Improving Distribution Network Hosting Capacity

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***Abstract*— The increasing penetration of Decentralized Generation (DG) among other factors rises the essential need to adapt and plan the distribution systems in an optimal way to achieve an appropriate cost-efficient development of networks to be prepared for the future grid development. This paper analyzes the impact to using higher nominal voltage levels in distribution networks to improve the hosting capacity of the network, its performance, and at the same time reducing network losses.**

Through a repetitive process for different scenarios proposed, the benefits of the voltage level increase for an IEEE test network were determined. Three voltage levels (13.2kV, 20kV and 24,9kV) were analyzed starting with a base case and different variations to simulate practical cases respecting voltage limits and capacities of the elements. DG location, DG capacities, DG integration levels were also considered as part of the Hosting Capacity calculation.

Using equivalent grid characteristics, this work compares also the performances of overhead networks (OHL) and networks using underground cables for the various scenarios in order to analyze further improvements which are part of distribution networks in Europe.

Conclusions and recommendations for the planning stage of these improvements are also presented.

Keywords—Hosting capacity, Decentralized Generation, Planning Scenarios, Distribution Networks.

I. INTRODUCTION

A distribution feeder capacity of providing electricity to end consumers with unidirectional flow is mainly limited by the branch element's capacity and the lowest voltage level, normally at the end of the feeder.

However, the traditional electricity grid is evolving from a very centralized generation and unidirectional flow to a decentralized generation and bidirectional flow, due to the penetration of DG and the implementation of microgrids that are being installed along the distribution grids, leading to new planning and operational challenges for the distribution operators.

The grids in Europe have experienced the penetration of important levels of DG during the last decade and some countries like Denmark have ambitious goals to achieve an electricity supply of 100% from renewable sources by 2050 which will impose additional penetration of DG.

An overview of this penetration has shown two factors that have allowed a gradual growth of DG with relative minimum impact: 1) Voltage levels in the range of 20-25 kV and 2) Underground networks. The first one leads to the obvious consideration that a higher voltage implies larger capacity while the second facilitates the supply at a voltage closer to nominal value.

On the other hand networks in Latin America following mostly criteria used in the USA, employ voltage levels around 13 kV with overhead configurations for important areas of cities and also rural networks. In order to review some criteria for a better planning of the distribution networks in Latin America the increase of Hosting Capacity based on voltage increase and underground design is explored in this paper.

Hosting capacity (HC) is defined as the amount of Distributed Energy Resources (DER) that can be accommodated without adversely impacting power quality or the reliability of the distribution network.

Documented HC studies show analysis of DG integration respecting the following constraints: i) voltage violation, ii) protection mis-operation, iii) Thermal overloads, iv) Reduction of safety/reliability criteria.

Two levels of Hosting capacity have been identified:

- Hosting capacity without system improvement. It is the maximum amount of DG that a distribution feeder can host with no system upgrade needs.
- Hosting Capacity with system Improvements. If more DG is expected, distribution system upgrades are required to allow additional DG integration. In this case system upgrade costs are to be added.

In this paper the first level HC without system improvements is analyzed.

The aim in this work is to open the possibility, for future grids o grids modernization, of a change of the nominal voltage used by the distribution networks in Latin America to a higher one, as existing in Europe and in some parts of the USA, with a number of benefits.

First the impacts of the voltage increase with some variants is presented complemented by a HC calculation to evidence the conditions and challenges to integrate DG into distribution grids and prepare the landscape for e-mobility loads and energy storage.

II. LOAD FLOW ANALYSIS

In order to analyze the effect of increasing the voltage level in a network, the IEEE 123 nodes network of the IEEE is analyzed using the NEPLAN® software. Different variants (scenarios) have been created using three phase symmetrical network. The loads were modeled using a constant current model. The voltage levels considered for the analysis were the most commonly used in USA and in Europe (13.2 kV, 20 kV and 24.9 kV). The selected conductor is a 4/0 ACSR. According to [2], a positive sequence resistance and reactance of 0.2103 Ω/km and 0.138 Ω/km respectively were used. The susceptance was added in the model because it has a significant change in the network, in particular when used as an undergrounded cable. Positive sequence assumed is 3.5 µS/km by overhead lines and 150 µS/km by underground cable. The assumed maximum current capacity is 316 A.

A simplified single-line diagram of the network is shown in Fig. 1.

A. *Base Case:*

The first scenario was the base case at 13.2 kV. To simplify the calculations, the IEEE 123 nodes model was adapted to convert the original one to a symmetrical network; this conversion lead to a change in the number of nodes to 117 given that some switching nodes were grouped. Table I shows the result respecting the allowed percentage of voltage drop and branch loading.

