Evaluation of Decentralized Voltage Harmonic Mitigation through DRES converter active filtering capability

Kyriaki-Nefeli D. Malamaki[1], Christos Tzouvaras[1], Manuel Barragán-Villarejo[2], Georgios C. Kryonidis[1], Charis S. Demoulias[1]*

[1]*Department of Electrical & Computer Engineering, Aristotle University of Thessaloniki, Thessaloniki, Greece*
[2]*Department of Electrical Engineering, Universidad de Sevilla, Seville, Spain*
**chdimoul@auth.gr*

Keywords: VOLTAGE SOURCE CONVERTER, ACTIVE FILTERING, ANCILLARY SERVICE, THERMAL LIMIT, HARMONIC MITIGATION

Abstract

The increased penetration of Converter-Interfaced Distributed Renewable Energy Sources (CI-DRES) has posed power quality challenges into the distribution system. In the future CI-DRES may have the responsibility to cope simultaneously with several issues. One function that has already been presented in the literature, but has not been included yet in Standards, is the operation of the DRES converters as active harmonic filters. This paper firstly develops an active filtering control for the CI-DRES, taking into account its thermal limit. This parameter is important, since DRES are already prescribed by Standards to participate in the voltage regulation process by providing reactive power. If the CI-DRES operates also as active filter, it may exceed its thermal capacity. Secondly, the decentralized operation of CI-DRES is evaluated in the CIGRE Benchmark LV distribution system by considering several scenarios of DRES/Non-linear loads penetration and mixture. Time-domain (TD) simulations are carried out in PowerSim Software to demonstrate the contribution of each CI-DRES in the active filtering process. The derived conclusions will serve as a basis for the development of a new coordinated algorithm, so as the CI-DRES can mitigate properly voltage harmonic distortion (HD) in the most efficient techno-economic way. In this way, the active filtering can be treated as a new ancillary service to be introduced in respective markets.

1 Introduction

The increased penetration of Converter-Interfaced Distributed Renewable Energy Sources (CI-DRES) has caused several problems into the distribution system, e.g. reverse power flows, voltage regulation issues, power quality problems, [1]. Power electronic devices are sources of both low- and high-frequency current components, and pose several challenges on distribution system equipment and loads, [1], since the current harmonics lead to voltage harmonics. According to [1], type and severity of harmonic problems depend -amongst other parameters- on the loading conditions of the host distribution feeder. To address these problems, several standards (Stds), e.g. IEEE Std 519, [2], and IEC 61000-3-6,[3], define limits for individual and total harmonic distortion (HD) at the Point of Common Coupling (PCC) voltages and currents of a CI-DRES. Until now, the research community has focused into several categories with respect to the presence of harmonics. In general, the studies concern: (*1*) the impact of the CI-DRES penetration and non-linear loads (NLLs) on the power systems, e.g. posing a limit to the DRES hosting capacity (HC); (*2*) the optimal placement of active and passive filters considering the limits on the system HC; (*3*) the control of active filters as well as the operation of CI-DRES as active filters.

With respect to the 1st category, in [2], [4] it has been discussed that, CI-DRES are considered as high-frequency harmonic sources that impact the current quality in the network leading to limited HC in power systems. Some studies [5], [6], have investigated the impact of the CI-DRES generated HD units on the HC of distribution systems taking into account the limits imposed by the aforementioned Stds. The importance of including HD limits in the HC assessment is presented in [7], while in [8] the Harmonic-Constrained HC term is introduced to highlight that the power system HC can be determined by considering only the voltage HD limits.

With respect to the 2nd category, different methods of optimal placement and sizing of passive filters have been proposed for managing the grid-HC,[9], [10] and maximize the CI-DRES penetration, [11]. A specific passive filter is suggested to be placed centrally, in an industrial system with load nonlinearities through the harmonic-constrained HC assessment considering several limits, e.g. over-voltages. Moreover, total and individual HD percentages are the performance indices that may be violated first. The optimization is solved as mixed integer optimization problem. Furthermore, different active filtering techniques have been proposed considering that HD is a locational variable (decentralized approaches). The installation of additional filters is not a cost-effective choice, therefore, it is proposed in [12] that a CI-DRES -in addition to its major power delivery function- can provide harmonic mitigation Ancillary Services (AS) without additional costs if its apparent power is sufficient. The CI-DRES usually does not exhaust the inverter limits for its primary function, therefore, this AS is technically feasible. In [12] a review is performed to classify the CI-DRES active filtering control schemes and two main approaches are recognized: virtual impedance-based method, [13], and active harmonic filtering-based method. Virtual impedance can emulate the effect of physical impedance without the need to connect a real component to a system and it can be either at the fundamental or harmonic frequencies, [13]. In the active filtering approach, the main control objective is to generate an appropriate compensating current in the inverter, which is produced by comparing the load current with a predetermined reference current. The operation of grid-connected PV converters to provide this AS is studied in [14], [15] and [16]. With respect to wind turbines, a review is conducted in [17], an active damping technique is proposed in [18] to mitigate harmonic resonances, while in [19] a double tuned PI-R based

