

Probabilistic Planning of Virtually-Hybrid Harmonic Filters in Modern Distribution Systems

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Abstract—The increasing number of Power-Electronic (PE) interfaced devices in the new generation of distribution systems results in concerns about the power quality of modern grids. Besides the loads, the harmonic-injecting devices are increasingly penetrating the generation, storage, and delivering levels of energy dispatch systems in the microgrids and the LV networks which can be easily reflected in the primary distribution systems. As an economic, applicable, and efficient solution, the passive filters can be optimized and added to the grid to absorb the harmonics. Furthermore, in the presence of controllable devices such as PE-interfaced DGs and storage units, a coordination strategy can be implemented to actively decrease the effect of the nonlinear loads. Accordingly, the idea of a virtually-hybrid filter can be developed by the use of passive filters and the coordinated active harmonic filtering strategy. In this paper, by providing an explanation for the developed coordination strategy of active filters, the probabilistic techno-economic planning of virtually-hybrid filters is studied considering the different combinations of the linear and nonlinear loads in a modern primary distribution system. Simulation results have proved that the proposed method is capable of minimizing harmonic distortions and grid loss by the use of the optimal passive filters and the suggested coordination strategy of the active devices.

Keywords—passive filters, power quality, planning, active filters, coordination, virtually-hybrid filters.

I. INTRODUCTION

Many of the devices connected to microgrids and modern distribution systems cause power quality problems like harmonic distortions in the grids. The motor drives, electric vehicle chargers, Compact Fluorescent Lamps (CFL), LEDs, and the inverters used as the interfaces of the storage systems and DG units are some of the important origins of harmonics in modern distribution systems [1]–[4].

The harmonic currents may result in problems like excessive grid loss, transformer losses, motor heating, metering and protection problems, interference, resonances, and grid instability [5]–[7]. As the penetration of the nonlinear devices is considerable and even increasing in the modern grids, the problems can be more severe in the future.

Due to the undesirable effects of harmonics on both customer devices and grid facilities, the researchers have focused on economic and effective solutions for power quality improvement in distribution systems. In order to increase the applicability of the solutions, they should be further developed to conform to the specifications and possibilities available inside the modern grids. Moreover, the solutions should handle both the higher levels of harmonics

in these grids and the dynamic behavior of nonlinear loads while the total costs are minimized.

According to published studies, several solutions have been applied by researchers for harmonic mitigation in the grids. Passive filters [8], active filters [9], DSTATCOM [10], UPQC [11], and Open-UPQC [12] are some of the main devices proposed to address power quality improvement and the harmonic mitigation in the grids. As a general comparison, although there are lots of benefits provided by all of the active solutions, the passive filters are still widely applied by researchers due to the simplicity, and economic/technical benefits [13].

Passive filter planning in distribution systems has been studied regarding different problem definition perspectives and solution strategies in the previously-published papers. The general decision made through the studies is the optimal place and specifications of the passive filters. Grid loss, current and voltage harmonic distortions, voltage profile, reactive power compensation level, and filter investment cost are some of the main indices assessed during the passive filter planning studies which are applied to the problem through the constraints and objective functions [13]–[16].

Although the passive filter is regarded as an efficient and applicable solution for harmonics, it cannot completely deal with the high level of loading uncertainty. In other words, the severe and dynamic variations in the type, place, and power of the nonlinear and linear loads of the grids may result in some failures of the harmonic mitigation strategies based on the passive filters. Moreover, the excessive installation of passive filters increases the risk of resonance in the grid that may necessitate extra monitoring and protection systems.

According to the stated problems, many studies focus on the planning of active filters for harmonic mitigation in distribution systems. Similar to the strategy applied for passive filters, the active filter allocation is also studied considering the investment cost, grid losses, and the power quality indices in the distribution systems [17], [18].

