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Study of Voltage Stability in a Distribution Network by Integrating Distributed Energy Resources into a Virtual Power Plant

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Abstract

In this paper, voltage stability in a distribution network is studied by integrating distributed energy resources (DER) as distributed generation and compensating elements, into a Virtual Power Plant for a distribution level (DVPP). Integration into a DVPP arises from the need to counter the various problems that DERS represents, due to different factors such as its dependence on climatic conditions, which are difficult to predict. A distribution network with industrial loads and distributed generation is considered, being fed by a power system IEEE - 9 nodes

Keywords: DER, STABILITY VOLTAGE, VPP

1 Introduction

The penetration of Distributed Energy Resources (DER, for short) in distribution networks is rapidly growing worldwide due to different factors, such as: a reduction of the environmental impact, energetic efficiency and the energetic market's tendency to change regulatory policies, searching for a continuous process of self-liberation [1], [2].

The DER represent various challenges to consider:

- Intermittent nature of renewable energies: Most of the distributed energy resources are renewable, which causes intermittences in their generation processes depending on the climatic conditions, therefore hindering the management of the generation and provoking technical and economic difficulties [1].
- Network topology: Most distribution networks have a radial topology, which is why they can be overall affected by different scenarios related to the main supply system (disconnection of supply lines) and changes on the network's own conditions[3]. Such effects on the network can become more notorious when implementing the DER on different points of the system.

When combining the intermittent nature of the DER and the network topology with the normal behavior of the distribution system and different perturbations (Load Variations), voltage stability problems can arise or even worsen if present beforehand [4].

As an alternative solution to counter the impact of DER on voltage stability, the concept of Virtual Power Plant (VPP) is introduced [3]. The VPP base their functioning on energetic management techniques as a response to the demand, energetic self-consumption and integration of the energy resources distributed within a network for their functioning as a single power station [5]. Since the study will be limited to the integration of DER into a distribution network, a DVPP (Distribution Virtual Power Plant) will be used. Based on the previous arguments, a question arises: how to integrate into a DVPP the distributed energy resources of a distribution network interconnected to a transmission system, aiming at improving the voltage stability during load and topology variations?

2 Theoretical Framework

Currently, the competitiveness in the generation of energy through renewable resources has reached historic levels. Despite the formulation of weak and inconsistent economic policies, the renewable energies have managed to satisfy 19% of the global energetic demand for the 2013-2014 timeframe [6],[7] For the first time, photovoltaic solar energy reached higher levels than wind power in 2014; surpassing 40 GW as estimated in 2014 [6].

However, DER and renewable energies' main drawback is the difficulty to manage them efficiently, which can make them competitive and visible on the energy market [1], [8].

The difficulty of managing such renewable energy resources lies in the following aspects [1]:

- Market participation: Smaller power stations based on renewable energies are often forbidden to participate on the current energy market.
- Intermittent nature: It is possibly the most complicated of the aspects because technologies such as photovoltaic solar panels depend on environmental factors such as solar radiation intensity.
- Independent and non-cooperative functioning of the DER unities belonging to a network, obstructing their control and exploitation.

Voltage stability

From the technical standpoint, instability in voltage is evidenced when the system bars have voltages outside of the limits allowed by regulation.
It is important to understand that voltage stability must be guaranteed during normal operation conditions and after the network is subjected to perturbations [4]. One of those perturbations are variations in load or generation [4].
When distributed-generation DER units are used with renewable energies, these show continuous fluctuations in their production that evidently may affect the system's stability. One simple form of analyzing the voltage stability is through PV curves. Through these curves, the stability limit can be determined and its construction requires no additional elements into the system [4].
For each curve, there is a stability limit, indicated by the dotted line. Below that line are the points within the instability region, where an increase in the active power requested on a node does not cause a voltage drop. In contrast, the zone located above the dotted line is the stability region since injecting more active power leads to a voltage drop. The power factor has a direct relationship with a higher stability limit, as Figure 1 evidences.

