by using the voltage controller loop, deadband and band pass filters. Moreover, there are PR controllers and VI at the primary controller.

In [67], a complex secondary controller including the harmonic compensator block, PI controllers, deadbands and SOGI-FLLs in addition to the primary controller including PR controller, droop controller and VI is proposed to compensate harmonic distortion at the critical bus and noncritical buses in a multi-bus islanded microgrid. In [147], a secondary controller based on current control approach is introduced to mitigate harmonic distortion in a single phase grid tied microgrid. The main inputs of the secondary controller are the amplitude of the output current, which are then passed through a PLL and a moving average filter is used to extract harmonic components, and the PCC voltage. Moreover, the current control scheme is employed in the secondary controller for each control window to compensate the voltage harmonic

distortion on PCC. In [63], the input and outputs of the secondary controller are voltage of PCC, and current and virtual admittance harmonics, which are used in addition to the local RC to compensate THD of an islanded microgrid. In [46], an optimization method is used at the secondary controller in addition to only proportional and conventional droop controllers at the primary side in order to minimize the harmonic distortion at the critical and non critical buses of a multi bus islanded microgrid. In [148], a two level controller including primary and secondary controllers is proposed to reduce the selected harmonic components of output voltage in an islanded microgrid. The voltage harmonic components are extracted and compensated at the secondary controller. In [149], a GPS based secondary controller is proposed to reduce selected voltage harmonic components in an islanded microgrid by using an integral controller. An adaptive droop controller is proposed at the primary level as follows:

$$v_{ref}^* = E_0 - r_v(\hat{i}_o) \cdot \hat{i}_o \quad (20)$$

where  $E_0$  and  $r_v(\hat{i}_o)$  are the sinusoidal reference voltage, and the adaptive virtual resistance determined by the largest peak of the output currents  $\hat{i}_o$ , respectively. At the secondary level, the voltage conditioning block including a harmonic extraction block and an integral controller is implemented to eliminate voltage harmonic distortion. Finally, the droop controller output signal is added to the one from the secondary controller to generate the reference voltage of each DG.

#### A. Comparison and Trends in Secondary Level Harmonic Minimization Methods

Tables III and IV summarize and compare the methods used at the secondary level of the microgrid controller for improving power quality. The controller types used at both primary and secondary controllers to mitigate the harmonic distortion are explained in details in Table III. Moreover, the objective of each proposed controller are specified in this table. In Table IV, the input(s) and output(s) of the proposed secondary controllers as well as sensitivity to the microgrid parameters, communication links analysis, and multi-bus microgrid verification of the proposed controllers are summarized.

As demonstrated in Table III, the harmonic extraction and mitigation methods used in the secondary level are very similar to the approaches used in the primary controller such as SOGI, FLL, DB, PI and so on, which are former shown in Table II. It seems that the use of the proposed methods in single phase and grid connected microgrids are not well explained. As shown in Table IV, all the proposed methods except the one in [142] are using the voltage of PCC as an input as well as often along with current. On the other hand, the output(s) of the secondary controller sending to the local or primary controller are varied, which might be voltage, current or harmonic compensation factors ( $C^h, \alpha^h$ ). It is observed from Table IV that the methods used in the secondary controller are less sensitive to the microgrid parameters than the ones used in the primary controller. Moreover, it is concluded that the communication link delays and faults, which are the main drawbacks of the secondary controller in comparison to the primary controller are not well analyzed in the literature.

Therefore, based on the analysis of what is summarized in Tables III and IV, future trends of the harmonic mitigation methods in the secondary level might be as follows:

- 1) It could be useful to use other methods such as predictive control and artificial intelligence approaches at this level,
- 2) The communication link delays and faults should be considered in each of the proposed method,
- 3) The microgrid can have multi-bus and multi-inverter included. Moreover, the plug and play, the harmonic mitigation of CB and all buses can be analyzed,
- 4) The robustness of harmonic mitigation methods to cyber attacks can also be analyzed.