Citation information, DOI: 10.1049/icp.2021.1360

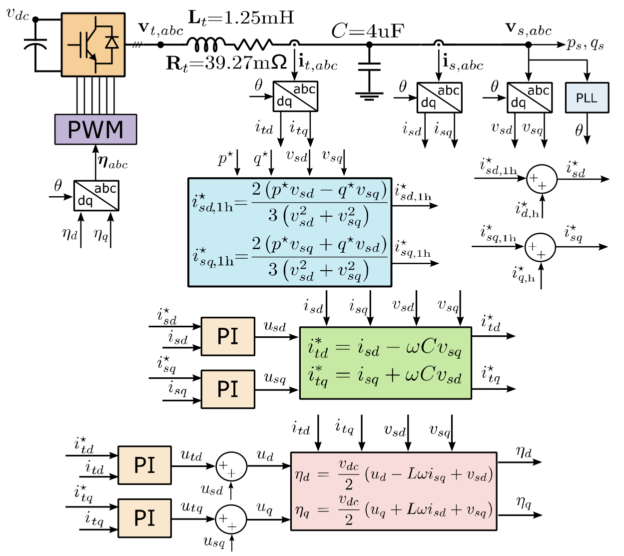

Fig. 1 Control Structure of the VSC

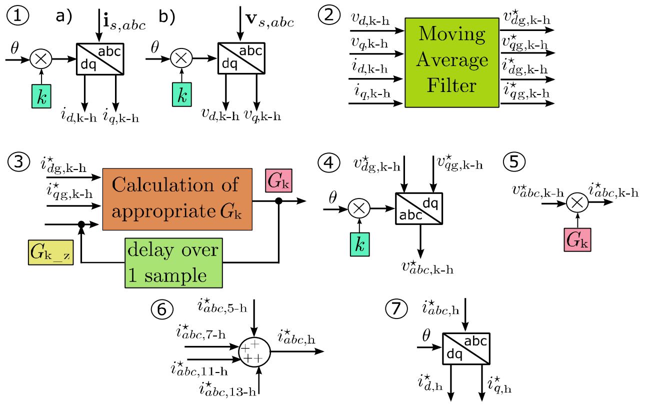

Fig. 2 Harmonics Control (***k*= -5, 7, -11,13**)

current controller is presented for DFIGs.

Although there are several scientific papers on the aforementioned topics, there yet exist several gaps. In the future, CI-DRES may have the responsibility to perform multiple functions, e.g. provision of virtual inertia and reactive power for voltage regulation, etc. Some of these functions are already included in recently issued Stds, e.g. [20], [21]. The operation of the CI-DRES as an active filter needs to be co-evaluated with the other functions of the CI-DRES keeping in mind that when performing various functions, the CI-DRES may exceed its thermal capacity. To the authors' best knowledge there exist no such control scheme. Moreover, up to now, the harmonic mitigation by CI-DRES has been treated in a decentralized manner. Similar to the voltage rise, high voltage HD is also a locational phenomenon, and is co-related mostly with the presence of NLLs, which emit low-order harmonics. The sensitivity of a CI-DRES location with respect to the low-order harmonics has not been studied yet. Therefore, when performing a decentralized algorithm for harmonic mitigation, the contribution of a CI-DRES to the process needs to be examined with respect to its location and in terms of its thermal capacity. These investigations may lead to an optimized harmonic mitigation process by CI-DRES, considering the above parameters and the associated costs. This is missing from the current technical literature.

This paper contributes to the raised issues in the following manner: Firstly, a method for harmonic filtering is proposed, which is activated only when the 1st harmonic current is lower that the nominal CI-DRES current. A harmonic conductance G_k per harmonic k is calculated, so that the CI-DRES injects a proper harmonic current. Secondly, this method is evaluated in the CIGRE Residential LV Network under different CI-DRES/ NLLs under several penetrations and mixtures, in order to investigate the contribution of each CI-DRES with respect to its location and thermal limit. Indices for the contribution are selected to be achieved reduction of the average Total HD (THD) of the voltage and the THD per node. In addition, some thoughts on the optimized provision of this AS are presented together with the possible associated costs. These results will serve as a basis for the development of a coordinated voltage regulation/harmonic mitigation algorithm in future work.

2. Harmonics Control Algorithm

In this section the new control scheme of the grid-connected CI-DRES is described. The examined topology of the CI-DRES is a 3-phase 3-wire Voltage Source Converter (VSC) with an LC filter (depicted in Fig. 1), which ensures THD_V<2.5% at normal conditions, i.e. when the CI-DRES injects active and reactive power at fundamental frequency. This is the actual filter topology of the CI-DRES prototype constructed at University of Sevilla, which is going to perform multiple AS as a part of the EASY-RES H2020 project. The input DC voltage of the DRES inverter was set v_{DC}=730V and the switching frequency is 10kHz. Firstly, the voltages and currents at the CI-DRES PCC ($\mathbf{i}_{s,abc}$, $\mathbf{v}_{s,abc}$) and the current at the inductor of the LC filter, $\mathbf{i}_{t,abc}$, are measured and transformed to a synchronous $\boldsymbol{dq}$ reference frame, while the angle $\boldsymbol{\theta}$ and angular frequency are detected through a PLL. This control scheme is illustrated in Fig. 1, where the reference signals are denoted with stars (*). With respect to the control, firstly, the reference values of $\boldsymbol{i}_{s,dq}$ at the 1st harmonic ($\boldsymbol{i}^*_{sd,1h}$,$\boldsymbol{i}^*_{sq,1h}$) are calculated by the reference active (p^*) and reactive power (q^*), as depicted in the blue box of Fig. 1. Then, these currents $\boldsymbol{i}^*_{sdq,1h}$ are summed to the harmonic $\boldsymbol{dq}$ reference currents, $\boldsymbol{i}^*_{dq,h}$, (derived in Fig. 2) so as to generate the total reference currents at the PCC, $\boldsymbol{i}^*_{sd,q}$. The latter, in turn, are compared with the actual output $\boldsymbol{dq}$ current, $\boldsymbol{i}_{s,dq}$. The error is passed through PI controllers to derive $\boldsymbol{u}_{s,dq}$. The reference inductor currents $\boldsymbol{i}^*_{td,q}$ are generated according to the expressions of the green box in Fig. 1. These currents $\boldsymbol{i}^*_{td,q}$ are compared with the actual inductor current in both $\boldsymbol{dq}$ axes, $\boldsymbol{i}_{t,dq}$ and the error between them is inserted into PI controllers. The modulation signals (η_d, η_q) of the CI-DRES are calculated with the expressions in the orange boxes of Fig. 1 and then, they transformed into the $\boldsymbol{abc}$ frame (η_{abc}). The proportional and integral gains of the current PI controllers are specified from the time constant of this control, which is $\tau_i = 0.25ms$, as $\boldsymbol{K}_{p,i} = \frac{L_t}{\tau_i}$ and $\boldsymbol{K}_{i,i} = \frac{R_t}{\tau_i}$ respectively, according to [22].