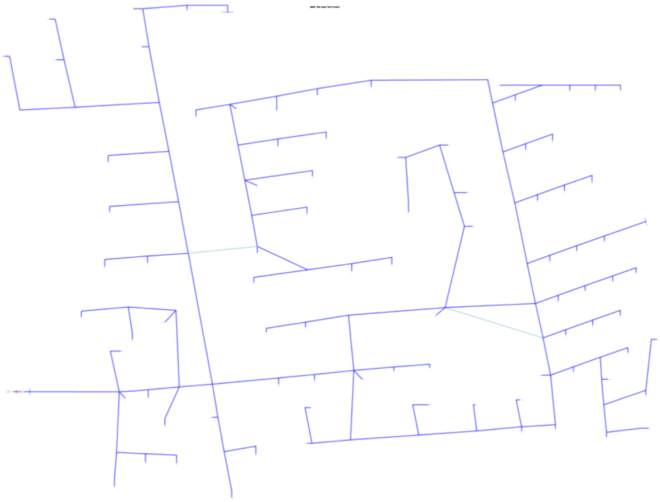

Fig. 1. Distribution Network of 117 nodes.

The results of the 2nd and 3rd scenarios (20 kV and 24.9 kV), with the same demand as the base case (13.2 kV) are shown in the 2nd and 3rd row of Table I.

TABLE I.
SIMULATION OF THE 13.2KV BASE CASE AND THE PERFORMANCE OF THE SAME NETWORK WITH HIGHER VOLTAGE LEVELS.

Voltage [kV]	**S Total [kVA]**	**P Total [kW]**	**Q Total [kvar]**	**P Losses [kVA]**	**Q Losses [kvar]**	**S Load [kVA]**	**P Load [kW]**	**Q Load [kvar]**	**Total feeder length [km]**	**Max feeder length [km]**	**Lowest Voltage [%]**
13.2	6924.1	6047.9	3371.4	613.6	324.7	6311.3	5527.3	3046.6	32.3	14.188	90.1%
20	6913.1	6061.6	3323.8	226.1	106.1	6663.8	5835.4	3217.8	32.3	14.188	95.7%
24.9	6987.6	6141.4	3333.2	145.5	26.5	6847.2	5995.9	3306.6	32.3	14.188	98.5%

This result show important losses reduction by more than 60% while voltage levels are also maintained much closer to nominal values.

B. *Case- Max. Demand to Technical Limits:*

Next, the aim was to show how much load could be increased respecting the voltage and loading capacity limits. The results can be observed in the **Fehler! Verweisquelle konnte nicht gefunden werden.**. It is shown that the network can support almost double demand and reduce substantially the losses compared with 13.2 kV base case.

TABLE II.
SIMULATION OF 20 KV AND 24.9 KV NEARING ITS OPERATIONAL LIMITS

Voltage [kV]	**S Total [kVA]**	**P Total [kW]**	**Q Total [kvar]**	**P Losses [kW]**	**Q Losses [kvar]**	**S Load [kVA]**	**P Load [kW]**	**Q Load [kvar]**	**Total feeder length [km]**	**Max feeder length [km]**	**Lowest Voltage [%]**
20	10853.5	9496.5	5254.9	565.9	331.3	10994.7	9830.6	4923.6	32.3	14.2	92.4
24.9	13507.4	11831	6517.4	557.6	301.5	12873.5	11273	6215.9	32.3	14.2	94.5

From 6,3 MVA for 13.2 kV the load could be increased to 10,9 MVA for 20 kV and 13,5 MVA for 24,9 kV and the losses from 0.613 kW to 0.565 kW for 20 kV and 0,557 kW for 24,9 kV.

Increasing the voltage in the distribution levels leads to cover much longer areas, carry more power for a given ampacity and reduce the number of substations, because of the longer circuits [1]. Additionally, as the losses depends on the square of the current, the higher the voltage, the lower the current and a substantial losses reduction.

The results of this first analysis leads to the next step, consisting to determine the possible extensions of the grid that a higher voltage open.

C. *Case- Grid Extension:*

This case was created to verify how much load can be added to the net, maintaining the same ratio load/length and respecting the operating limits. The additional loads were assumed with the same ratio load / length of the network. Fig. 2 includes the additional load for 20 kV and Fig. 3 for 24.9 kV. The extensions are in the blue rectangle. The results of this simulation are shown in Table III.

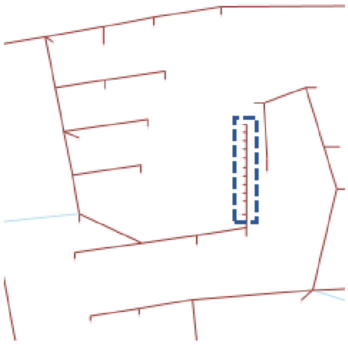

Fig. 2. 20 kV Distribution networks extended to 128 nodes.