Although there are lots of advantages of applying active filters for harmonic elimination in the grids compared to the passive solutions, the higher costs limit their applicability in real-world implementations. Moreover, the low-cost loss reduction provided by the reactive support of passive filters is not effectively provided by the active solutions. Hence, the idea of hybrid harmonic filters that are a combination of passive and active solutions is developed by researchers [19]. Accordingly, both cost reduction and more-accurate dynamic harmonic mitigation capability can be provided by the use of active filters beside the passive ones [20]. It should be noted

that in the hybrid solution, the low-cost passive filters are commonly installed for the most prominent low-order harmonics while the higher orders are usually compensated by the active filters. Altogether, applying the hybrid filtering strategy, the problems regarding the presence of a very high number of passive filters in the grids can also be resolved.

On the other hand, due to the presence of communication systems inside the modern grids, the active filtering service can be provided by coordinated control of several distributed Power-Electronic (PE) interfaced devices such as storage systems and DG units. Hence, the idea of simultaneous active and passive filtering can be studied from a different point of view with respect to the specifications of modern electrical distribution systems. In this way, the grid-wide power quality improvement can be implemented in a virtually-hybrid framework considering the costs related to the implementation of the filter and the losses in the grid. In other words, when there is the possibility of selecting a set of PE-interfaced devices to participate in the coordinated active harmonic filtering, the location and specification of the passive filters can also be determined in a more effective way while providing a lower grid loss, improved system specifications and lower investment costs.

In this paper, the planning of virtually-hybrid filters is implemented inside a primary distribution system considering the installation of passive filters and coordinated active harmonic filtering while the latter is applied in the framework of Open-UPQC. Accordingly, the size and location of the single-tuned passive harmonic filters are optimized while selecting the PE-interfaced shunt units to participate in coordinated active harmonic filtering; furthermore, in order to integrate the probable loading scenarios, different combinations of linear and nonlinear load levels are applied in the study.

The rest of the paper is organized as follows. The definition of virtually-hybrid filters is given in Section II. The virtually-hybrid filter optimization problem and the solution strategy are characterized in Section III. Simulation results are provided in Section IV. Finally, the paper is concluded in Section V.

II. VIRTUALLY-HYBRID FILTERS

Regarding the descriptions provided in Section I and due to the benefits of implementing simultaneous passive and active filters, in this paper, the hybrid filtering strategy is implemented using a set of passive filters installed in the electrical distribution network while applying the coordinated active harmonic filtering strategy. Accordingly, while the passive filters are selected to be installed in some buses of the grid, a set of PE-interfaced shunt units participate in the active harmonic filtering strategy. It should be noted that the shunt units are selected from the set of the available ones in the grid and the coordination is applied in the framework of Open-UPQC. A short description for the applied passive and active harmonic filtering strategies is provided in the following subsections.

A. Passive filters

Passive filters are favorable both in academic studies and in real-world implementations due to the low-cost, high harmonic elimination capability, reactive power compensation, voltage improvement, and loss reduction. Generally, in the theory of hybrid filters, the passive part can be implemented by any of the passive filter types or a set of them. However, single-tuned passive filters are among the

ones that are most commonly used to suppress the harmonic distortions. Therefore, in this paper, single-tuned passive filters are selected and applied in the studied virtually-hybrid filter. In order to install the single-tuned passive filters for grid-wide harmonic elimination, assessments should be done on the optimal location and specification of each of them to provide both power quality improvement and overall cost minimization.

B. Coordination strategy for active harmonic filtering

In this paper, based on the control method proposed for harmonic mitigation in LV networks using Open-UPQC in [21], a coordination strategy is developed to decrease the harmonics of the primary distribution systems using the available capacity of PE-interfaced devices. In this method, there is a meter in the substation of the distribution system which can extract the magnitude and phase angle of each individual harmonic current order. With respect to the measurements, the central controller shares the harmonics between the available PE-interfaced devices through a simple control strategy. It is clear that such a capacity from the PE-interfaced devices should be delivered to the grid and central controller using contracts between the DSO and the owners.