The Harmonics Control developed to generate the harmonic $\boldsymbol{dq}$ reference currents, $\boldsymbol{i}^*_{dq,h}$, is illustrated in Fig. 2. In this control it is considered that the low-order voltage harmonics 5th, 7th, 11th and 13th are compensated via the proper injection of respective harmonic currents. Firstly, both $\mathbf{i}_{s,abc}$ and $\mathbf{v}_{s,abc}$ are analysed per harmonic k via $\boldsymbol{dq}$ transformation considering as rotation angle with equal to $\boldsymbol{k}\cdot\boldsymbol{\theta}$ (Block 1 of Fig. 2). The transformed $\boldsymbol{dq}$ voltages and currents ($\boldsymbol{i}_{dq,\mathrm{k-h}}$, $\boldsymbol{v}_{dq,\mathrm{k-h}}$)

are passed through a moving-average filter to generate the respective reference values ($\boldsymbol{i}^{*}_{dg,\mathrm{k-h}}, \boldsymbol{i}^{*}_{qg,\mathrm{k-h}}, \boldsymbol{v}^{*}_{dg,\mathrm{k-h}}, \boldsymbol{v}^{*}_{qg,\mathrm{k-h}}$) in Block 2. These $\boldsymbol{i}^{*}_{dg,\mathrm{k-h}}, \boldsymbol{i}^{*}_{qg,\mathrm{k-h}}$ are used to calculate if there is available capacity within the CI-DRES and to determine the appropriate value of G_k per harmonic in Block 3 of Fig. 2. The $\boldsymbol{v}^{*}_{dg,\mathrm{k-h}}, \boldsymbol{v}^{*}_{qg,\mathrm{k-h}}$, for each harmonic k are transformed again into the ***abc*** frame,$v^{*}_{abc,\mathrm{k-h}}$, (Block 4) and are multiplied by G_k to generate the reference harmonic currents ($\boldsymbol{i}^{*}_{abc,\mathrm{k-h}}$), which are shifted 180° from the k voltage harmonic (Block 5). In Block 6 all the $\boldsymbol{i}^{*}_{abc,\mathrm{k-h}}$ are summed and in Block 7 they are transformed to the ***dq*** axes ($\boldsymbol{i}^{*}_{dq,h}$) in order to serve as an input to the control of Fig. 1.

The detailed calculation of G_k per harmonic and the thermal capacity check with respect to the 1st harmonic are depicted in Fig. 3. Firstly, this block checks if there is capacity availability with respect to the 1st harmonic ($\boldsymbol{I}^{base}_{rms} > \boldsymbol{i}^{*}_{s,\mathrm{rms,1h}}$). If there is not, G_k is set zero. If there is capacity, the total RMS current $\boldsymbol{i}^{total}_{rms}$ is calculated based on the inputs $\boldsymbol{i}^{*}_{dg,\mathrm{k-h}}, \boldsymbol{i}^{*}_{qg,\mathrm{k-h}}$ (Block 3 of Fig. 2) to check if there is available capacity with respect to the injection of harmonic currents and G control is activated. The value $\boldsymbol{e}_\mathrm{i}$ is equal to $\boldsymbol{I}^{base}_{rms} - \boldsymbol{i}^{total}_{rms}$. In case there is capacity ($\boldsymbol{e}_\mathrm{i}$>$tol$), G_k is increased. The term tol denotes that there is a tolerance zone around $\boldsymbol{I}^{base}_{rms}$ and has been taken equal to 0.5A. In case $\boldsymbol{e}_\mathrm{i}$ lies within the tolerance zone, the value of G_k remains equal to the previous value (previous measuring period=50us) $G_{\mathrm{k\_z}}$. By adding this zone, it is ensured that the harmonic currents and power do not oscillate. The initial value of G_k is set equal to a factor f_k per harmonic. This factor is equal to

$$f_k = \frac{h_\mathrm{k}}{\sum_{k=5,7,11,13} h_\mathrm{k}} \tag{1}$$

Where h_k are the EN50160 limits of voltage distortion at nominal voltage, i.e. h_5=6%, h_7=5%, h_{11}=3.5% and h_{13}=3%.

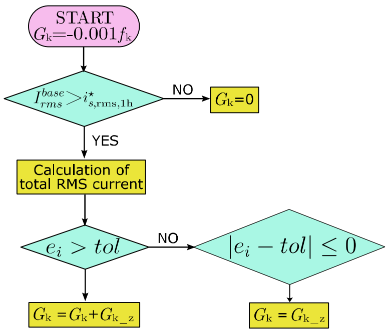

Fig. 3 Calculation of G_k per harmonic k

3 Evaluation at LV grid level

The proposed scheme has been tested in PowerSim Software in the TD. The examined network is a modified version of benchmark European LV network Cigre Task Force C6.04, [23]. The NLLs are modelled as a 3-phase diode bridges with P_NL=40kW at V_NL=0.4kV, while the DC output of the bridge is a capacitance C_NL=1mF parallel to a resistance, R_NL=7.05Ω. This type of NLL has been chosen on purpose, since it is causes high THD$_\mathrm{V}$ at harmonics 5th, 7th, 11th and 13th. The distortion power of the loads is measured based on the stationary frame, [24], and at nominal voltage it is equal to 34kVAr, therefore, it is comparable with their active power. The distortion power, D_h, of the CI-DRES is calculated for 5th, 7th, 11th and 13th harmonics according to the definitions of IEEE 1459 Std. The simulations concern the Cases depicted in Fig. 4. In all simulations the reactive power is set to 0.

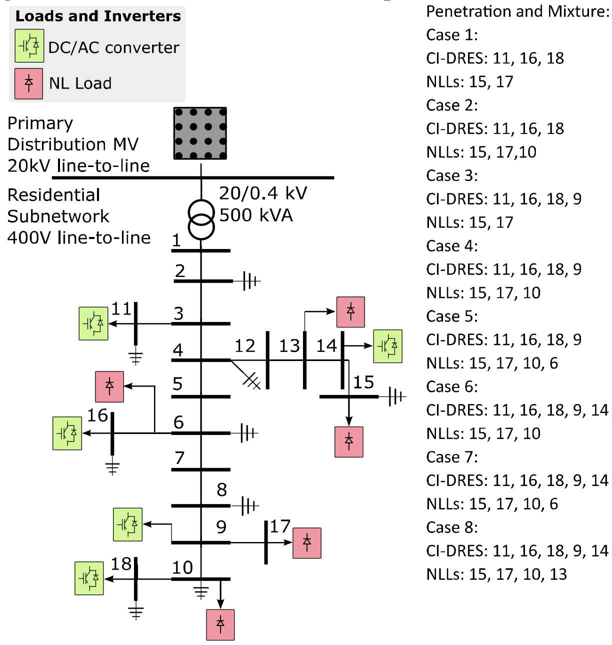

Fig. 4 Examined Topology of the CIGRE LV network

Firstly, several investigations where performed with the **Case 1** configuration to examine the following issues: (*i*) which CI-DRES is most efficient when only one or two of them is activated; (*ii*) how does the size of the inverter affect the active filtering process. All studied scenarios of **Case 1** appear in Table 1 and Fig. 5. This case is considered as base case, since all CI-DRES are in the main feeder. Table 1 provides the injected active powers per node (P) and the respective apparent power (S). In order to study issue (*i*) the following scenarios are defined: In case denoted as "*No Control*" it is assumed that there is no active filtering control performed by the CI-DRES. In case denoted as "*With Control*" it is assumed that ***all*** CI-DRES perform G-control. In cases denoted as "R_{11}", "R_{16}" and "R_{18}" it is assumed that ***only one*** CI-DRES performs G-control at the respective node. In cases "R_{11}+R_{16}", "R_{11}+R_{18}" and "R_{16}+R_{18}" it is assumed that ***two*** CI-DRES perform G-control in the respective nodes. In order to test issue (*ii*) regarding also the location of the CI-DRES, S_inv at nodes *11* or *18* is changed at either 10kVA or 15 kVA. The cases denoted as "S_{18}=10k" and "S_{11}=10k" means that the CI-DRES at node *18* or *11* respectively, has S_inv=10kVA and operates also at P_ref=10kW, therefore, G-control is not activated, because there is no capacity with respect to the 1st harmonic. In the other two nodes there is remaining capacity and the CI-DRES perform G-control. In scenarios denoted as "S_{18}=15k" and "S_{11}=15k", all CI-DRES perform G-control and the CI-DRES apparent power at the respective node is increased. Therefore, this node has enhanced G-performance.

Table 1 Case 1 Scenarios Active (kW) and Apparent power (kVA)/node

	P_{11}	P_{16}	P_{18}	S_{11}	S_{16}	S_{18}
No Cont.	10	10	10	12.5	12.5	12.5
With Cont.	10	10	10	12.5	12.5	12.5
R_{11}	10	10	10	12.5	12.5	12.5
R_{16}	10	10	10	12.5	12.5	12.5
R_{18}	10	10	10	12.5	12.5	12.5

R_{11}+R_{16}	10	10	10	12.5	12.5	12.5
R_{11}+R_{18}	10	10	10	12.5	12.5	12.5
R_{16}+R_{18}	10	10	10	12.5	12.5	12.5
S_{18}=10k	10	10	10	12.5	12.5	10
S_{18}=15k	10	10	10	12.5	12.5	15
S_{11}=10k	10	10	10	10	12.5	12.5
S_{11}=15k	10	10	10	15	12.5	12.5

Next, in **Cases 2-8** of Fig. 4 all the CI-DRES are assumed to have S_{inv}=12.5kVA, while P_{ref}=10kW considering different CI-DRES/NLLs penetration and mixture. The cases have been built considering each time that a CI-DRES or a NLL is introduced in the LV grid, and preferably next to an existing element. The purpose of this examination is to check how the penetration and mixture of non-linearities affect the LV grid performance with and without the *G*-control and how the location of the NLL affects the nearby CI-DRES. The power quality index that is studied is the average THD_V,% of the 18 nodes within the grid.

