Hosting Capacity Enhancement Using Open-UPQC in LV Distribution Networks

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***Abstract*—The deviation of the demand levels of the modern LV distribution systems due to the more loads and distributed generations connected in the same grid leads to the loss of acceptable quality of voltage. These voltage quality problems occur in case of the high difference between the power of the loads and distributed generations in the same area. Accordingly, the high loading conditions lead to the bus voltage decrease while the bus voltage increment occurs in scenarios with the excess of generation. In this condition, the successful voltage stabilization in MV/LV substation can effectively suppress the deviations of the grid voltage values and increase the hosting capacity of the network. There are different custom power devices introduced in the literature which can provide the stabilization of voltage in the grids. In this paper, among the available tools, the application of Open-UPQC is examined in hosting capacity improvement maintaining a desired power quality level; this capability is provided through the successful voltage regulation in the different probable high/low loading scenarios in the grid. According to the results, while the uncoordinated operation of the series and shunt devices does not have the capability of stabilization of the base grid, the Open-UPQC has successfully maintained the voltage profile inside the limits in both the base case and in the presence of high load and PV penetration levels. It should be emphasized that the services of the Open-UPQC are provided in an economical and effective way making the solution strategy applicable in real-world cases.**

Keywords—hosting capacity, voltage stabilization, Open-UPQC, PV.

I. INTRODUCTION

The policies towards emission-neutral electrical grids have led to the high penetration of Distributed Generators (DGs) like PV units in many LV electrical distribution systems worldwide [1]–[4]. However, this condition must be managed carefully to maintain an acceptable quality of voltage and guarantee the safe operation of these energy systems [5]–[8]. Accordingly, while electrical energy with a higher level of quality will be requested by the customers of active distribution systems in the future, the unfavorable effects of the PV units on the grid in critical cases should be investigated by the Distribution System Operators (DSO) [9]–[12]. Furthermore, while an LV distribution network faces technical problems like voltage sag and swell in some customer points, the integration of the PVs and higher load levels will be strongly limited without successful voltage stabilization strategies. Accordingly, the quality of power should be comprehensively studied and monitored by DSOs during the implementation of the high renewable energy penetration [13]–[15].

Regarding the published studies, there are different strategies applied by the researchers for voltage profile stabilization and power quality improvement in distribution networks [16]–[21]. Accordingly, the definition and implementations of different FACTS and Custom Power Devices (CPDs) are carried out in the published papers [22]–[24]. As an applicable and low-cost solution for voltage stabilization in LV distribution networks, Dynamic Voltage Conditioner (DVC) is examined in [25], [26]. Regarding the provided results in the studied grid, the device is capable of stabilizing the voltage for the whole year.

However, the capacity of the series-connected compensators affects their capability in substation voltage stabilization. In other words, for the cases with more severe low/high voltage scenarios, the series-connected compensators may not have the capability for fixing the voltage at the desired value in the substation of the LV distribution system. Accordingly, Open-UPQC, made by a series unit and different shunt ones, has been developed by researchers to deal with these more severe voltage stabilization problems in the LV distribution networks [27].

In this paper, the capability of Open-UPQC in the improvement of voltage profile and grid hosting capacity has been investigated in an LV distribution network. In order to assess the effect of this device in detail, the series unit only (Case A), the shunt units only (Case B), both series and shunt units without (Case C), and with (Case D) coordination between them are applied to the same grid with the same yearly data. Considering the capacity limit of each device the results are compared and discussed.

The rest of the paper is organized as follows. The strategies applied for voltage improvement and hosting capacity enhancement are described in Section II. The studied network and the simulation results are given in Section III. A discussion of the results is provided in Section IV. The paper is finally concluded in Section V.

II. VOLTAGE PROFILE IMPROVEMENT AND HOSTING CAPACITY ENHANCEMENT STRATEGIES

The diagram of an Open-UPQC installed in an LV network is illustrated in Fig. 1. As depicted in the figure, this device includes a series unit connected in the MV/LV substation and a number of shunt elements located close to the load points in the LV grid. These shunt units can be managed to cooperate with the series unit to provide the maximum PQ-improvement capability in the distribution systems. In other words, when the series unit of Open-UPQC faces its limitations in the PQ-improvement, the shunt devices are asked through a communication system to participate in providing the service in the network.

However, in this paper, the capability of series and shunt units is investigated through different scenarios of independent application and/or cooperation. These scenarios are described in the following subsections.