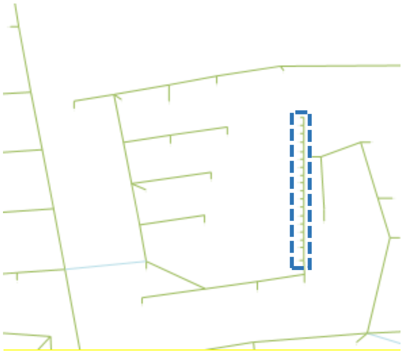

Fig. 3. 24.9 kV Distribution network extended to 144 nodes.

TABLE III.
SIMULATION OF 20 KV AND 24.9KV EXTENDED NET.

Voltage [kV]	**S Total [kVA]**	**P Total [kW]**	**Q Total [kvar]**	**p Losses [kVA]**	**Q Losses [kvar]**	**S Load [kVA]**	**P Load [kW]**	**Q Load [kvar]**	**Total feeder length [km]**	**Max feeder length [km]**	**Lowest Voltage [%]**
20	10775.4	9429.6	5214.6	653.4	376.1	10021.6	8776.2	4838.5	43.3	25.2	90.2%
24.9	13517.9	11846	6512.8	747.7	393.4	12673.2	11098	6119.3	50.3	32.2	91.0%

For the 20 kV network a change from 6.3 MVA to 10,0 MVA is possible with an additional length of 11 km (>33%

of the base case). For the 24,90 kV network the length can be further be increased by 18 km. (>54% of the base case).

III. Intermediate Assesment

After each simulation, the percentage of change between the 13.2 kV network and the two with higher voltages levels (20 kV and 24.9 kV) with the same demand was calculated, with the results shown in Table IV. It is noted an important active power losses reduction by 43% and by 28% respectively of the value obtained for the base case. The reactive power losses were also reduced by 66% and 92%, respectively.

Given the constant current load model used, the power demanded for the load increased by 6% for the 20 kV network and by 8% for the 24.9 kV one. Please also note that the extreme voltage condition (the minimum voltage of each case) is improved, by 6% for the 20 kV network and by 9% for 24.9 kV.

Table IV.
Comparison between 13.2 kV with respect to 20 kV and 24.9 kV results.

Compared whit	S Total [kVA]	P Total [kW]	Q Total [kvar]	p Losses [kVA]	Q Losses [kvar]	S Load [kVA]	P Load [kW]	Q Load [kvar]	Lowest Voltage [%]
20 kV	100%	100%	99%	43%	33%	106%	106%	106%	106%
24.9 kV	101%	102%	99%	28%	8%	108%	108%	109%	109%

If the networks are carried to the maximum demand (technical limit) level, the results of this comparisons are shown in Table V.

It is observed that the network can increases its load demand by 78% active power (kW) (20 kV) and by 105% (24.9 kV) with relatively few losses increase, 9% and 8% for each case.

Table V.
Comparison between 13.2 kV with respect to 20 kV and 24.9 kV in limit conditions.

Compared whit	S Total [kVA]	P Total [kW]	Q Total [kvar]	p Losses [kVA]	Q Losses [kvar]	S Load [kVA]	P Load [kW]	Q Load [kvar]	Lowest Voltage [%]
20 kV	157%	157%	156%	109%	102%	174%	178%	162%	103%
24.9 kV	196%	197%	194%	108%	94%	205%	205%	205%	105%

Additionally, if each network is extended maintaining the demand of the base case (Table III), the comparison can be observed in Table VI, where it is shown that the load demand can be increased significantly with small losses increase.

Table VI.
Comparison between 13.2 kV with respect to 20 kV and 24.9 kV extended.

Compared whit	S Total [kVA]	P Total [kW]	Q Total [kvar]	p Losses [kVA]	Q Losses [kvar]	S Load [kVA]	P Load [kW]	Q Load [kvar]	Total feeder length [km]	Max feeder length [km]	Lowest Voltage [%]
20 kV	156%	156%	155%	126%	116%	159%	159%	159%	134%	178%	100%
24.9 kV	195%	196%	193%	144%	121%	201%	201%	201%	156%	227%	101%

IV. Overhead (OHL) vs Underground (UG) cable

Another aspect considered in this work was the difference between underground and overhead networks. The analysis was done to verify the effect on network performance by increasing the susceptance of the circuits due to the use of cables (Table VII). The results show the advantages of using undergrounded cables because of the large reactive power that is injected which raises the end voltage and imposes the need of controlling possible high voltage limit violations.

Table VII.
Comparison between 13.2 kV with respect to 20 kV and 24.9 kV whit changes in the susceptance.

Compared whit	S Total [kVA]	P Total [kW]	Q Total [kvar]	p Losses [kVA]	Q Losses [kvar]	S Load [kVA]	P Load [kW]	Q Load [kvar]	Delta Voltage [%]
20 kV	95%	101%	58%	40%	41%	106%	106%	106%	7%
24.9 kV	93%	101%	16%	24%	689%	108%	108%	108%	9%

V. