PV Hosting Capacity Improvement Through an Aggregate Study of Single-tuned Passive Filter Planning and Grid Reconfiguration

Ehsan Kazemi-Robati
Department of Electrical Engineering
Shahid Beheshti University
Tehran, Iran
e_kazemi@sbu.ac.ir

Hossein Hafezi
Faculty of Information Technology and Communication Sciences
Tampere University
Tampere, Finland
hossein.hafezi@tuni.fi

Mohammad Sadegh Sepasian
Department of Electrical Engineering
Shahid Beheshti University
Tehran, Iran
m_sepasian@sbu.ac.ir

***Abstract*— The high penetration of Photovoltaic (PV) units may lead to harmonic and overvoltage problems in electrical distribution systems. Accordingly, the PV Hosting Capacity (PVHC) of the grid is limited when the distribution network faces high penetration of harmonic-injecting loads or low demand-level conditions. On the other hand, the combination of passive filters and grid reconfiguration can improve the voltage profile and decrease the distortion levels in the distribution systems. Hence, in this study, an aggregate optimization of passive harmonic filters and grid topology is implemented to maximize the PVHC of the active distribution systems. Accordingly, the planning study is applied to provide the possibility of maximum PV installation capacity in the network while the grid indexes are maintained within the standard limits. It should be noted that the study is constrained by the total filter number and maximum allowed grid power loss. According to the simulation results of a sample grid without the capability of PV installation in the base case, the PVHC can be improved to 78% using the proposed strategy.**

Keywords*— *Photovoltaics, hosting capacity, passive filters, grid reconfiguration.

I. INTRODUCTION

Due to the environmental and economic considerations of modern societies, renewable-energy-based electrical energy sources are going to be widely integrated in supplying the load demands. Accordingly, many of the distribution networks may face some limitations in integrating the extra distributed generation units in the future. Hence and with respect to the considerable share of PV technology in the modern energy production strategies, the harmonic distortions and overvoltage problems should be taken into account as the effects of high penetration of these units in the grid [1].

In order to increase the capability of distribution systems for hosting more PV units, there are several solutions proposed by the researchers in the literature [2] [3]. Some of these studies focus on the implementation of additional devices while others apply corrective actions using the available infrastructure. The use of smart inverters [4], storage systems [5], active transformers [6] and the implementation of load management strategies [7] are a set of methods applied by the researchers for increasing the capacity of hosting PV-units in the grid.

On the other hand, there are studies that focus on the PV Hosting Capacity (PVHC) in harmonic-polluted grids [8] [9]. Regardless of the study objectives, the passive filters are widely implemented by researchers as the effective and applicable low-cost solution for harmonic mitigation in these grids [9] [10]. Accordingly, passive filters are applied for increasing the grid hosting capacity in [11] [12] while considering the different nonlinearity levels of the loads and the background voltage harmonics. According to the results, this strategy is found effective in increasing the grid capability for hosting more PV units while maintaining the specifications within the standard limits.

As a solution based on the available infrastructure without the need for additional investment costs, distribution system reconfiguration is found an effective strategy for PVHC improvement in the grids [13]–[15]. Such a capability is provided by voltage profile improvement and lowering the grid loss and line flow. Furthermore, the grid reconfiguration can also affect the harmonic distortion levels in distribution networks [16] [17]. Hence, it can have a supplementary effect on PVHC while the grid harmonic distortions are taken into account.

Based on the descriptions, the simultaneous use of the passive filters and grid reconfiguration can provide a high capability for hosting more PV units in the grid. As this combinational method is based on both the available infrastructure and low-cost additional devices, the advantages of these two strategies can be provided simultaneously. Moreover, in real-world applications, the possibility of developing the passive filters by the use of the capacitors available in the grid can also enhance the applicability of the strategy by decreasing the costs.