Mechanisms to integrate DER: Virtual Power Plants

In [13], the use of micro-networks is proposed for the integration of renewable energies. A micro-network can be defined as a network able to integrate efficiently the actions and behaviors of generators and consumers, plus agents that can perform both roles. Searching for technical, environmental and economic efficiency, micro-networks and virtual power plants are presented as identical concepts [9], [10]. However, in [11] the differences between both concepts are clarified:

- One of the approaches of micro-networks is the island operation but it is not recommended that the VPP operates under this contingency.
- Micro-networks require storage systems, although VPP can be conceived without them.
- Micro-networks are functional for DER located in limited geographical areas, whereas VPP can integrate DER that are widely dispersed geographical areas.
- Micro-networks are normally commercialized on energy market retailers. VPP may participate on wholesale markets.

Therefore, it is recommended to study the alternatives that allow the integration of DER overcoming the limitations of micro-networks.
The concept of VPP is still a case study, hence it does not have a standardized definition on the scientific literature. The different definitions of VPP are found on several works developed since 2011 up to 2016 [1], [11], [12], [13]. It is noteworthy to mention that the first definitions of VPP (2008) considered it as an integration mechanism equivalent to a micro-network. However, as investigation has moved forward on both micro-networks and VPP, the differences between them have been identified. For instance, it is postulated that the focus of micro-networks lies in allowing an island operation in portions of the electrical system on small areas; in opposition to the VPP that allow the integration of DER on larger geographical areas [11]. Lastly, since the year 2012, the concept of VPP seeks to center its efforts on allowing renewable energies to participate on a wholesale electric market.

Colombian Regulation Context

In Colombia, the main entities in charge of the normativity and regulation on energy are the CREG (Commission for the Regulation of Energy and Gas) and the Ministry of Mines and Energy. Circumscribed to that ministry is the UPME (in Spanish, Unity of Mining and Energy Planning).
In terms of renewable energies and DER, the main normative is in the law 1715 of May the 13th of 2014, that poses the integration of non-conventional renewable energies into the national energy system and whose regulation revolves around the Decree 2143 of 2015. In 2016, the UPME published the Resolution 045 of February the 3rd of 2016.
Since the optimal use of DER and the regulation of renewable energies in Colombia focuses, among other things, on energetic efficiency, it is important to mention the norm ISO 5001 and the NTC 5001 which is the normativity related to this field.
It is important to keep in mind the reactive flux, since this is a prepondering factor when analyzing the voltage on a system. The corresponding normativity to reactive power and power factor is equal o greater than 0,9 in Colombia.
Regulation NTC 1340 defines a mid-level voltage (between 1kV and 62 kV), a maximum nominal voltage of +5% and a minimum of -10%. Having the definitions of maximum and minimum voltage as the maximum effective value that occurs under normal operating conditions in any point of the system at any moment [2].
In [2], normalized indices are proposed to evaluate the voltage regulation of a distribution network as:

$$I_V = \frac{V_{nodo} - V_{min}}{V_{max} - V_{min}} \quad (1)$$

In[2], the sub-index benefit is used to evaluate the impact of the generation distributed based on the concept of percentage. In this manner, the benefit of an action in a study can be quantified through the variation of any indicator or value.

$$I_{BENEFICIO} = \frac{I_1 - I_2}{I_1} * 100 \quad (2)$$

These two variables will be used to evaluate the voltage stability on the testing network for the proposed simulation scenarios.

3 Testing network and simulation scenarios

The network used for testing will be a distribution network, dimensioned with CODENSA normativity. The network includes MT conductors of different calibers according to network operator criteria, distribution transformers and 26 nodes, 10 of them have a load. Additionally, the three nodes with the higher load have photovoltaic solar panels as distributed generation units.
The supply of a distribution network is done through a power substation. However, for simplicity, the supply substations have an infinite node. For this project, the substation will not be modeled as an infinite node but instead as a node fed by a power system (IEEE 9-node). This can be explained by the fact that most of the distribution networks have a radial topology and the variation of the topology in such systems would be reflected in system portions without service. Therefore, topology variations will be performed on the system that feeds the testing network's main substation, i.e., one of the lines of the IEEE 9-node system that feeds the node interconnected to the distribution network's substation will be disconnected (LINE 5 and LINE 6).

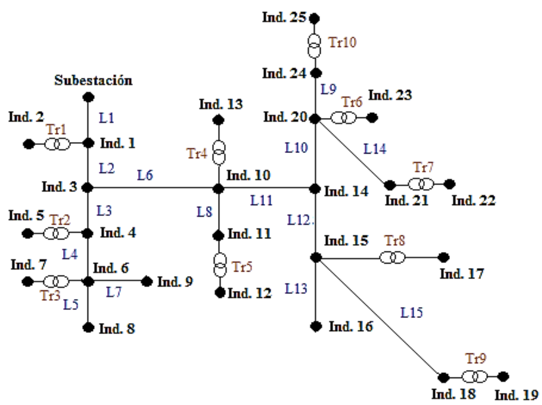


Figure 5. Distribution network used.

Figure 5 corresponds to the used distribution network. All nodes have the characteristic consumption of an industrial load curve. These loads present the highest consumption at 16 hours, the lowest one at 05 hours and the average consumption at 09 hours.

The elements that constitute the network (loads, transformers, lines) are described in Tables 2 to 4. According to the selected calibers, the electric parameters can be reviewed in the CODENSA S.A. documentation.

Table 2. Circuit loads.

Ind.	Load	kW	kVAR	PF
2	Load 1	240,00	180,00	0,80
5	Load 2	75,65	38,75	0,90
7	Load 3	32,00	24,00	0,80
13	Load 4	259,96	65,15	0,97
12	Load 5	275,40	199,39	0,81
25	Load 6	95,70	54,24	0,87
23	Load 7	49,68	21,16	0,92
22	Load 8	284,49	161,23	0,87
17	Load 9	186,00	73,51	0,93
19	Load 10	53,40	27,36	0,90

Table 3. Circuit transformers.

Name	Power (kVA)	Primary (kV)	Secondary(kV)
Tr1	500	11,4	0,208
Tr2	112,5	11,4	0,208
Tr3	45	11,4	0,22
Tr4	300	11,4	0,44
Tr5	400	11,4	0,208
Tr6	75	11,4	0,208
Tr7	300	11,4	0,44
Tr8	225	11,4	0,22
Tr9	75	11,4	0,208
Tr10	112,5	11,4	0,208

Table 4. Circuit lines.

Name	L1	L2	L3	L4	L5	L6	L7	L8	L9	L10	L11	L12	L13	L14	L15
Length [km]	2,00	1,00	0,76	0,43	0,16	1,30	0,25	0,13	0,36	0,62	0,26	0,12	0,10	0,24	0,57
Caliber [AWG]	1/0	1/0	1/0	1/0	1/0	1/0	1/0	2	2	2	1/0	2	2	2	2

The distribution has distributed generation on the industrial nodes 2, 22 and 12. The installed power of each generator is 68 kW, 50 kW and 7 kW respectively. However, this generation depends on the irradiation value that affects the generators and their temperature. Each generator's power generation must be determined based on the analyzed demand hours. With history data provided by the IDEAM and Montecarlo simulations the possible irradiation and temperature values were determined on each demand hour. With these values, the power generation of each generator is established under those weather circumstances. The results are presented on Table 5 (all generators have a unitary power factor). To be able to determine these values, a solar panel characteristics are: 315 MW peak power, 64,6 V open circuit voltage, 54,7 V voltage at maximum power, 5,76 A maximum power current. Table 6 represents the simulation scenarios where the network will be analyzed.

Table 5. DG Information.

Hour	**Irradiation [W/m2]**	**Temperature [°C]**	**Generator 1 [kW]**	**Generator 2 [kW]**	**Generator 3 [kW]**
9	400,4	15	26,98	19,86	2,87
16	387	20	25,62	18,86	2,72

Table 6. Simulation scenarios and their respective events.

Scenario	**LINE 6**	**LINE 5**	**Demand**
One	Working	Working	High
Two	Disconnected	Working	High
Three	Working	Disconnected	High
Four	Working	Working	Medium
Five	Disconnected	Working	Medium
Six	Working	Disconnected	Medium
Seven	Working	Working	Low
Eight	Disconnected	Working	Low
Nine	Working	Disconnected	Low

4 Capacitors

As the purpose of the DVPP is to achieve improvements on the voltage stability and on the profile, it is important to analyze the advantages and limitations of the DER previously installed on the network. For example, when performing a voltage control, the distributed generation allows to increase the voltage on the node where it binds in a linear proportion with the rise of the power injected in such node [12]. Besides that, depending on the location (such as connection lines), the GD also influences the voltage of nearby nodes [2]. However, the GD at a unitary power factor does not affect the voltage stability since it does not allow the increasing of the power factor. Hence, capacitor banks will be used in both low and medium voltage as complementary DER, considering the technical benefits that integration seeks and that may be obtained with adequate location of capacitors.

For the positioning of low-voltage capacitors, the application “Calculation of Bank Capacitors in low-voltage” developed by the authors was used. It allows to determine the kVAR from the capacitor bank necessary to avoid penalizations according to the provided information, be it on an energy bill or an energy quality study. The loads that will have low-voltage capacitors will be those with a power factor lower than 0,9 as Table 2 shows. Table 8 indicates the value in kVAR of the capacitor banks required to improve the loads' power factor up to 0,96.

Table 8. Low-voltage capacitors.

Ind	Current PF	New PF	Bank Cap. [kVAR]	Mandator Passses [kVAR]	Automatic Passes	Capacity per automatic pass [kVAR]
Ind. 2	0,8	0,96	92	15	5	17
Ind. 7	0,8	0,96	13	3	2	5
Ind. 12	0,81	0,96	103	18	5	17
Ind. 25	0,87	0,96	24	5	2	9
Ind. 22	0,87	0,96	69	13	2	28

For the location of low-voltage capacitors, the software DigSILENT Power Factory was chosen. It determines the candidate nodes in which it is viable to install the capacitor banks (of one or more passes) and organizes them from the most beneficial to the network to the least beneficial in terms of voltage regulation. Candidate nodes are defined considering technical and economic criteria. Some of the technical criteria are the voltage regulation limits and the system losses. Some of the economic criteria include the cost of the energy losses on the network and the cost of the capacitors (investment). The software uses a methodology based on the optimization of losses and voltage levels and compares their variations to the capacitor installed on the bar [DSPF]. The medium-voltage capacitors for each scenario. For scenario one (ind. 15) the reactive power is 125 kVAR. Scenario three (ind. 11) the reactive power is 100 kVAR Scenario four (ind. 20-21) the reactive power is 125 kVAR Scenario five (ind. 20) the reactive power is 125 kVAR Scenario six (ind. 3-11) the reactive power is 125 kVAR and for ind. 21 the reactive power is 100kVAR. Scenario eight (ind. 10) the reactive power is 175 kVAR Scenario nine (ind. 3-4) the reactive power is 150 kVAR and for ind. 10 the reactive power is 100kVAR. In some scenarios, the location of the capacitors did not bring any technical or economic benefits with the given references.

5 DVPP planned structure (artificial neural networks) and integration parameters

To define the DVPP structure, it is necessary to first introduce the concept of Artificial Neural Network which consists of an entry layer "n", a hidden layer "m" where the necessary calculations between the different entries are performed according to the assigned weights and in terms of those entries; and the "exit layer" where the results obtained on the layer "m" are visualized.

The DER located on the entry layer will be classified within the hidden layer (DVPP) on DER that deliver active energy (Generators) and reactive energy (Capacitors). The functioning of each group will be assigned in terms of the benefit that it represents for the network following the operator’s restrictions. Finally, the exit layer includes the improvement in both voltage regulation and limit stability. They are delivered to the network operator who oversees that information. The combination of generators for each scenario is proposed (active generators with generators out of service) and the reactive power values in both low and medium voltage for each scenario. Table 10 encompasses that information.

Table 10. DVPP Configuration for each scenario.

Scenario	Active generators	Active power [kW]	LV Capacitors [kVAR]	MV Capacitors [kVAR]
One	Generator One	25	301	125
Two	Generators One and Three	27,7	301	0
Three	Generators One, Two and Three	46,7	301	100
Four	Generators One and Two	47	210	250
Five	Generator Two	20	210	125
Six	Generators Two and Three	22,8	210	400
Seven	None	0	76	0
Eight	None	0	76	175
Nine	None	0	76	400

6 Results

a. Nodes outside of the regulation – Voltage index

Analyzing the voltage regulation with the voltage index exposed on chapter 2, the nodes outside of regulation can be determined for the network with and without DVPP. Improvements can be quantified in this manner for each scenario as follows: Scenario 1, 20% of nodes outside of the regulation without DVPP, 0% of nodes outside of regulation with DVPP, 20% of Improvement. Scenario 2, 96% of nodes outside of the regulation without DVPP, 50% of nodes outside of regulation with DVPP, 46% of Improvement. Scenario 3, 88% of nodes outside of the regulation without DVPP, 0% of nodes outside of regulation with DVPP, 88% of Improvement. Scenario 5, 42% of nodes outside of the regulation without DVPP, 0% of nodes outside of regulation with DVPP, 42% of Improvement.

The improvement of scenario 3 enables all nodes outside of regulation to be located within regulation, allowing an 88% improvement in that specific scenario. A critical case occurred on scenario 2 where 96% of nodes were outside of regulation. Nevertheless, integrating the DER into DVPP shows that 50% of the network nodes are within regulation causing a 46% improvement. Scenarios four and six to nine, do not present nodes outside of regulation before or after the integration so the improvement percentage cannot be quantified.
Figure 9 presents the graph of the voltage index for each node on scenarios 1, 3 and 5 respectively. In those scenarios, integration causes all nodes to stay within regulation putting in evidence the improvement on Table 11 since at least 20% of the nodes were outside of regulation before integration (Scenario 1) and even 88% of the nodes on scenario 3; Although, in this scenario, the nodes are very close to the lower regulation limit so they manage to be within the authorized limits. For all graphs, on the upper part, the voltage index with DVPP is indicated for each node and, on the lower part, the voltage index for the basic case is indicated.