Table 2 Case 1 Scenarios – Average THD_V of nodes in %

Examined Case	No Cont.	With Cont.	R_{11}	S_{11}=10k	S_{11}=15k	R_{16}
Average THD_V,%	5.60	4.37	5.28	4.70	4.18	5.18
Examined Case	**R_{18}**	**S_{18}=10k**	**S_{18}=15k**	**R_{11}+R_{16}**	**R_{11}+R_{18}**	**R_{16}+R_{18}**
Average THD_V,%	5.12	4.86	4.08	4.86	4.80	4.78

In all cases that have been simulated with *G* control all the CI-DRES inject currents up to $I_{rms}^{base} - tol$, when they have available capacity. It has been observed via these test cases that the CI-DRES with the lowest RMS voltage senses the highest THD_V. This is justified by the fact that the NLL causes voltage drop to the nearby CI-DRES and simultaneously, it increases the THD_V sensed by the CI-DRES. Therefore, these CI-DRES *(9,18)* always reach first the thermal capacity compared to the other CI-DRES nodes. Moreover, the D_h of each CI-DRES depends on the RMS voltage. Hence, CI-DRES that operate at $I_{rms}^{base} - tol$ with lower voltage exhibit larger amounts of D_h.

Considering the scenarios of **Case 1** and with respect to both issues, it can be observed from Fig. 5 (c) that the *G*-control does not affect the RMS voltages, but only the THD_V (evident also in Fig. 6(c)). With respect to issue (*i*), from Fig. 5 (a) and Table 2 it is noticed that when only one CI-DRES has active filtering capabilities, lowest THD_V appears in "R_{18}", while "R_{11}" has the highest one. Therefore, better compensation is achieved when *G* control is activated at *18*. If two CI-DRES have this ability, the most efficient combination is "R_{16}+R_{18}". However, for the same apparent and active power, if all three CI-DRES are activated, they can achieve the lowest average THD_V (4.32%). With respect to issue (*ii*) aggregated results are depicted in Fig. 5 (b). It can be deduced that by de-activating *G*-control (through no space of thermal capacity) at *18* leads to higher THD_V with respect to "S_{11}=10k". The lowest THD_V appears when all three CI-DRES are activated and CI-DRES at *18* has more available capacity ("S_{18}=15k"). Therefore, it is much better when *G*-control is allocated at all the available CI-DRES, but the most efficient solution is that the most remote nodes have more available capacity.

Table 3 contains the results of **Cases 2-8**. **Case 2, 4** and **6** have almost the same average THD_V under no control, since all concern 3 NLLs. Including more CI-DRES with *G*-control is

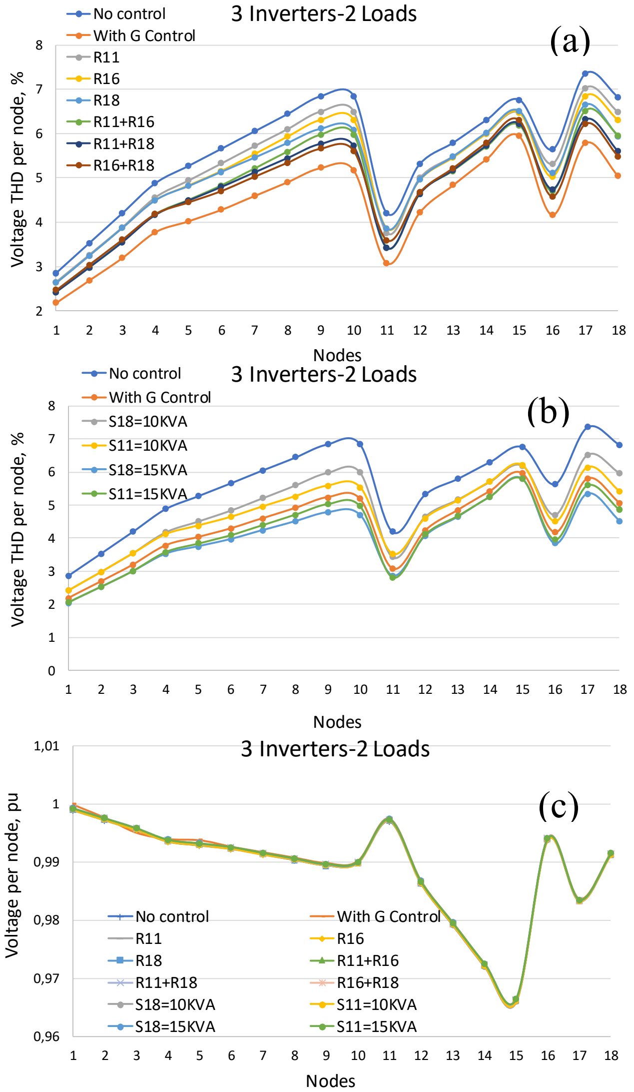

Fig. 5 Investigations in Case 1:(a) influence of the CI-DRES location on the THD_V/node, when *G*-control is activated; (b) influence of the CI-DRES location and available capacity on the THD_V/node, when *G*-control is activated at all CIDRES; (c) voltage value/ node in pu