From a technical point of view, the combinational method of using both passive filters and grid reconfiguration can provide several benefits compared to the use of each single strategy. As an example, while the lower harmonic reduction capability of grid-reconfiguration is covered by the passive filters, the overvoltage due to the reactive power injection of the filters in lower demand levels is diminished by applying a more appropriate grid topology. Furthermore, in the higher loading conditions with lower PV generation, the capacitor of the passive filters will aid the grid-topology-selection strategy to more effectively stabilize the grid voltage profile.

Accordingly in this paper, a novel strategy of PVHC improvement is implemented based on simultaneous optimization of single-tuned passive harmonic filters and grid topology in a harmonic-polluted distribution system. In this method, the PV penetration is gradually increased and the different indexes are monitored in presence of the candidate filters in the selected topology of the grid. It should be noted that during these studies, the stable operation of the grid is ensured through the implementation of different load levels in presence of each PV penetration. However, during the process of increasing the PV levels, when one index reaches its limits,

the penetration studied in the previous step is considered as the maximum PVHC of the distribution system.

The details of implementing the proposed method are given in the following sections. Then the strategy is applied in a sample distribution system with nonlinear loads and the results are discussed.

The rest of the paper is organized as follows. The mathematical modeling of the problem is given in section II. The solution strategy is described in section III. The simulation results are given and discussed in section IV and the paper is concluded is in section V.

II. MATHEMATICAL MODELING

According to the descriptions, the hosting capacity maximization is selected as the objective of the optimization study. Hence, the objective function of the problem can be defined as (1).

$$Max\ PVHC \tag{1}$$

Assuming the PVs working in unity power factor [11], in this paper the hosting capacity is measured as the portion of the total-grid PV active power generation to the total rated power of the grid load-demand. Accordingly, the PVHC can be calculated using (2).

$$PVHC = \frac{\sum_i P_{pv,i}}{\sum_i |S_i|} \tag{2}$$

In which $P_{pv,i}$ and S_i are the rated fundamental power of the installed PV unit (kW) and demand level (kVA) in ith bus.

However, during the solution procedure of the study, there are different constraints that should be taken into account in all the different loading scenarios. Accordingly, the bus voltages are maintained within the specified limits using (3).

$$V^{min} < V_i < V^{max} \tag{3}$$

In which V_i is the RMS voltage value in bus i and the maximum and minimum limitations are defined by the operator with respect to the standard and requested quality of power. However, in presence of harmonic distortions, RMS voltage can be calculated using (4) in which $V_{i,h}$ is the hth harmonic order voltage in bus i.

$$V_i = \sqrt{\sum_{h=1}^{H} V_{i,h}^2} \tag{4}$$

The branch flow limit given in (5) should also be considered as the thermal limit of the lines.

$$C_j < C_j^{max} \tag{5}$$

In which C_j is the current flow in line j calculated by (6) and C_j^{max} is the maximum allowed flow determined with respect to the line specifications.

$$C_j = \sqrt{\sum_{h=1}^{H} C_{j,h}^2} \tag{6}$$

In which $C_{j,h}$ is hth order harmonic current in line j.

From a harmonic limitation point of view, the individual and total voltage harmonic distortions are maintained within the standard limits by the use of (7) and (8).

$$THD_i^v < THD^{v,max} \tag{7}$$

$$IHD_{i,h}^v < IHD^{v,max} \tag{8}$$

In which THD_i^v and $IHD_{i,h}^v$ are the total and hth individual harmonic distortion of voltage in bus i which are calculated by (9) and (10).

$$THD_i^v = \frac{\sqrt{\sum_{h=1}^{H} V_{i,h}^2}}{V_{i,1}} \times 100 \tag{9}$$

$$IHD_{i,h}^v = \frac{V_{i,h}}{V_{i,1}} \times 100 \tag{10}$$

Furthermore, the total demand distortion of the grid is monitored on the substation as the Point of Common Coupling (PCC) point with the upside grid. Accordingly, the TDD is limited by (11) with respect to the standards while it is monitored on both sides of the substation transformer.

$$TDD_{sub} < TDD^{max} \tag{11}$$

In which TDD_{sub} is the total demand distortion measured on the substation and TDD_{max} is the standard limit with respect to voltage level, short circuit capacity and the rated current flow.

During the optimization study, the number of passive filters and the total reactive power capacity of them is also constrained using (12) and (13).

$$n_f < n_f^{max} \tag{12}$$

$$\sum_i Q_{c,i} < Q_c^{max} \tag{13}$$

In which the rated reactive power of the capacitors used in the filters of bus i and the total number of single-tuned passive filters in the whole grid are represented by $Q_{c,i}$ and n_f. However, the number of filters and the capacity of their capacitors in the whole grid are limited to n_f^{max} and Q_c^{max}, respectively. Moreover, the system total loss in presence of the PV units and the filters is also maintained in the limit demonstrated in (14).

$$TPL < PL^{max} \tag{14}$$

In which TPL is the total grid power loss (kW) and PL^{max} is the upper limit considered for it. However, in this study, PL^{max} is selected to be the total grid loss (kW) in the main distribution network without the reconfiguration and any passive filter.

It should be noted that the grid assessment during the simulations of this paper is carried out by the use of loadflow calculations which are completely described in [18] [19]. However, a short review is given on the formulations in the following subsections.

A. Loadflow (LF)

The distribution system loadflow is carried out in an iterative procedure using the set of equations given in [18] which are shown in summarized form in (15)-(16).

$$I_i^k = \left(\frac{S_i}{V_i^k}\right)^* \quad (15)$$

$$[V^{k+1}] = [V^0] + [BCBV][BIBC][\,I^k] \quad (16)$$

In which S_i is the apparent power of the demand in bus i while V_i^k and I_i^k are the voltage and current injection in bus i in iteration k of the solution process. It should be emphasized that the fundamental power of both linear and nonlinear loads are included in this process. However, $[V^k]$ and $[\,I^k\,]$ are the grid voltage and current matrices in iteration k while $BCBV$ (branch current to bus voltage) and $BIBC$ (bus injection to branch current) are calculated based on the distribution system data [18]. Calculating these two equations in an iterative procedure while considering the other solution details can provide the loadflow results in the radial distribution system [18].

B. Harmonic loadflow

The harmonic loadflow can also be implemented using the iterative solution of the set of equations given in (17)-(19) [19].

$$[Is^{h,k}] = -([HLF^h]\,)^{-1}[HA_{sh}^h]\,[Ih^{h,k}] \quad (17)$$

$$[I^{h,k}] = \begin{bmatrix} Ih^{h,k} \\ \dots \\ Is^{h,k} \end{bmatrix} \quad (18)$$

$$V^{h,k+1} = V^{h,0} + [HA^h][I^{h,k}] \quad (19)$$

In which $[Ih^{h,k}]$ and $[Is^{h,k}]$ are the harmonic current matrices for the loads and shunt elements in iteration k while HLF^h, HA_{sh}^h and HA^h are matrices formed based on grid data in the hth order harmonic loadflow [19]. However, by the iterative solution of the aforementioned set of equations in each of the studied orders, the harmonic loadflow results can be provided in a fast and effective process.

III. SOLUTION STRATEGY

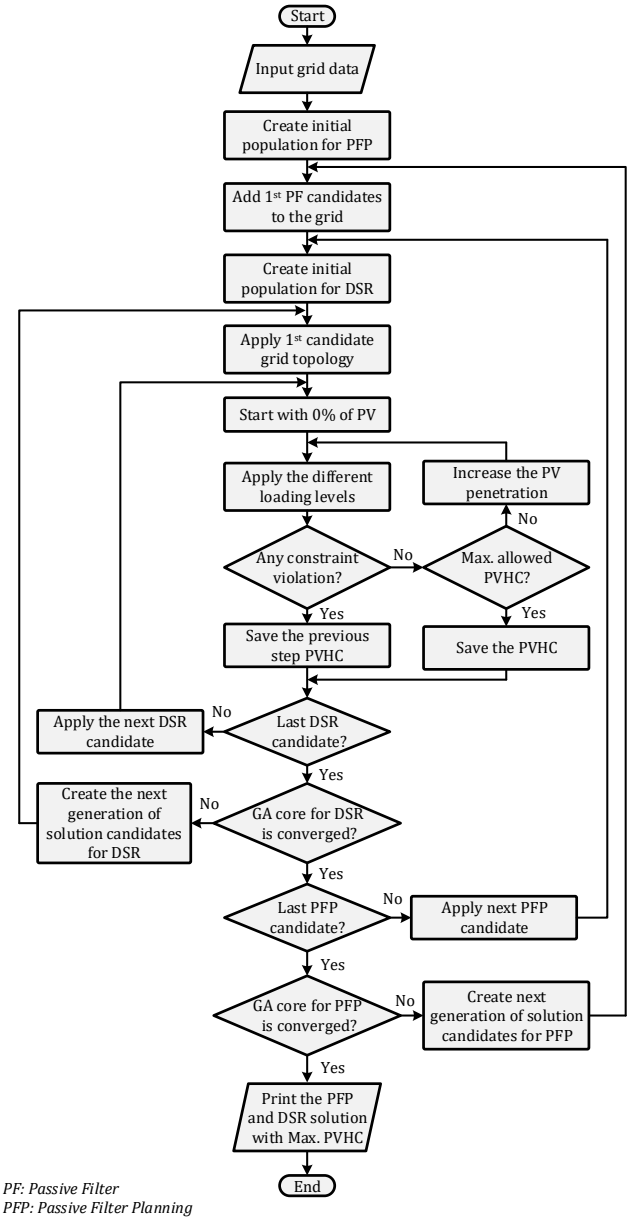
In this paper, the determination of the passive filter design and location and the grid topology is carried out by the use of two independent Genetic-Algorithm (GA) cores based on the strategy described in [10]. In this way, for each candidate solution of the passive filter planning problem, an optimization is carried out to find the optimal grid topology which effectively provides the objectives of the study.

The main flowchart of the proposed solution strategy is given in Fig. 1. As shown in the figure, when the initialization of the both GA-cores is completed, the 1st candidates of single-tuned passive filters and grid reconfiguration are implemented. Then the grid assessment is started without PV installation in the distribution network. If the grid is stabilized in all the loading conditions, the 1st step of the PV penetration is applied and the assessments are repeated for all loading levels. By increasing the PV penetration gradually, all the assessments are repeated until a constraint violation occurs in the grid. When a violation is monitored in a specified PV penetration, the previous level is regarded as the maximum PVHC allowed in presence of the studied passive filters and grid topology.

When all the candidate solutions for grid reconfiguration are examined, the GA operators are implemented to create the next set of candidates for the next GA iteration. Completing all the calculations of this core, another set of passive filters are selected and studied considering the optimization for the grid reconfiguration. When all the filter candidates are assessed, the new generations will be created by the GA-core and the solution strategy is continued until the optimal passive filters and grid topology with maximum PVHC are determined.

IV. SIMULATION RESULTS

In this section, the results of applying the described PVHC improvement strategy in a distribution network are presented. Accordingly in this paper, the 33 bus distribution system presented in [20] is implemented to test the applicability of the strategy in MATLAB. In order to study the grid in presence of harmonic distortions, half of the loads in each bus are modeled as a harmonic-injecting source and the spectrum table of a six-pulse converter given in [21] [22] is implemented. The harmonic injection by the PV unit is also modeled based on the data given in [23]. It should be noted that the harmonic data and all the studies are applied until 25th order of harmonic and the rest of the orders are neglected.