#### VI. METHODS PROPOSED IN TERTIARY LEVEL

The last level of hierarchical control is the tertiary level (see Fig. 1), which is mainly responsible for the optimal operation of microgrid in both modes, and also power flow control in grid connected mode. In recent years, some authors tried to use this level for harmonic mitigation purposes. In [145], besides the proposed secondary controller, there is a proposed tertiary level, which is used to improve the voltage quality on the other buses of multi buses microgrid. However, the main drawbacks of the secondary or tertiary controllers are the communication line delays and faults, which are not considered in [145]. Since the approach used in [46] is an optimization method, and the tertiary controller is used for such methods, the proposed approach can also be considered as a tertiary controller. The voltage reference in the local controllers of DGs is modified as follows:

$$v_{ref} = v_{ref}^* + \sum_h v_{inj,h} \quad (21)$$

where  $v_{inj,h}$  is the injected voltage harmonic components by the proposed particle swarm optimization (PSO)-based harmonic minimization approach. The three following objective functions are used in the PSO optimization algorithm at the tertiary level in order to reduce voltage harmonic components of the critical bus  $|V_{cr,h}|$ , THD of the critical bus  $THD_{cr}$ , and the average THD of the multi-bus microgrid  $THD_{avg}$  to be below the harmonic standard limitations given as:

$$\begin{aligned} |V_{cr,h}| &< |V_h^*| \\ THD_{cr} &< THD^* \\ THD_{avg} &= \frac{\sum_{i=1}^N THD_i}{N} < THD^* \end{aligned} \quad (22)$$

where  $N$  is the total number of buses in an islanded microgrid.

Due to significant development of infrastructure and measurement approaches in smart grids, some of the harmonic optimization methods like the ones proposed in [150]–[154] could be used in the tertiary controller of the microgrid to improve the power quality. The only variable measured in these methods is voltage, which makes the optimization of the controller simpler and faster. The measured voltage is received by the tertiary controller to apply optimization approaches. Then, the optimized variable is sent to the local controller as proposed in [46]. With the use of these online optimization methods at the tertiary level, different optimization methods,

TABLE III  
COMPARISON OF HARMONIC COMPENSATION METHODS AT THE SECONDARY LEVEL

References	Method		Harmonic mitigation goals
	Primary level	Secondary level	
[139]	PI	Voltage controller-LPF	THD <sub>v</sub> and THD <sub>i</sub> at PCC
[63], [140]	PI-PR	Virtual admittance calculator-PI	THD <sub>v</sub> at PCC
[141]	DrC	SOGI-PLL-LPF	THD <sub>v</sub> at PCC
[142]	DrC-PR-VI	Harmonic Calculator-PI	Selected harmonics
[52]	SDFT-PLL-PR-VI	SDFT-PLL	THD <sub>v</sub> at PCC
[61]	SOGI-PR-DrC-Harmonic compensator	Harmonic calculator-PLL-LPF-PI	THD <sub>v</sub> and THD <sub>i</sub> at of PCC
[143]	DrC	Harmonic compensator and consensus controller	THD <sub>v</sub> at PCC
[144]	PR-VI-DrC-selective hamronic compensator	Harmonic extractor	THD <sub>v</sub> and THD <sub>i</sub> at PCC
[145]	PR-VI-DrC	Harmonic calculator-PI-DB	THD <sub>v</sub> at CB
[146]	PR-VI-DrC	SOGI-FLL-DB	THD <sub>v</sub> at PCC
[67]	PR-VI-DrC	Harmonic compensator-MSOGI-FLL-PI-DB	THD <sub>v</sub> at PCC
[147]	Current reference generation	PLL-Moving average filter	THD <sub>v</sub> and THD <sub>i</sub> at PCC
[148]	PR-VI-DrC	PI-DB	Selected harmonics
[46]	DrC-P	Voltage magnitude optimization	Selected harmonics-THD <sub>v</sub> at both CB and microgrid
[149]	DrC-P-VI	PI-LPF-Harmonic extractor	THD <sub>v</sub> at CB

DrC: Droop Controller, VI: Virtual Impedance, PR: Proportional Resonance, PI: Proportional Integral, DB: Dead Beat, PLL: Phase Locked Loop, LPF: Low Pass Filter, CB: Critical Bus, P: Proportional, SOGI: Second Order Generalized Integrator, MSOGI: Multi SOGI, FLL: Frequency Locked Loop, SDFT: Sliding Discrete Fourier Transform, THD<sub>v</sub>: Voltage THD, THD<sub>i</sub>: Current THD