The diagram of the proposed control strategy for the coordinated harmonic mitigation using the available capacity of the PE-interfaced devices is given in Fig. 1. The control method is illustrated only for the fifth harmonic order in the figure to avoid the similar descriptions for the other studied harmonics. It should be noted that the Supplementary Control Unit (SCU) is applied to the system with respect to the system delays and some other real-world considerations which are out of the scope of this paper and can be studied in [21]. Altogether, it should be noted that in this study, the dynamics of the system are ignored; hence, the measured harmonics are generated with 180 degrees of phase change through the implementation of the flowchart in steady state mode; in other words, the process is not repeated to simulate the dynamics of the control system as it is described in [21]. However, in case of reaching the limits of the capacity in any of the loading scenarios, the harmonic current injections are limited up to the capacity of the PE-interfaced unit.

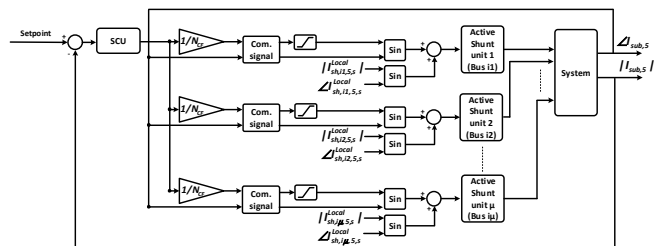


Fig. 1. Diagram of the coordinated control of the active devices inside the grid for harmonic mitigation

In this paper, the set of busses with the availability of shunt units is pre-defined; however, among the available shunt units, a set of them is selected to participate in the harmonic elimination strategy. This is done at the same time with the optimization of the passive filters; furthermore, the owners of the PE-interfaced devices are paid based on their participation in the harmonic elimination.

III. OPTIMIZATION MODEL AND SOLUTION STRATEGY

In this paper, a probabilistic multiobjective techno-economic optimization of the proposed virtually-hybrid harmonic filters is addressed regarding the different combinations of the linear and nonlinear loads. Accordingly, the determination of the place and capacity of passive filters

is implemented as well as the selection of the busses for participating in active harmonic filtering while considering the investment and loss cost minimization and power quality improvement.

In this study, the participation of the PE-interfaced devices in harmonic elimination is paid based on the involved power that is calculated in the probabilistic framework. Furthermore, due to the presence of the active harmonic elimination facilities, a limited set of fixed orders is selected for the passive filters regarding the most prominent harmonic orders. Details on the modeling of the problem and the applied solution strategy are provided in the following subsections.

A. Mathematical model of virtually-hybrid filter planning

The mathematical representation of the optimization problem is discussed in this section. In order to clarify the model, each of the objective functions and constraints are described independently.

1) Objective functions

The costs regarding the installation of the virtually-hybrid filters can be divided into filter implementation and loss costs. These costs are modeled as the first objective function of the study; moreover, regarding the quality of power, a combinational index of voltage and demand harmonic distortion is selected as the second objective of the study. The objective functions of the optimization problem can be represented by (1) and (2).

$$OF_2: \min(TC) \quad (1)$$

$$OF_1: \min(HDI) \quad (2)$$

in which the TC is the total cost while HDI represents the applied harmonic distortion index of the grid that is calculated among the whole combinational loading scenarios. The objective functions are described in detail in the following subsections.

a) Cost function

The costs are calculated based on the loss of energy and passive filter investments as well as payments for active filter coordination; accordingly, the total cost is represented in the annualized format using (3).

$$TC = C_{EL} + AC \times C_F \quad (3)$$

In which TC is total cost of the project that is calculated on annualized basis, C_{EL} is the cost of yearly energy loss, C_F is the cost representing the implementation of the virtually-hybrid filter, and AC is the coefficient used for transforming the filter cost to the annualized value calculated by (4).

$$AC = \frac{IR \times (1 + IR)^N}{(1 + IR)^N - 1} \quad (4)$$

in which IR is the interest rate and N is the study horizon.

Regarding the descriptions provided in [22], the cost of energy loss applying the different loading scenarios can be calculated using (5).

$$C_{EL} = 8760 \times K_{EL} \times \sum_s p_s \times P_{L,s} \quad (5)$$

in which K_{EL} is the unit cost of energy (\$/MWh), p_s is the probability of loading scenario s , and $P_{L,s}$ is the power loss of the grid in the same scenario.