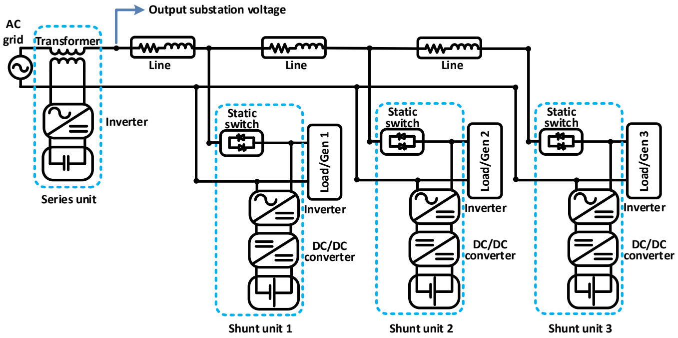

Fig. 1. The structure of an Open-UPQC in an LV network [28]

A. Case A: Series unit of Open-UPQC

As the first candidate strategy for voltage profile improvement and hosting capacity enhancement, the series unit of Open-UPQC is added to the grid independently without considering any shunt unit in the grid. It should be emphasized that in this study, the series unit is meant to operate with the quadrature voltage injection method which requires only reactive power [18]; furthermore, the capacity limitation of the series unit is also taken into account. Accordingly, the upper and lower boundaries of compensable voltage values in the substation are considered. The highest voltage that can be stabilized in the MV/LV substation using the series unit of Open-UPQC applying the pure reactive strategy is calculated by (1) [29], [30].

$$V_{s,up} = \sqrt{\left|V_{PCC,ref} \cdot sin(\gamma) + V_{x,max}\right|^2 + \left|V_{PCC,ref} \cdot cos(\gamma)\right|^2} \qquad (1)$$

in which $V_{s,up}$ is the maximum compensable voltage, $V_{x,max}$ is the maximum voltage of the series unit converter, $V_{PCC,ref}$ is the reference voltage, and γ is the load angle. On the other hand, for the minimum voltage that can be stabilized by the series unit applying the pure reactive power, two different equations should be considered which are given in (2) and (3).

$$V_{s,down,a} = \sqrt{\left|V_{PCC,ref} \cdot \sin(\gamma) - V_{x,max}\right|^2 + \left|V_{PCC,ref} \cdot \cos(\gamma)\right|^2} \qquad (2)$$

$$V_{s,down,b} = \left|V_{PCC,ref} \cdot \cos(\gamma)\right| \qquad (3)$$

Accordingly, the lowest voltage in the substation that can be compensated to the reference value is calculated using (4).

$$V_{s,down} = \begin{cases} V_{s,down,a} & V_{x,max} < V_{PCC,ref} \cdot \sin(\gamma) \\ V_{s,down,b} & V_{x,max} \geq V_{PCC,ref} \cdot \sin(\gamma) \end{cases} \qquad (4)$$

However, in the case that the substation voltage is out of the specified limits, the reference of the series unit is modified regarding the flowchart given in Fig. 2. It should be noted that the strategies stated in the flowchart for updating the reference voltage are comprehensively described in [29].

B. Case B: Shunt unit of Open-UPQC

As the second strategy, in this paper, the customers are considered to be equipped with the shunt units without any series unit installed in the substation. These shunt units only compensate the reactive power of the local load; in other words, in this case, it is considered that they do not receive any external command from a central controller.

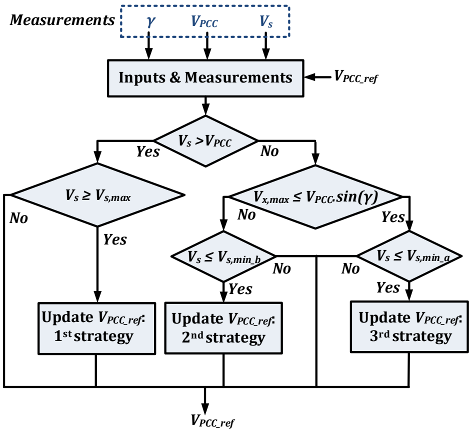

Fig. 2. Flowchart of updating the reference voltage of the series unit regarding the limit of the nominal capacity of the device [29]

C. Case C: Series and shunt units of Open-UPQC without coordination

As the third case, in this paper, both series and shunt units are added to the grid with no coordination between them. In other words, this case is the combination of the strategies described for Case A and Case B. Accordingly, while the shunt units compensate the reactive power of the local load, the series unit fixes the voltage in the substation on the reference voltage. However, in the case that the voltage in the substation is out of the limits of the series unit, the reference is updated following the flowchart given in Fig. 2.

D. Case D: Open-UPQC

As the final strategy, the application of the Open-UPQC in the improvement of voltage profile and hosting capacity is examined in this paper. Comparing to Case C, the series and shunt units collaborate in the Open-UPQC scheme to increase the capability of the series unit for fixing the voltage in the substation. In other words, in this case, when the voltage in the substation is out of the limit specified by (1)-(4), the reference voltage of the series unit does not change; instead, the shunt units are asked through the communication line to inject the reactive power to provide the possibility of fixing the voltage of the substation in the desired reference value.

The target reactive power for fixing the voltage of the substation is calculated using (5).

$$Q_{target} = V_{PCC,ref} \cdot I_L \cdot \sin(\gamma_{ref}) \qquad (5)$$

in which I_L is the current in the substation; furthermore, the formulation for calculating $\sin(\gamma_{ref})$ has been given in [30] and provided in (6) and (7) for the case of overvoltage and undervoltage compensation cases, respectively.

$$\sin(\gamma_{ref}) = \frac{\left|V_{s,max}^2 - V_{x,max}^2 - V_{PCC,ref}^2\right|}{2 \cdot V_{x,max} \cdot V_{PCC,ref}} \cdot sign(\gamma) \qquad (6)$$

$$\sin(\gamma_{ref}) = \begin{cases} \dfrac{\left|V_{s,min}^2 - V_{x,max}^2 - V_{PCC,ref}^2\right|}{2 \cdot V_{x,max} \cdot V_{PCC,ref}} \cdot sign(\gamma) & V_{s,down} = V_{s,down,a} \\ \sqrt{1 - \left(\dfrac{V_{s,min}}{V_{PCC,ref}}\right)^2} \cdot sign(\gamma) & V_{s,down} = V_{s,down,b} \end{cases} \qquad (7)$$

According to [30], in the next step, the reference reactive power regarding the target one provided by (5) and the existing reactive power can be calculated by (8).

$$Q_{T\_ref} = Q_{target} - Q_{LVnet} \quad (8)$$

in which Q_{LVnet} is the reactive power of the grid calculated using (9).

$$Q_{LVnet} = V_{PCC} \cdot I_L \cdot \sin(\gamma) \quad (9)$$

in which γ is the network power angle and V_{PCC} is considered the same with $V_{PCC,ref}$ in the steady state study. However, it should be taken into account that the shunt units compensate the local load in normal operation when no command is received from the series unit. Hence, when a high share of the loads is equipped with the shunt units, Q_{LVnet} is relatively low if no command is received from the central controller.

III. SIMULATION RESULTS

In this section, the effect of the implementation of the candidate strategies given in Section II are investigated in an LV distribution grid. The diagram of the network is illustrated in Fig. 1. A nominal power of 125 kVAr is also applied to the study for the per-unit calculations. Previous studies on the grid are given in [25], [26]; however, in this study, new pre-assessments are applied to the available yearly data to extract the appropriate parts of measurement and ensure the correct integration of the data. It should also be emphasized that the busses of the real network of Fig. 1 include loads and generation units. Moreover, for the current study, in the cases that shunt units exist, it is assumed that all customer points are equipped with the shunt unit as well. In other words, when the shunt units work as a local compensating mode with no command received from the central controller, the reactive power of the busses is set to zero in the study.

A. Voltage Profile Improvement (VPI)

In this subsection, voltage assessment results are given regarding the data of the existing grid with and without the voltage stabilization strategies.

1) VPI-Base-Case (no series or shunt units)

The voltage assessment result in the whole busses of the grid in the whole year is given in TABLE I. Regarding, the grid has been working with no problem for the whole year without any voltage-stabilizing device; however, the lower boundary of monitored voltage is close to the standard limit. Altogether, voltage stabilizing strategies are examined to bring an improved level of power quality for the customers as well as preparing the grid for hosting more loads and generation units.

TABLE I. VOLTAGE ASSESSMENT RESULT IN THE VPI-BASE-CASE

Parameter	Value
Output substation voltage range (V)	210.9 – 243.3
Load voltage range (V)	209.7 – 244.6

2) VPI-Case-A

In the next step, the series unit of Open-UPQC is added to the grid and the studies are repeated for the whole year. The reference voltage of the series unit is fixed to 230V in normal conditions of all cases of the paper. It should be re-emphasized that in this paper, the capacity limitation of the series unit is considered regarding the device data provided in [25]; hence the reference voltage updating regarding the flowchart of Fig. 2 is also implemented.