TABLE IV  
COMPARISON OF HARMONIC COMPENSATION METHODS AT THE SECONDARY LEVEL

References	Secondary controller		Sensitive to system parameters	Communication delays and faults analysis	Complexity	Multi-bus verification
	Input	Output				
[139]	$v, i$	$i$	-	×	Low	×
[63], [140]	$v$	$i, Y_v$	✓	×	Moderate	×
[141]	$v$	$i$	-	×	Moderate	×
[142]	$i$	$v$	✓	✓	High	×
[52]	$v$	$v$	-	×	Moderate	×
[61]	$v, \omega$	$v$	-	×	High	×
[143]	$v$	$v$	✓	×	Moderate	×
[144]	$v, i$	$v, i$	-	×	Low	×
[145]	$v$	$C^h$	-	×	High	✓
[146]	$v$	$v$	-	×	Moderate	×
[67]	$v$	$C^h$	-	×	Too high	✓
[147]	$v, i$	$\alpha^h$	-	✓	Moderate	×
[148]	$v, \omega$	$v, \omega$	-	×	Low	×
[46]	$ v $	$v$	-	×	Low	✓
[149]	$v, i$	$v$	-	✓	Moderate	✓

as well as different objective functions should be considered in the optimization approaches. Although, emerging optimization approaches at the tertiary level for power quality improvement seems to be useful, some challenges such as coordination between sending and receiving signals, communication link faults, and also robustness towards the cyber-attacks could appear. Therefore, it is necessary to find solutions for these problems when it comes to use methods at the tertiary con-

troller of the microgrid.

## VII. DISCUSSION AND CONCLUSION

The main structure, characteristic, and feature of the proposed methods in the literature for mitigating voltage and current harmonic distortion in the ac microgrids are introduced, explained and compared in this paper. The methods used in single or three phase, and islanded and/or grid connected ac