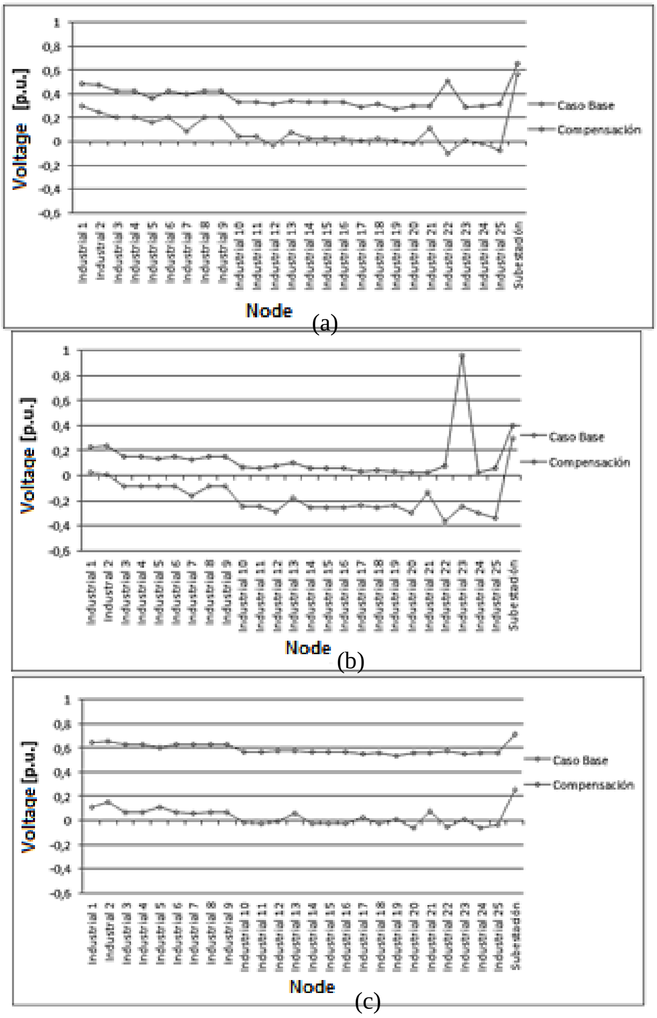


Figure 9. Voltage index per node a) Scenario one. (b) Scenario three. (c) Scenario five

b. Stability limits – PV curves and benefit index

In scientific literature, the analysis of voltage stability with PV curves is limited to selecting the node with the lowest active power value at the stability critical point. In such manner, the preventive o corrective actions focus on that node. However, focalizing the analysis on a single node is risky for networks with numerous bars and branches, since other nodes can repeatedly suffer from instability under different demand or topology scenarios.

An analytic procedure to determine the three nodes that lose voltage stability the easiest are presented:

1. The number of scenarios where the critical nodes is established (in this case 9)
2. The three nodes that have the minimal stability (lowest active power values) according to PV curves for each scenario.
3. A weight is assigned to each classification that can generate a node within the three critical ones for each scenario. A node with a reiterative lower stability limit on all nine scenarios is not as critical as an equally reiterative node with a higher stability limit. Therefore, the critical node of one scenario will have a weight of 1, 0.67 if it is the second one or 0.33 if it is the third one (these weights are obtained through the absolute frequencies of the three possible options).
4. The criticality percentage is obtained for each candidate node (i.e., the node that represents a higher risk in terms of collapsing the network's voltage), considering all scenarios. This criticality percentage is determined by using the concept of arithmetical average (taking into account the assigned weights) with equation 4.1:

$$\%Criticidad = \frac{a*P_1+b*P_2+c*P_3}{\#\ Escenarios} \tag{4.1}$$

Where:

$a =$ Number of scenarios where the analyzed node has the lowest stability limit.
$b =$ Number of scenarios where the analyzed node has the second lowest stability limit.
$c =$ Number of scenarios where the analyzed node has the third lowest stability limit.

$P_1 = 1$ *; P_2 =0,67* ; P_3 =0,33*
*Constants obtained through absolute frequencies

When a node obtains a criticality percentage of 100% it indicates that, on all considered scenarios, that node is the first one to collapse or reach voltage instability (according to PV curves it has the lowest active power value in the critical point).

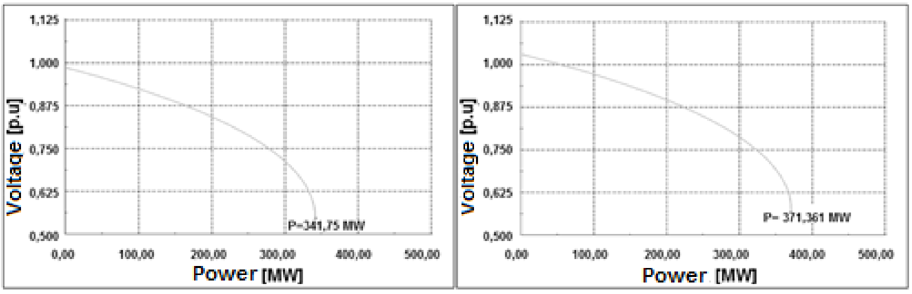
Applying the previous analysis, it is concluded that the critical nodes for the basic case are:

- Industrial node 7: Critical node with a criticality percentage of 100%

- Industrial node 19: Second critical node with a criticality percentage of 60%
- Industrial node 23: Third critical node with a criticality percentage of 41%

With this analysis, the study will focus on those nodes where the voltage stability is critical (industrial nodes 7, 19 and 23) and voltage regulation will be verified with special emphasis on industrial nodes 20, 21 and 24 which are medium-voltage and surpass the minimum regulation limit other than industrial nodes 12, 22 and 25 for low-voltage.