Moreover, the cost of the filter includes the investment of the passive filter and the payments regarding coordinated active filtering that can be summarized as (6).

$$C_F = C_{PF} + C_{AF} \quad (6)$$

in which C_{PF} and C_{AF} represent the cost of passive and active filtering strategies, respectively. The equations for the calculation of passive and active filtering costs are given in (7) and (8), respectively.

$$C_{PF} = \sum_i \sum_m (K_C \times QC_{i,m}^n + K_L \times QL_{i,m}^n) \quad (7)$$

$$C_{AF} = K_{AF} \times \sum_i \sum_s (AFS_{i,s}) \quad (8)$$

in which i and m represent the index of busses and passive filters, respectively; K_C , K_L , and K_{AF} are the unit cost of capacitor investment, inductor investment, and active filtering strategy implementation respectively; $QC_{i,m}^n$ and $QL_{i,m}^n$ are the nominal capacity of the capacitor and inductor of passive filter order m in bus i , respectively; finally, $AFS_{i,s}$ is the occupied apparent power of PE-interfaced unit of bus i for the sake of coordinated active harmonic filtering in scenario s of loading. It should be noted that the other details regarding the cost of the passive filters can be found in [13].

b) Harmonic distortion index

Total harmonic distortion of voltage is one of the most common objectives in filter planning studies in the literature [23]–[25]. On the other hand, there are also several studies focusing on the current or demand level distortion in the PCC of the network [24]–[28]. Altogether, in this paper, a combinational decrease of the voltage harmonic distortion of the feeder and the demand distortion level of the substation is selected as the second objective function of the study. Accordingly, HDI index given in (2) is represented as (9).

$$HDI = \max\{THDV^{max}, TDD_{sub}^{max}\} \quad (9)$$

in which $THDV^{max}$ is the maximum total harmonic distortion of voltage among all busses and TDD_{sub}^{max} is the total demand distortion in the substation of the network; it should be emphasized that both $THDV^{max}$, TDD_{sub}^{max} are determined with respect to all the loading scenarios. Hence, applying (9) through (2), the maximum value among $THDV^{max}$ and TDD_{sub}^{max} is minimized providing the decrease of both voltage harmonic distortion in the network and the demand distortion in the substation.

2) Constraints

It should be noted that the set of busses with available PE-interfaced units is defined prior to the implementation of the optimization; however, regarding each candidate solution, a number of these units are selected to participate in coordinated active harmonic elimination. Moreover, it should be emphasized that the maximum available capacity of the selected PE-interfaced units is pre-determined; however, the share of capacity utilized for harmonic mitigation is applied for cost determination in (8). Accordingly, considering the set of scenarios of the combinational linear/nonlinear loads in the grid, the involved capacity of active filters is determined in the probabilistic framework. This value is however constrained using (10).

$$AFS_{i,s} \leq AFS_i^n \quad (10)$$

In which AFS_i^n is the available capacity of PE-interfaced units in bus i .

Moreover, regarding the passive filters, the orders are limited to $m = \{5, 7\}$ as the most prominent harmonic orders in the grid; this is applied to the problem using (11).

$$IPF_{i,7} = IPF_{i,5} \quad (11)$$

in which IPF_7 and IPF_5 are binary variables stating the presence of 5th and 7th order passive filters in bus i . Based on (11), each bus selected for the installation of passive filters will have it for both the 5th and 7th orders. However, the total number of passive filters is limited using (12).

$$N_{PF} \leq N_{PF}^{max} \quad (12)$$

in which N_{PF} is the number of passive filters, and N_{PF}^{max} is the maximum number of passive filters that can be installed.

Finally, the voltage quality constraint is applied to the study using (13).

$$|V_{i,s} - 1| \leq \Delta V^{max} \quad (13)$$

in which $V_{i,s}$ is the p.u. voltage of bus i in scenario s and ΔV^{max} represent the maximum deviation of voltage allowed in the buses of the grid.