The voltage assessment results, in this case, are provided in TABLE II. Comparing TABLE I and TABLE II, the series unit has improved the quality of voltage however, due to the limit of the capacity of the unit, the device has worked with lower reference voltage values in some cases during the year.

TABLE II. VOLTAGE ASSESSMENT RESULTS IN THE PRESENCE OF THE SERIES UNIT OF OPEN-UPQC: VPI-CASE-A

Parameter	Value
Output substation voltage range (V)	213.5 – 230.0
Load voltage range (V)	211.7 – 233.6

3) VPI-Case-B

In this case, the series unit is ignored, and shunt units are considered in the customer points compensating the local reactive power; the whole yearly assessments are repeated in this case and the results are given in TABLE III.

TABLE III. VOLTAGE ASSESSMENT RESULTS IN THE PRESENCE OF THE SHUNT UNITS OF OPEN-UPQC: VPI-CASE-B

Parameter	Value
Output substation voltage range (V)	210.9 – 243.3
Load voltage range (V)	210.2 – 245.0

Comparing TABLE I and TABLE III, while the shunt unit has no effect on the voltage of the substation (same results of the VPI-Base-Case), it has provided almost no improvement in the voltage profile of the grid as well. It should be noted that these kinds of shunt-connected devices such as STATCOM are used for voltage regulation in power systems when they are installed at substations and/or medium and high voltage levels (as FACTS); this is however out of the scope of this paper focusing on LV network and shunt units are connected close to the load connection point.

4) VPI-Case-C

As the next step, the effect of the combination of the series and shunt units on the voltage profile of the grid is investigated in this subsection. Accordingly in the presence of the shunt unit compensating the local reactive power, the series unit fixes the voltage at the desired reference value or the updated one regarding the flowchart of Fig. 2. The grid voltage assessment result in this case is provided in TABLE IV.

Comparing TABLE II and TABLE IV, it is obvious that the presence of uncoordinated shunt units does not provide a positive effect on the capability of the series unit for voltage quality improvement; in other words, the minimum voltage monitored in the grid in the whole year in a case including a series unit with no shunt unit is even better than the case where the shunt units are added. This is due to the reactive power compensation of the loads by the shunt units; however, it is an important point that proves the necessity of the coordination between the shunt and the series unit for voltage stabilization.

TABLE IV. VOLTAGE ASSESSMENT RESULTS IN THE CASE OF COMBINATIONAL USE OF THE SERIES AND SHUNT UNITS: VPI-CASE-C

Parameter	Value
Output substation voltage range (V)	210.9 – 230.0
Load voltage range (V)	210.2 – 234.0

5) VPI-Case-D

In the final step, Open-UPQC is applied to the grid and the assessments are repeated. The summary of the grid assessment results in this case is given in TABLE V.

TABLE V. VOLTAGE ASSESSMENT RESULTS IN THE PRESENCE OF OPEN-UPQC: VPI-CASE-D

Parameter	Value
Output substation voltage range (V)	210.9 – 230.0
Load voltage range (V)	220.0 – 234.0

As given in the results, Open-UPQC successfully improved the voltage profile of the grid with the aid of the coordination between the series and the shunt units. Accordingly, the minimum voltage of the busses in the whole year is increased from 209.7 in the base grid to 220.0 in the presence of Open-UPQC. The maximum reactive power requested by the series unit in the whole year is 0.07 p.u.; however, it should be emphasized that this value is calculated while the shunt units are compensating their local reactive power. In other words, part of this reactive power may be provided only by decreasing the level of local compensation. Accordingly, the need for shunt unit capacity can also be less than this value.

B. *Hosting Capacity Enhancement (HCE)*

In the next step, the yearly loading/generation profile is gradually increased, and the assessments are repeated for the whole year to investigate the hosting capacity improvement by each of the strategies. It should be noted that in this paper, increasing the load/generation profile is applied with the steps of 10%. In this way, for each step of increasing the load and generation profiles, if the voltage or current values are out of the standard limits or the nominal installed capacity even for one sample during the whole year, the previous step is considered the highest possible hosting capacity of the grid. The simulation results for each of these cases are provided in the following subsections.