PV curves are built with DigSILENT through a DPL script (DigSILENT programming language) that is predetermined. Figure 10 shows PV curves before and after the integration of DER into a DVPP for industrial node 7 (critical node) on scenario 5.



(a) (b)

Figure 10. PV curves on industrial node 7, scenario 5. (a) Before integration. (b). After integration

The value of active power on the stability limit has an improvement when integrated with DER on DVPP. To quantify this improvement, the benefit index of equation 2 is used. The benefit index is established for the three critical nodes and for each simulation scenario. The benefit index results for each scenario are: Scenario 1 4,71%, scenario 2 7,46%, scenario 3 6,69%, scenario 4 0,86%, scenario 5 8,83%, scenario 6 1,58%, scenario 7 5,04%, scenario 8 0,71%, scenario 9 0,38%,

c. Discussion

As Table 10 can corroborate, the combination of FV generators is different for each scenario. When analyzing Figure 9, it is noticed that, if a FV generator works according to its network requirements, and not only from the load it is feeding, it can improve the voltage profile of various nodes of the network. This is due to several factors, related to the nature of the distributed generation. The impact that the GD has on a network depends on its location and size [2]. That is why different combinations were performed to determine which generators had to be turned on under each scenario's own characteristics. For scenario 5 (Figure 9 c), the voltage profile is flattened allowing it to be located very closely to the nominal value (index of 0.6).

On the economic aspect, the proposed models must allow the owners of a DER (as a FV generator) to have the same rentability when using their generator for self-consumption under certain situations, that unplugging it under the same situation. This is explained since keeping it connected to the network does not offer a higher benefit than if it were offline. For instance, the economic model must guarantee to the owner (user) of the generator FV One that, during the circumstances of scenario five (medium demand and disconnection of LINE 5) it is equally rentable to turn off his generator to benefit the network than to keep it on for self-consumption. This can diminish the cost of his bill even if it is not the most beneficial for the network in general.

7 Conclusions

The VPP structure in terms of the selection of the necessary complementary DER, the behavior of the installed DER and the events related to the demand and topology of the network. In this way, defining the structure of the VPP turns into a basic artificial neural network problem, where the DER of the system, the complementary DER and the topology variations are located on the entry layer and the VPP would be on the hidden layer. Hence, the VPP determines the combinations of DER that allow the improvement of the voltage stability and profile, displaying them on an exit layer to the operator.
When having the VPP structure defined as it is proposed in this article, and grouping the DER according to their capacity to deliver active and reactive power, a 9% improvement is achieved on both the voltage profile and stability limits when compared to the presence and absence of VPP within the network.

A method to determine the critical nodes within a network from the stability standpoint was proposed. The reason for it was that no analytic criteria was found in the scientific literature that would allow to establish the weakest nodes (prone to collapse) based on the PV curves' results. Thus, the analysis and comparison may center on the three nodes that represent a higher risk, if the analysis is combined with the evaluation of normalized indexes. In this manner, the specific goal number two is accomplished.

It is suggested that, on top of the DER installed in a network, the strategic location of a complementary DER must be performed in order to obtain the expected benefits (whether they are technical or commercial) when integrating them into a VPP. The purpose of this is that the economic benefit is not limited to the DER users, but also to the operator who has the information of the entire network at hand as well as the tools that allow him to know the technical limitations of his circuits. Furthermore, this selection of the adequate DER, can only be achieved through a VPP since its bidirectional flux of information can improve the communication between the operator and the other network participants. The mentioned DER can be located on any geographical area, without any type of limitations.

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