B. Solution strategy

In this paper, NSGA-II is applied to solve the multiobjective optimization problem while the fuzzy decision-making process is applied to select the final solution among the ones given as the Pareto front. The overall strategy is similar to the one described in [22]; however, the details of the implementation are provided in the following subsections.

1) Nondominated Sorting Genetic Algorithm (NSGA-II)

The structure of the chromosome applied for solving the problem is given in Fig. 2. As it can be seen, the chromosome includes three different parts stating the active filters and the 5th order passive filters as well as the 7th order ones. The overall size of the chromosome can be calculated by (14).

$$n_{chr} = n_{sh} + 2 \times n_b \quad (14)$$

in which n_{chr} is the number of genes in the chromosome, n_b is the number of the busses in the network, and n_{sh} is the number of busses with the PE-interfaced units as the candidates for participating in the active harmonic filtering. The details on the representation of the chromosome per each of the parts are given in Fig. 3.

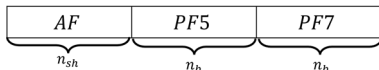


Fig. 2. Representation of the different parts of the chromosome

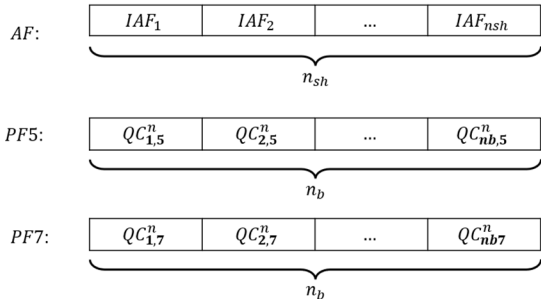


Fig. 3. Representation of the different parts of the chromosome

It should be re-emphasized that the single-tuned passive filters are set to be fixed for the 5th and 7th order as the most prominent harmonics existing in electrical distribution networks; accordingly, for each bus selected for the installation of passive filters, both filters are applied regarding the optimal reactive capacities per each. Regarding Fig. 3, the part related to the active filters, includes n_{sh} binary variable IAF_j , indicating whether the j th PE-

interfaced unit is selected to participate in the active harmonic filtering strategy or not. It should be noted that these candidate busses are defined prior to optimization based on the availability of the PE-interfaced devices. On the other hand, the parts of the chromosome related to the passive filters are represented by $QC_{i,m}^n$ indicating the nominal capacity of the capacitors utilized for the m th order passive filter in bus i ; the capacity can be selected to be either zero, indicating no filter or a value from the list of available capacitors.

Altogether, regarding the set of candidate solutions stated by the chromosome, the flowchart of the NSGA-II method applied to solve the multiobjective optimization problem is demonstrated in Fig. 4. The evaluation of objective functions in the flowchart, for each individual solution candidate, the passive filters are added to the grid and the selected PE-interfaced units also participate in coordinated harmonic filtering in all the defined combinational loading scenarios. After the assessment of all candidates and moving towards the examinations of new populations formed by the operators, the final set of ranked solutions is fed into the decision-making block.

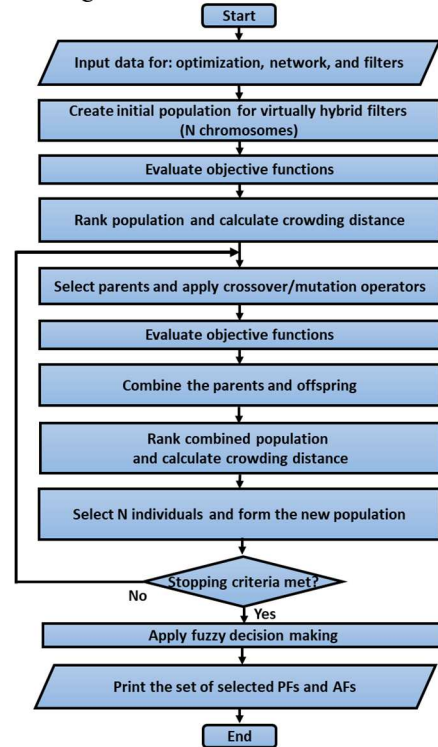


Fig. 4. Flowchart of the NSGA-II method applied to solve the virtually-hybrid filter optimization problem