more efficient, e.g. **Case 6** regards 5 CI-DRES with *G*-control and the THD drops at 5.2%. The same is true for **Case 3** with respect to **Case 1**. Moreover, **Cases 3**, **4** and **5** concern 4 CI-DRES and different number of NLLs. The highest THD_V appears in **Case 5**, where the NLLs are more than the other cases. Therefore, it can be deduced that the THD_V is heavily affected by the presence of the NLLs, and not the CI-DRES. Between **Cases 7** and **8**, which contain the same amount of CI-DRES and NLLs, NLL 4 has different location (*6* in **Case 7** and *13* in **Case 8**). Although the average THD_V is almost identical for these cases, *G* control is more effective when the NLL is placed at *13*, because the branch has lower *R/X* ratio than the main feeder.

Table 3 Average THD_V,% under different mixture/penetration

Examined Cases	Average THD_V,% No control	Average THD_V,% with *G* control
Case 2	6.77	5.91
Case 3	5.57	3.82
Case 4	6.76	5.55
Case 5	7.46	6.53
Case 6	6.75	5.20

Case 7	7.46	6.27
Case 8	7.50	6.17

Case 8 was selected to demonstrate the effectiveness of the *G* control and the sensitivity of the NLL/CI-DRES location, since under no control this case exhibits the highest average THD_V. As it can be noticed in Fig. 6, individual Harmonics are compensated in the most critical nodes with the applied control and in all cases the individual HD remains below the respective h_k. Although there is load at node *13*, highest THD appears at *15*, *17* and *10* (NLL nodes) and *18*, *9*, (CI-DRES nodes). Since the nodes with the highest THD_V are the remote nodes with the NLLs and their respective nearby CI-DRES, the RMS voltages at these CI-DRES nodes is also low, due to the existence of the NLLs. Similar to the voltage rise, the most remote nodes have a higher sensitivity with respect to others. In a scenario where both voltage regulation and active filtering process are about to be performed simultaneously, these two AS will probably not coincide for the same CI-DRES, since the CI-DRES with higher THD_V will have also lower RMS voltage (closer to a NLL), while CI-DRES with higher voltages will be the ones to be assigned with reactive power provision. In any case, for both voltage regulation and active filtering, the CI-DRES at most remote nodes need to have an oversized converter with respect to the primary source.

Thoughts on the Optimization Process: The optimal allocation of the harmonic mitigation among the CI-DRES has not been examined yet in the technical literature. A preliminary harmonic voltage sensitivity analysis performed by the authors with respect to the location, the amount of harmonic current by the CI-DRES at specific harmonic, and the phase of this current has shown that the value of the harmonic voltage depends heavily on the phase of the injected current. More specifically, the harmonic voltages are minimized when the downstream CI-DRES injects a current shifted 180° with respect to the respective harmonic current by the NLL. In this paper, the injected harmonic currents are shifted 180° with respect to the harmonic voltages, which have a small angle (0-3°). Of course, more mathematical analysis is required, but those preliminary cases revealed that in order to sense the phase of a specific harmonic current of the upstream NLL, highly qualified measuring devices need to be employed at both NLLs and CI-DRES. Consequently, in the optimization process several parameters need to be taken into account:

i) the operational losses on the feeders and the CI-DRES: According to [25],[26] the operation of the PV converters at relatively low power or with low power factor can cause operational power and energy losses;

ii) the thermal capacity of the CI-DRES when performing this AS: In the case of over-voltage mitigation in distribution systems, it has been proved that the CI-DRES located at the most remote nodes shall provide reactive power (since they have higher sensitivity), therefore, it is recommended that the DRES nominal power is oversized up to $S_{N,DRES}/P_{PV}$=1.41, [27]. Similar to reactive power, this AS needs an additional oversizing, especially at the most remote nodes close to a NLL, hence, there is an additional involved purchase cost.

iii) costs related to the CI-DRES controller implementation, e.g. in order to receive a signal related to other harmonics than the fundamental from a central controller, the CI-DRES is required to possess a highly qualified DSP;

iv) for a centralized implementation of a coordinated harmonic mitigation, each consumer with high harmonic pollution needs to possess a specialized measuring device to detect the voltage harmonic distortion in each low-order harmonic. In [28] an extension for PMUs is proposed, so that they include measuring capabilities for proper calculation of harmonic currents and voltages as defined by the IEEE 1459:2010 Std. However, including PMUs at distribution system level is rather an expensive approach.

v) In order to prove the effectiveness of an optimized voltage harmonic mitigation by CI-DRES, in the optimization procedure, the constraints with respect to the individual harmonic currents proposed in [2] and used in [9], [10] need to be relaxed. Special attention needs to be paid also in the objective function to be minimized. In this paper the average THD_V was studied, however, probably the average (with respect to nodes) individual HD per harmonic needs to be taken into account or the RMS THD_V at all nodes.

vi) A central controller within the distribution network will probably need to perform sequential harmonic power flows per harmonic to achieve an optimized result. The involved costs need to be considered for this implementation.