1) *HCE-Base-Case (no series or shunt units)*

The hosting capacity assessment result in the Base-Case with no shunt or series units is given in TABLE VI. Regarding the results, the maximum hosting capacity of the grid with no voltage stabilization strategy is less than 50%. In other words, less than half the installed feeder capacity can be applied for hosting the loads and generation units. It can be seen that in this condition, the bus voltage range reaches the standard limits. Accordingly, improving the voltage profile can provide the possibility of hosting more prosumers in the network.

TABLE VI. HOSTING CAPACITY ASSESSMENT IN THE HCE-BASE-CASE

Parameter	Value
Maximum load multiplier	1.5
Maximum feeder hosting capacity (%)	49.8
Maximum feeder current (A)	271.7
Load voltage range (V)	207.0 – 245.6

2) *HCE-Case-A*

The hosting capacity assessment results applying only the series unit of Open-UPQC are given in TABLE VII. It should be re-emphasized that the capacity limit of the series unit is also taken into account in this study.

TABLE VII. HOSTING CAPACITY ASSESSMENT IN THE PRESENCE OF THE SERIES UNIT OF OPEN-UPQC: HCE-CASE-A

Parameter	Value
Maximum load multiplier	1.6
Maximum feeder hosting capacity (%)	53.1
Maximum feeder current (A)	289.4
Load voltage range (V)	207.5 – 235.7

Regarding the results, the series unit has provided a little improvement in the maximum feeder hosting capacity. However, it is still around 53% which could be not enough for the grid operator considering the thermal limit of the feeder and the high loads and PVs penetration.

3) *HCE-Case-B*

The hosting capacity assessment applying only the shunt units is given in TABLE VIII. Comparing the results of this case with the HCE-Base-Case (no shunt or series units), the presence of shunt units has no effect on the hosting capacity of the grid; in this case, the maximum feeder hosting capacity is around 50%, with a similar maximum multiplier (e.g. 1.5).

TABLE VIII. HOSTING CAPACITY ASSESSMENT APPLYING SHUNT UNIT OF OPEN-UPQC: HCE-CASE-B

Parameter	Value
Maximum load multiplier	1.5
Maximum feeder hosting capacity (%)	49.7%
Maximum feeder current (A)	270.7
Load voltage range (V)	207.6 – 246.2

4) *HCE-Case-C*

Hosting capacity assessment results in the presence of uncoordinated series and shunt units are provided in TABLE IX. Similar to the previous cases, the capacity limit of the series unit is also taken into account. According to the results, the presence of the series and shunt units without coordination does not affect on the maximum feeder hosting capacity which is around 50%, with the same maximum multiplier (e.g. 1.5).

TABLE IX. HOSTING CAPACITY ASSESSMENT APPLYING SERIES AND SHUNT UNIT OF OPEN-UPQC: HCE-CASE-C

Parameter	Value
Maximum load multiplier	1.5
Maximum feeder hosting capacity (%)	49.6%
Maximum feeder current (A)	270.6
Load voltage range (V)	207.8 – 235.9

5) *HCE-Case D*

Finally, the hosting capacity assessment results in the presence of Open-UPQC are provided in TABLE X.

TABLE X. HOSTING CAPACITY ASSESSMENT IN THE PRESENCE OF OPEN-UPQC: HCE-CASE-D

Parameter	Value
Maximum load multiplier	2.1
Maximum feeder hosting capacity (%)	70.6%
Maximum feeder current (A)	384.9
Load voltage range (V)	207.9 – 238.2

Regarding the results given in TABLE X, in the presence of Open-UPQC, a considerable improvement is provided in the hosting capacity of the grid. Accordingly, the maximum load multiplier is 2.1 and more than 70% of the installed feeder capacity can be applied for hosting the load and generation units. The maximum reactive power requested by the series unit during the whole year in this case is 0.14 p.u; however, it should be re-emphasized that the reactive power is calculated while the shunt units are locally compensating the reactive power. Accordingly, a part of the requested reactive power may be provided with only decreasing the level of local compensation; however, in the case that there is no local reactive load, or it is less than the requested one, extra shunt unit capacity is needed to provide the possibility of voltage stabilization at the desired reference value.