2) Fuzzy decision making

In this study, the distance metric method described in [29] is applied to select the final solution of the virtually-hybrid filter planning problem. In this method, the selection of the final solution among the available ones is implemented by solving the optimization problem formulated as (15) [29].

$$\min_{\bar{X} \in \Phi} \sum_k |\mu_{rk} - \mu_{fk}(\bar{X})|^p \quad (15)$$

where k is the index of the objective function, μ_{rk} is the reference membership value of k th objective function, $\mu_{fk}(\bar{X})$ is the membership function value of k th objective for the solution candidate \bar{X} , and $1 \leq p < \infty$. It should be noted that in this paper, the linear membership function is applied to decision-making; the description needed for forming the function is provided in [22].

IV. SIMULATION RESULTS

In this section, the virtually-hybrid filter planning problem is studied in an electrical distribution network. After a short description of the specifications of the grid and the details regarding the optimization study, the results of virtually-hybrid filter planning are provided and discussed. In order to clarify the effect of the passive filters and the coordinated active filtering, they are also applied in independent scenarios and the results are compared with each other.

A. Study case and simulation data

In this paper, the virtually-hybrid filter planning problem is studied in the 33-bus distribution network. The single line diagram of the grid is given in Fig. 5 and the description regarding the grid and linear/nonlinear load data is provided in [15]; according to the description, half of the loads in the grid are considered to be harmonic-injecting regarding the harmonic spectrum of a six-pulse converter [15].

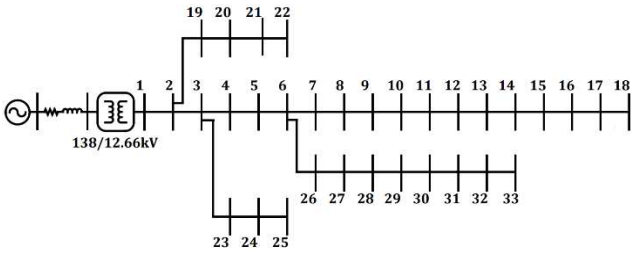


Fig. 5. Single line diagram of the 33-Bus distribution system

In order to apply the different combinational scenarios of linear and nonlinear loads, the strategy proposed in [22] is applied in this paper; however, instead of using Load Forecast Modified Load Curve (LFMLC), the three-step Load Duration Curve (LDC) is applied to both linear and nonlinear loads; altogether, the studied combinational loading scenarios are given in TABLE I in which LM and p stand for the loading multiplier and the probability while α , β , and s represent the linear load, nonlinear load, and the combinational scenario.

TABLE I. Combinational linear/nonlinear loading scenarios

Load level		Probability		
LM_α	LM_β	p_α	p_β	p_s
0.33	0.33	0.2	0.2	0.0400
0.33	0.67	0.2	0.45	0.0900
0.33	1.00	0.2	0.35	0.0700
0.67	0.33	0.45	0.2	0.0900
0.67	0.67	0.45	0.45	0.2025
0.67	1.00	0.45	0.35	0.1575
1.00	0.33	0.35	0.2	0.0700
1.00	0.67	0.35	0.45	0.1575
1.00	1.00	0.35	0.35	0.1225

In order to implement the study, the set of available capacitors and the unit cost of them are taken from [30]; the maximum available capacity of the PE-interfaced units is considered to be 100 kVA for all the candidate busses that are {6,10,14,26}. The unit cost of active filtering is also considered to be 72 \$/kVAR [31] neglecting the constant cost term since the units are existing in the grid. The interest rate, number of years in the study horizon, unit cost of inductor, and energy loss are 5%, 15, 3 \$/kVAR, and 50 \$/MWh, respectively [30]. The maximum number of busses for passive filter investment is considered to be 5 while the tuning orders are set at 4.7 and 6.6 for the 5th and 7th order filters, respectively. Finally, a $\pm 10\%$ maximum allowed voltage deviation from the rated value is applied to the optimization problem.