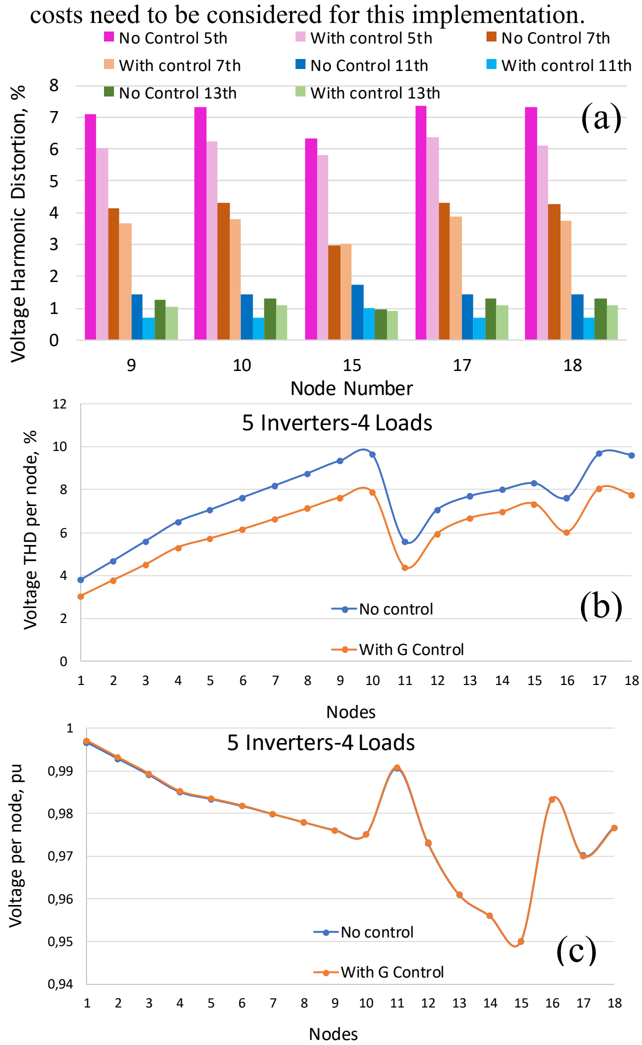

Fig. 6 Case 8: (a) HD_V per *k* harmonic at nodes *9*, *10*, *15*, *17* and *18* (b) THD_V/node; (c) voltage value/node in pu.

Therefore, it is crucial to include all costs involved for this AS in an optimized procedure, since it is yet not an established one by the Grid Codes. As an example, it is noted that even reactive power, which is already prescribed as system support function, is not remunerated for CI-DRES, [29].

4 Conclusions

In this paper, a voltage harmonic mitigation control strategy is developed for the CI-DRES, so that it does not exceed its thermal capacity. Secondly, several scenarios with respect to different penetration and mixture of CI-DRES and NLLs in the CIGRE Residential LV Network have been examined via TD simulations, to demonstrate the effectiveness of the proposed method vs. low-order harmonics, while the CI-DRES operate close to their thermal capacity. Furthermore, this paper comes to provide a further insight on the evaluation of the CI-DRES contribution for providing this AS with respect to its location within the grid and its available capacity. The proposed control is efficient for mitigating individual voltage harmonics. In all cases it has been shown that: *1*) the average THD_V is reduced; *2*) the CI-DRES downstream an NLL mitigates harmonics more efficiently: The location of the CI-DRES plays an important role in a similar manner as in the voltage regulation process, i.e. the DRES placed at the most remote nodes may be required to inject higher amounts of distortion power, therefore, the CI-DRES may require converter oversizing. In the future, CI-DRES may be required to perform several functions simultaneously, harmonic mitigation needs to be co-evaluated with respect to other AS, as well, both at DRES and system level. Since in the state-of-the art the harmonic filtering is performed in a decentralized manner, the evaluation presented in this paper will serve as a basis for the development and experimental validation of a distributed coordinated algorithm in future work, allocating properly two AS: active harmonic filtering and reactive power exchange without exhausting the DRES converters' thermal limit. This algorithm will be based on techno-economic criteria, taking into account the analysed costs and losses, so as to enable the proper allocation and remuneration of the DRES owners and make the trading of these AS in respective markets feasible.

5 Acknowledgements

This work is part of the EASY-RES project that has received funding from the European Union's Horizon 2020 Research & Innovation programme under Grant Agreement No 764090.

6 References

[1] A. S. N. Huda, R. Živanović: 'Large-scale integration of distributed generation into distribution networks: Study objectives review of models and computational tools', Renew. Sustain. Energy Rev., 2017, 76, pp. 974-988.

[2] IEEE Std. 519-2014: 'IEEE Recommended practice and requirements for harmonic control in electric power systems', 2014.

[3] IEC 61000-3-6: 'Electromagnetic compatibility (EMC) – Part 3-6: Assessment of emission limits for distorting loads in MV and HV power systems'

[4] M.H.J. Bollen, S. Bahramirad, A. Khodaei: 'Is there a place for power quality in the smart grid?', Proc. Int. Conf. Harmon. Qual. Power ICHQP, 2014.

[5] V. R. Pandi, H. H. Zeineldin, W. Xiao, A. F. Zobaa: 'Optimal penetration levels for inverter- based distributed generation considering harmonic limits', Electr. Power Syst. Res., 2013, 97, pp. 68-75.

[6] V. R. Pandi, H. H. Zeineldin and W. Xiao: 'Determining Optimal Location and Size of Distributed Generation Resources Considering Harmonic and Protection Coordination Limits', IEEE Trans. Power Syst., 2013, 28, (2), pp. 1245-1254.