IV. DISCUSSION

A summary of the simulation results for voltage stabilization and hosting capacity improvement are provided in Fig. 3 and Fig. 4. Altogether, according to the assessment results, although the presence of only the series unit can improve the voltage quality of the network, it cannot have a considerable effect on the hosting capability of the grid when the nominal capacity of the device is taken into account. Furthermore, the effect of the presence of only shunt units on voltage quality and hosting capacity is very limited when those are connected close to the load. In the case of adding the shunt units in the presence of the series unit, the hosting capacity is even less than in the case of having only the series unit. On the other hand, by the establishment of the coordination between the series and shunt unit, Open-UPQC can successfully improve the voltage quality and hosting capacity of the grid which leads to the optimum utilization of series and shunt devices.

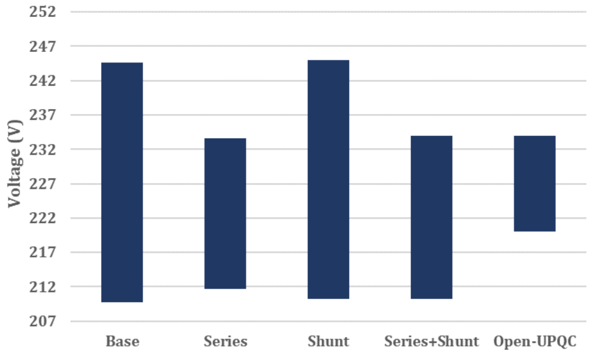

Fig. 3. Summary of VPI assessments

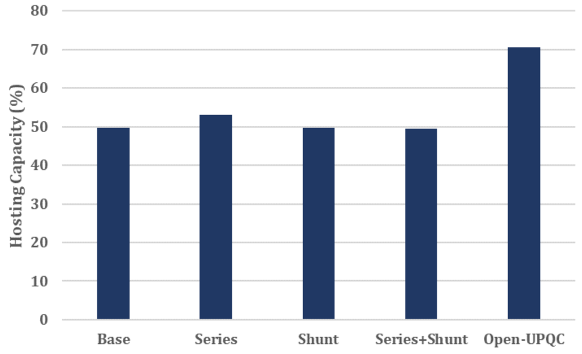

Fig. 4. Summary of HCE assessments

However, regarding the results, the voltage drop in the grid is often the bottleneck of improving voltage quality and hosting capacity while the upper boundary of the standard limit is far to reach even with the high value of load/generation multipliers. For the case of the series unit, it is clear that increasing the capacity of the device can improve its capability for the voltage adjustment on the reference value in a higher range of loading and substation voltage however, it will considerably increase the cost of the unit. Moreover, dynamic adjustment of the reference of the series unit based on the loading condition can also improve the capability of the device for voltage stabilization which is out of the scope of the current study.

Even in the case of Open-UPQC, although both the power quality and hosting capacity have been successfully improved, the low value of voltage observed in some cases during the year prevents the grid from reaching high hosting capacity values. Part of the low voltage values observed in the presence of Open-UPQC during the whole year is due to the request of inductive power by the series unit in the case of observing even a very low reactive power in the substation. Accordingly, for very low angles of the current in the substation indicating inductive power, the series unit requests more inductive power to increase the capability of voltage adjustment. In this way, although the voltage is fixed on the reference value in the substation, the higher inductive power flowing in the feeder leads to a higher drop in the voltage. Accordingly, by a modification to the control theory for requesting capacitive power in the case of low inductive loads, there can be an improvement in the capability of the unit for voltage quality improvement and hosting capacity enhancement; this modification will be applied in the future study of the authors.

V. CONCLUSION

In this paper, the effect of Open-UPQC on Voltage Profile Improvement (VPI) and Hosting Capacity Enhancement (HCE) in LV distribution grids has been assessed. In order to clarify the effect of Open-UPQC, the studies are also repeated in the presence of series or shunt units whether independently or as a joint scenario with no coordination. According to the results, the use of the shunt or the series unit can provide no considerable improvement in the VPI and HCE especially when the limitation of the capacity of the series unit is considered, as in the case under study. On the contrary, by applying coordination between all the units, Open-UPQC successfully improves the VPI and HCE of the grid. According to the results in the studied network, in the presence of Open-UPQC, the HCE becomes more than 70% of the installed feeder thermal capacity while it was less than 50% without this device; this means that the coordination of all the units can successfully improve both VPI and HCE considerably. So, it is possible to observe that the device can provide the possibility of having 40% more loads and generation units compared to the Base-Case or in the presence of series, shunt, or combinational series and shunt devices with no coordination.

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