B. Virtual-hybrid filter planning results

The results of applying the strategy described for virtually-hybrid filter planning are provided in TABLE II. The grid assessment results in the presence of the filters are also compared with the main grid in TABLE III.

TABLE II. Virtually-hybrid filter planning results

Bus No	Filter type	Supplementary Information
6	Active	-
10	Active	-
16	Passive	$QC_{10,5}^n = 350 \text{ kVAR}$ $QC_{10,7}^n = 150 \text{ kVAR}$
26	Active	-
30	Passive	$QC_{30,5}^n = 450 \text{ kVAR}$ $QC_{30,7}^n = 350 \text{ kVAR}$

TABLE III. Grid assessment results in the presence of the virtually-hybrid filters

Index	Base grid	In presence of virtually-hybrid filters
$THDV^{max}$ (%)	6.46	2.13
TDD_{sub}^{max} (%)	10.01	3.22
Max. vol. deviation (%)	10.58	7.14
Annualized overall cost (k\$)	48.74	36.99

According to the results, by the combinational implementation of the passive and active harmonic filtering strategies, both the voltage harmonic distortion in all buses and demand distortion level in the substation are successfully decreased. Furthermore, the voltages of all busses are maintained within the specified limits. Finally, the annualized overall cost of the system is successfully decreased through the reduction of the system losses. However, in order to clarify the effect of the passive and active filtering strategies, they are applied independently regarding the solution and the results are discussed in the following subsection.

C. Specifying the effect of the passive and active filtering strategies

According to the description, in this section, the passive filters and the selected PE-interfaced shunt units given in TABLE II are applied to the grid independently and the results are provided in TABLE IV.

TABLE IV. Grid assessment results in the independent presence of the selected passive and active filters

Index	Base grid	Passive filters	Active filters	Virtually-hybrid filters
$THDV^{max}$ (%)	6.46	3.18	2.60	2.13
TDD_{sub}^{max} (%)	10.01	10.31	3.46	3.22
Max. vol. deviation (%)	10.58	7.14	10.58	7.14
Annualized overall cost (k\$)	48.74	35.40	50.36	36.99

According to the results, the passive filters successfully decreased the voltage harmonic distortion and the voltage deviation; moreover, by the low-cost voltage stabilization and reactive power compensation, the annualized cost of the system successfully decreased due to the lower costs. However, the demand distortion level in the substation is still high in the presence of the passive filters. On the other hand, the coordinated active harmonic filtering strategy has considerably decreased the demand distortion level in the substation; moreover, it provided an even lower voltage harmonic distortion level. However, the active harmonic filtering strategy could not decrease the voltage deviations in the grid. Moreover, due to the high implementation cost and the lower level of effect on the losses, the annualized cost of the system is high in this case. However, according to the results, with the combinational use of both strategies, the quality of power successfully improved while the overall

cost of system is maintained at a reasonable level. Moreover, due to the expectable decrease of the costs regarding the active filtering strategy in the future, the economic feasibility of the virtually-hybrid filters can even be improved.

V. CONCLUSION

In this paper, a virtually-hybrid harmonic filtering strategy is proposed for modern electrical distribution systems. Accordingly, by selecting a set of PE-interfaced shunt units inside the grid and the implementation of a coordinated active harmonic filtering strategy besides the determination of the size and place of the single-tuned passive filters, the hybrid filtering of harmonics is implemented in a novel framework. Assessing the planning study as a multiobjective techno-economic optimization problem, both the overall costs of the system and the quality of power are optimized while characterizing the specifications of the virtually-hybrid filter. Then, the framework proposed for the virtually-hybrid filter planning considering the different linear and nonlinear load combinations is applied to a sample harmonic-polluted distribution system and the results are discussed. According to the results, the combinational use of the passive filters and the active harmonic filtering strategy successfully decreases the harmonics of both voltage in the busses and the demand distortion in the substation as well as decreasing the overall costs of the system. Accordingly, it can be an interesting applicable method for power quality improvement and loss minimization in modern electrical distribution systems.

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