- PF: Passive Filter
- PFP: Passive Filter Planning
- DSR: Distribution System Reconfiguration

Fig. 1. Flowchart of the PVHC improvement strategy

Due to the implementation of harmonic studies in this paper (especially the use of total demand distortion), it is important to model the impedances of the transformer and the links to the infinite bus. As the standard data of 33 bus system does not contain these details of information, in this paper they are taken from the IEEE 18 bus system which is commonly implemented in harmonic-related studies [24]. Accordingly, it is assumed the IEEE 33 bus system is connected to the 138 kV grids through the 138/12.66kV transformer.

The single line diagram of the studied system is given in Fig. 2. It should be noted that the problem objective and constraints are calculated in the 33 bus system starting from the secondary of the transformer. In other words, the additional busses, line, transformer and the implemented short circuit capacity are integrated in order to provide more accurate harmonic-related results in the 33 bus system. However, as an exception, the Total Demand Distortion (TDD) is monitored on both terminals of the transformer as the potential PCCs.

As described before, the PV penetration is calculated with respect to the total demand in the main grid. However, in each penetration level, the PV capacity is distributed equally in all busses of the system. Furthermore, in presence of the equal PV capacity installed in all busses with respect to the penetration level, all the grid loads are applied from 50% to 110% of the nominal capacity in IEEE 33 bus system during 7 different scenarios with 10% step changes. It should be emphasized that the load-leveling is applied to the both linear and nonlinear loads of each bus. The simulation results for the base grid are given in the following subsection.

A. *Base grid*

The simulation results of the base grid without the filters and PV units are given in Fig.3 and Fig.4. It should be noted that these figures are provided through the assessment of the grid in all the defined load levels. As shown in these figures, there are violations in both voltage RMS values and harmonic distortion levels. Accordingly, there is no possibility for adding PV units to the distribution network. The summary of the grid assessment results is also provided in TABLE I.

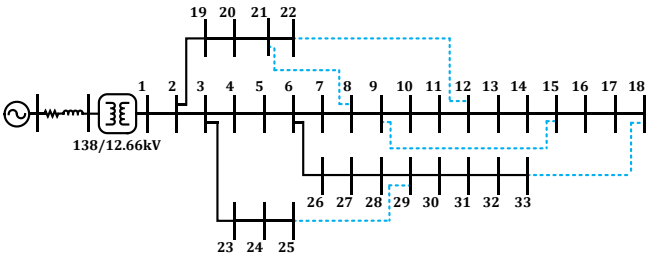


Fig. 2. Single line diagram of the studied grid

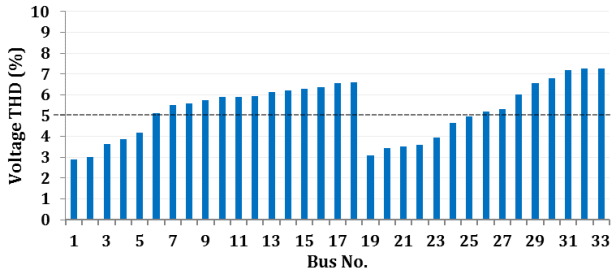


Fig. 3. Maximum voltage THD of the base grid without PV units

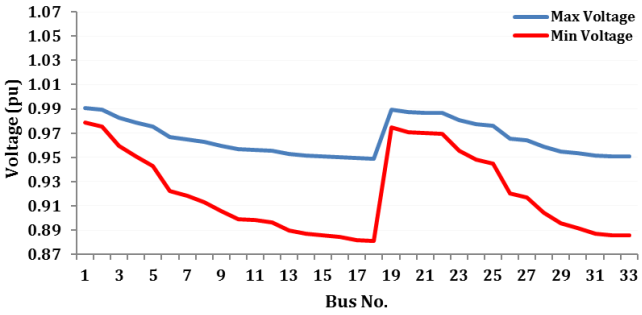


Fig. 4. Maximum and minimum voltage profile of the base grid without PV units

TABLE I. THE SUMMARY OF BASE GRID ASSESSMENT RESULTS CONSIDERING THE DIFFERENT LOADING SCENARIOS

Variable	Value
Max. voltage THD in the grid (%)	7.25
Max. voltage IHD in the grid (%)	4.29
Max. TDD in substation (%)	9.71
Max. grid total loss (kW)	264.6