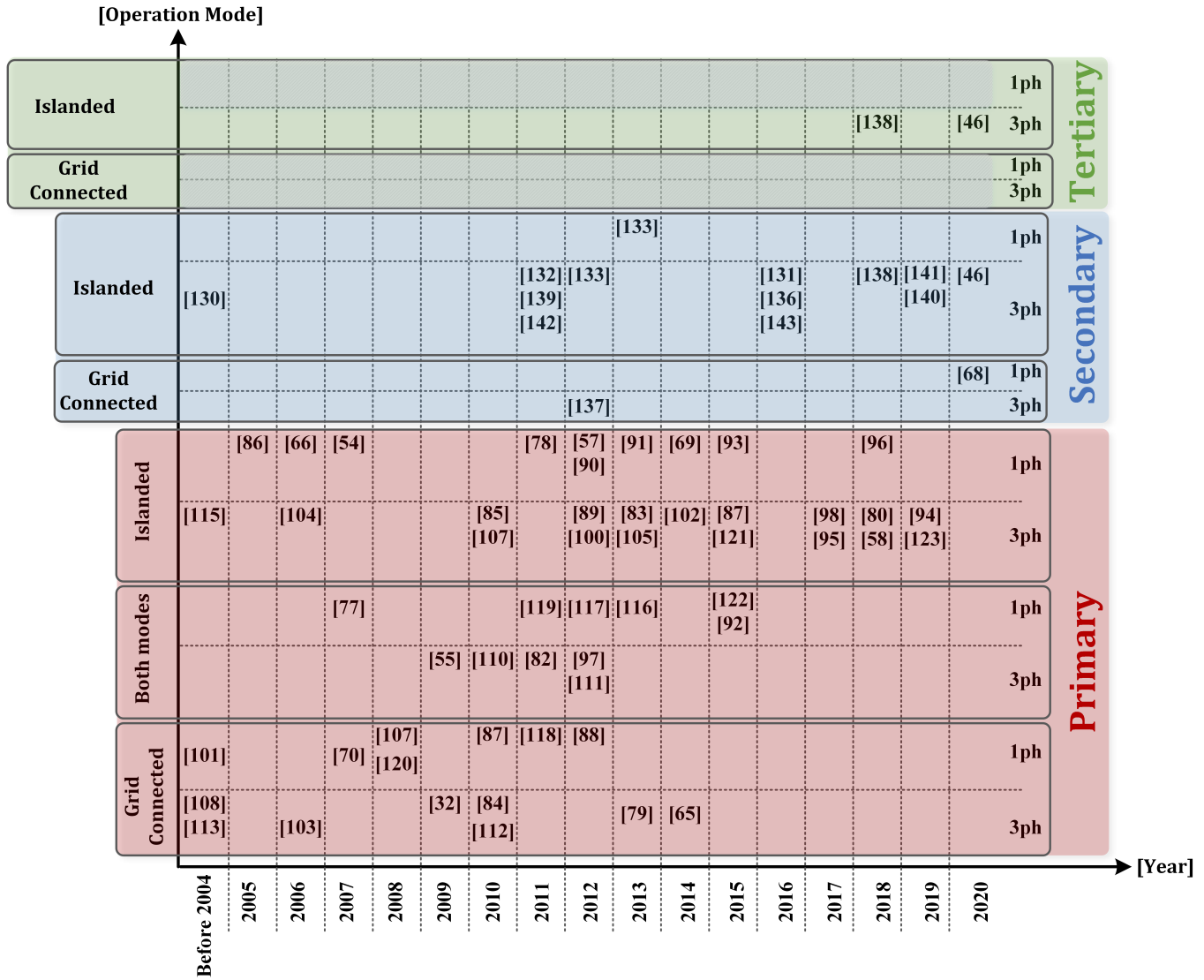


Fig. 7. Historical overview of harmonic mitigation methods of microgrids

microgrids are classified based on the level of hierarchical controller. Most of the harmonic mitigation methods proposed in the literature are implemented at the primary level due to the risk of communication link faults and delays at the other levels. However, the primary controller would be more complex and have computational burden to carry out the harmonic mitigation goals along with the other functions such as active and reactive power sharing and stability in the microgrid.

A historical overview of the harmonic mitigation methods used at three control levels is shown in Fig. 7. The operation modes studied in the references, which are islanded, grid connected, and both kinds of microgrid operation modes are presented in the left horizontal axis. The single and three phases of the microgrid considered in the references, and also the hierarchical control level of the proposed harmonic mitigation methods are demonstrated in the right horizontal axis. The vertical axis is the time (year) of the reference published. It is revealed that the secondary and tertiary levels have gained more attention in the recent years in comparison to the primary

level. Moreover, both modes, and the transient between these modes have not been well analyzed in the literature using secondary and tertiary levels for harmonic distortion issues. Moreover, a summary of the features, disadvantages, and application of the methods outlined in the previous sections are listed in Table V. The comparison is presented to show when and where these methods can be used in microgrid to mitigate harmonic distortion.

PR-based, VI-based, and MDC controllers are often used at the primary level of microgrids to provide selective harmonic compensation. Although, these methods can be simply implemented in both single and three phase systems, and also, for both islanded and grid-tied microgrids to reduce voltage harmonic distortion in PCC without any communication links, the voltage and frequency fluctuations, and the inability to mitigate harmonics in multi-bus microgrids would still be a challenge for such methods. It should also be noted that the VI-based controllers are highly dependent to the system parameters such as line impedances. A combination of PR