[7] W. Sun, G. P. Harrison and S. Z. Djokic: 'Incorporating harmonic limits into assessment of the hosting capacity of active networks', CIRED 2012 Workshop: Integration of Renewables into the Distribution Grid, Lisbon, 2012.

[8] I. N. Santos, V. Cuk, P. M. Almeida, M. H. J. Bollen, P. F. Ribeiro:'Considerations on hosting capacity for harmonic distortions on transmission and distribution systems', Electr. Power Syst. Res., 2015, 119, pp. 199- 206.

[9] S. Sakar, M.E. Balci, S.H.E. Abdel Aleem, A.F. Zobaa: 'Integration of large-scale PV plants in non-sinusoidal environments: Considerations on hosting capacity and harmonic distortion limits', Renew. Sustain. Energy Rev., 2018, 82, pp. 176-186.

[10] S. Mohsen Ismael, S. H. E. Abdel Aleem and A. Youssef Abdelaziz: 'Hosting Capacity Enhancement of Electrical Distribution Systems under Sinusoidal and Non-Sinusoidal Conditions', 2018 Twentieth International Middle East Power Systems Conference (MEPCON), Cairo, Egypt, 2018, pp. 168-173.

[11] W. Sun, G. P. Harrison and S. Z. Djokic: 'Distribution network capacity assessment: Incorporating harmonic distortion limits', 2012 IEEE Power and Energy Society General Meeting, San Diego, CA, 2012, pp. 1-7.

[12] X. Liang and C. Andalib -Bin- Karim: 'Harmonics and Mitigation Techniques Through Advanced Control in Grid-Connected Renewable Energy Sources: A Review', IEEE Trans. Ind. Appl., 2018, 54, (4), pp. 3100-3111.

[13] X. Liang: 'Emerging power quality challenges due to integration of renewable energy sources', 2016 IEEE Industry Applications Society Annual Meeting, Portland, OR, 2016, pp. 1-9.

[14] M. Hojo and T. Ohnishi: 'Adjustable harmonic mitigation for grid-connected photovoltaic system utilizing surplus capacity of utility interactive inverter', 2006 37th IEEE Power Electronics Specialists Conference, Jeju, 2006.

[15] B. H. Yong and V. K. Ramachandaramurthy:'Double Tuned filter design for harmonic mitigation in grid connected solar PV', 2014 IEEE International Conference on Power and Energy (PECon), Kuching, 2014, pp. 293-297.

[16] A. Kulkarni,V. John: 'Mitigation of Lower Order Harmonics in a Grid-Connected Single-Phase PV Inverter,' IEEE Trans. Power Electron., 2013, 28, (11), pp. 5024-5037.

[17] S. H. Qazi, M. W. Mustafa: 'Review on active filters and its performance with grid connected fixed and variable speed wind turbine generator', Renew. Sustain. Energy Rev., 2016, 57, pp. 420-438.

[18] M. Céspedes and J. Sun: 'Modeling and mitigation of harmonic resonance between wind turbines and the grid', 2011 IEEE Energy Conversion Congress and Exposition, Phoenix, AZ, 2011, pp. 2109-2116.

[19] A. Hazrati and A. Jalilian: 'Grid side power quality enhancement in DFIG based grid connected wind plants', 2012 Proc. of 17th Conference on Electrical Power Distribution, Tehran, 2012, pp. 1-7.

[20] IEEE Std 1547-2018: 'IEEE Standard for Interconnection and Interoperability of Distributed Energy Resources with Associated Electric Power Systems Interfaces', 2018.

[21] European Committee for Electrotechnical Standardization (CENELEC): EN50549-1:2019 'Requirements for generating plants to be connected in parallel with distribution networks - Part 1: Connection to a LV

distribution network- Generating plants up to and including Type B', 2019.

[22] M. Barragán-Villarejo et al, 'Harmonic and Imbalance Compensation in Grid-Forming VSC', 2020 IEEE International Conference on Industrial Technology (ICIT), Buenos Aires, Argentina, 2020, pp. 757-762.

[23] E. O. Kontis et al: 'Power Flow Analysis of Islanded AC Microgrids', 2019 IEEE Milan PowerTech, Milan, Italy, 2019, pp. 1-6.

[24] H. Akagi, E. H. Watanabe, M. Aredes: 'Shunt Active Filters' in IEEE 'Instantaneous Power Theory and Applications to Power Conditioning', 2017, pp. 153-157.

[25] K. D. Malamaki and C. S. Demoulias: 'Estimation of Additional PV Converter Losses Operating Under PF ≠ 1 Based on Manufacturer's Data at PF = 1', IEEE Trans. Energy Convers., 2019, 34, (1), pp. 540-553.

[26] C. S. Demoulias: 'A new simple analytical method for calculating the optimum inverter size in grid-connected PV plants', Electr. Power Syst. Res., 2010, 80, (10), pp. 1197–1204.

[27] G. C. Kryonidis, C. S. Demoulias, G. K. Papagiannis, 'A Nearly Decentralized Voltage Regulation Algorithm for Loss Minimization in Radial MV Networks With High DG Penetration', IEEE Trans. Sustain. Energy, 2016, 7, (4), pp. 1430-1439.

[28] Granados-Lieberman, D.: 'Global Harmonic Parameters for Estimation of Power Quality Indices: An Approach for PMUs', Energies, 2020, 13.

[29] Oureilidis, K. et al: 'Ancillary Services Market Design in Distribution Networks: Review and Identification of Barriers', Energies, 2020, 13, (917).