B. *PVHC improvement strategy*

The results of applying the proposed strategy for PVHC improvement in the aforementioned distribution system are provided in this subsection. It should be noted that in this study, the voltage THD and IHD are constrained with 5% and 3% limits, respectively [25]. The RMS voltage of the grid busses are also maintained inside ±5% deviation limits around the nominal value (1.00 pu) [11].

The grid-topology which is selected using the proposed strategy is given by the definition of open-switches of the distribution network in TABLE II and its diagram is shown in Fig. 5. The tuning order of the selected filters and the reactive capacity of their capacitors are also given in TABLE III.

TABLE II. OPEN SWITCHES OF THE GRID WITH RESPECT TO THE AGGREGATE SOLUTION STRATEGY

Starting-bus	End-bus	Line status in base grid
8	21	Open
9	10	Closed
13	14	Closed
18	33	Open
28	29	Closed

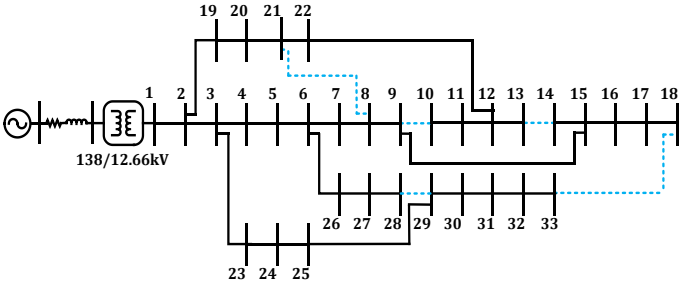


Fig 5. Demonstration of the selected grid topology with respect to the aggregate solution strategy

TABLE III. SPECIFICATION OF THE FILTERS SELECTED USING THE AGGREGATE SOLUTION STRATEGY FOR PVHC IMPROVEMENT

Bus No.	Filter Tuning Order	Q_c (kVAr)
7	4.7	1500
11	4.7	600
25	4.7	800
31	4.7	350
31	6.6	150

The simulation results of the distribution system considering the optimal grid topology and filters are given in Fig. 6 and Fig. 7 when no PV unit is installed in the network. The summary of the results is also provided in TABLE IV. As it is clear in the results, applying these supplementary actions has led to the successful stabilization of the grid which can provide the capability for hosting PV units even with high penetration levels.

According to the PVHC determination strategy, the PV penetration is gradually increased in presence of the passive filters until a constraint violation occurs in the new topology of the grid. According to the simulation results, in this system, 78% of PV penetration can be applied without any constraint violation. The assessment results in presence of these PVs installed in the grid are given in Fig. 8, Fig 9 and TABLE V. According to these results, while the grid constraints are maintained within the limits defined by the standard and the grid operator in all the loading scenarios, the solution strategy have provided 78% PV hosting capacity and a considerable decrease in the system total power loss.

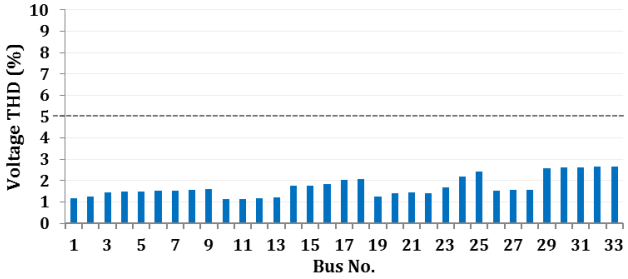


Fig. 6. Maximum voltage THD of the grid with new topology in presence of the filters and 0%-PV