TABLE V  
ADVANTAGES, LIMITATIONS, AND APPLICATION OF HARMONIC MITIGATION METHODS IN MICROGRIDS

Method	Advantages	Limitations	Application
PR-based controllers	<ul style="list-style-type: none"> <li>- Simple to implement</li> <li>- Provide selective harmonic compensation</li> <li>- Compensate both voltage and current harmonics</li> </ul>	<ul style="list-style-type: none"> <li>- Voltage and frequency fluctuations</li> <li>- Inability to compensate harmonics in the multi-bus microgrids</li> </ul>	<ul style="list-style-type: none"> <li>- Inherently use at primary level</li> <li>- Both single and three phase systems</li> <li>- Both islanded and grid-connected microgrids</li> </ul>
DrC-based Controllers	<ul style="list-style-type: none"> <li>- Simple to implement</li> <li>- Provide selective harmonic compensation</li> </ul>	<ul style="list-style-type: none"> <li>- Slow dynamic response</li> <li>- No harmonic current regulation</li> <li>- Inability to compensate harmonics in the multi-bus microgrids</li> </ul>	<ul style="list-style-type: none"> <li>- Used at the primary level</li> <li>- Both single and three phase systems</li> <li>- Both islanded and grid-connected microgrids</li> </ul>
VI-based controllers	<ul style="list-style-type: none"> <li>- Provide selective harmonic compensation</li> <li>- Compensate both voltage and current harmonics</li> <li>- Fast dynamic response</li> </ul>	<ul style="list-style-type: none"> <li>- Voltage and frequency fluctuations</li> <li>- High dependency of system parameters</li> <li>- Inability to compensate harmonics in the multi-bus microgrids</li> </ul>	<ul style="list-style-type: none"> <li>- Used at the primary level</li> <li>- Both islanded and grid-connected microgrids</li> <li>- Both single and three phase systems</li> </ul>
VI and PR-based controllers	<ul style="list-style-type: none"> <li>- Provide selective harmonic compensation</li> <li>- Compensate both voltage and current harmonics</li> <li>- Voltage harmonic compensation in multi-bus microgrids</li> </ul>	<ul style="list-style-type: none"> <li>- Complex control loops</li> <li>- Dependency of system parameters</li> <li>- Dependency of communication lines (if the secondary level is used)</li> </ul>	<ul style="list-style-type: none"> <li>- Both single and three phase systems</li> <li>- Both islanded and grid-connected microgrids</li> </ul>
Compensation effort-based controllers	<ul style="list-style-type: none"> <li>- Provide selective harmonic compensation</li> <li>- Voltage and current harmonic compensation in multi-bus microgrids</li> </ul>	<ul style="list-style-type: none"> <li>- Complex controllers</li> <li>- Dependency of communication lines</li> <li>- Slow dynamic response</li> </ul>	<ul style="list-style-type: none"> <li>- Used at secondary controller</li> <li>- Both single and three phase systems</li> <li>- Both islanded and grid-connected microgrids</li> </ul>
Optimization-based controllers	<ul style="list-style-type: none"> <li>- Provide selective harmonic compensation</li> <li>- Compensate both voltage and current harmonics</li> <li>- Voltage and current harmonic compensation in multi-bus microgrids</li> </ul>	<ul style="list-style-type: none"> <li>- Voltage and frequency fluctuations</li> <li>- Dependency of communication lines</li> </ul>	<ul style="list-style-type: none"> <li>- Both single and three phase systems</li> <li>- Islanded microgrids</li> <li>- Inherently use at tertiary level</li> </ul>

PR: Proportional Resonance, DrC: Droop Controller, VI: Virtual Impedance

and VI controllers, which are sometimes used along with the secondary controller to provide better harmonic compensation, can reduce the voltage harmonic distortion in multi-bus microgrids like in [52], [67], [144], [146], [148]. However, the control system would be complex to design, and they are dependent to the system parameters and communication links. Other methods, which are based on the compensation effort calculation at the secondary level of the microgrid can be used to mitigate both voltage and current harmonics in the multi-bus microgrids like in [61], [142], [145]. However, the computational burden of the control system, communication link faults and delays, robustness towards the cyber-attacks would still be challenges for such methods. Moreover, the optimization-based methods, which are inherently used at the tertiary level of microgrid can be used to compensate both voltage and current harmonics in the multi-bus microgrids like in [46]. However, these methods are suffering from the communication link issues and cyber-attacks.

It has been disclosed that the use of secondary controller

might also be a solution for harmonic distortion problems of the single phase grid connected microgrids, which has not comprehensively investigated in the literature. Furthermore, the optimization, predictive control based, and artificial intelligence approaches could be used at the secondary and tertiary levels as an effective tool to mitigate harmonic distortion in ac microgrids. Moreover, the microgrid should be considered as a network including multi-buses and multi-inverters due to the increase of microgrids' penetration. In such a network, the harmonic mitigation goals would be: voltage and current harmonic mitigation in CB, as well as other buses, PCC of each DG, and reducing THD of the whole multi bus microgrid.

In conclusion, further research works on the following subjects are expected:

- 1) Better control modeling including harmonic analysis, bode plots, and transient and steady state equations of power converters and their controllers, which are dependent on the microgrid operation mode, their parameters, and structure.

- 2) More powerful control methods, which should be robust and reliable under the different microgrid harmonic distortion situations.
- 3) Efficient hierarchical control methods for multiple converters in multiple buses microgrid is demanded.
- 4) How to reduce the number of units participating in the harmonic compensation in order to minimize microgrid expenses in terms of communication.

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