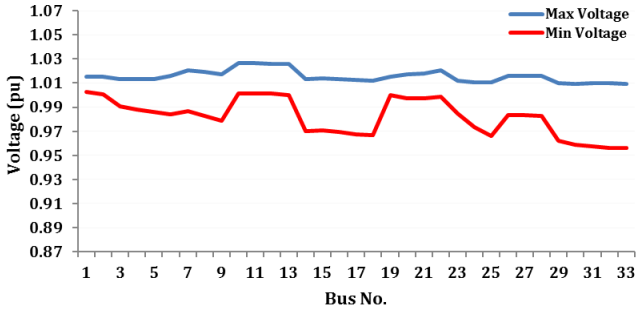


Fig. 7. Maximum and minimum voltage profile in the new grid topology in presence of the filters and 0%-PV

TABLE IV. THE RESULT SUMMARY OF THE NEW-TOPOLOGY OF GRID IN PRESENCE OF THE FILTERS AND 0%PV

Variable	Value
Max. voltage THD in the grid (%)	2.67
Max. voltage IHD in the grid (%)	1.32
Max. TDD in substation (%)	4.76
Max. grid total loss (kW)	140.4

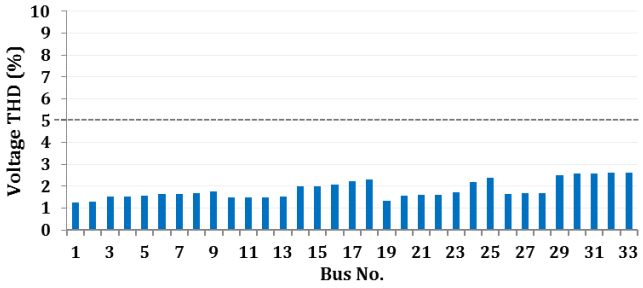


Fig. 8. Maximum voltage THD of the grid with new topology in presence of the filters and 78% PV penetration

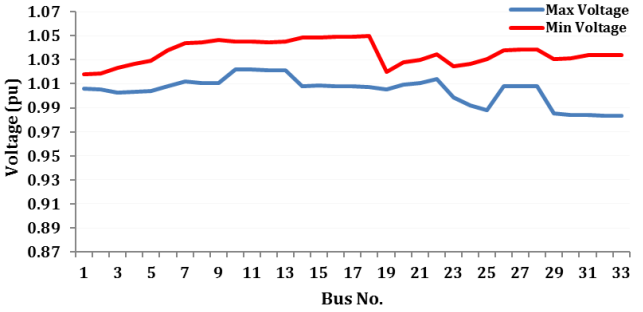


Fig. 9. Maximum and minimum voltage profile in the new topology of the grid with 78% PV penetration and the passive filters

TABLE V. THE ASSESSMENT SUMMARY OF THE GRID WITH NEW TOPOLOGY IN PRESENCE OF THE FILTERS AND 78% PV PENETRATION

Variable	Value
Max. voltage THD in the grid (%)	2.77
Max. voltage IHD in the grid (%)	1.78
Max. TDD in substation (%)	5.69
Max. grid total loss (kW)	63.2

V. CONCLUSION

In this paper, the potential of PV hosting capability enhancement using the planning of harmonic filters and modification of the grid configuration is addressed in distribution systems. Accordingly, a two-layer strategy for optimization of the single-tuned passive filters and grid topology is proposed for PVHC improvement in harmonic-polluted distribution networks. The proposed method is implemented in a modified distribution network and the results are discussed in presence of a high level of harmonic-injecting loads. The results given in the paper proved that the applied novel strategy can effectively provide 78% of PVHC in the distribution network while the grid specifications are maintained within the standard and operator-defined limits. However, further assessments of the solution strategy, the implementation of other types of filters and the detailed modeling of grid uncertainties are some of the supplementary studies which will be done on the topic in the future.

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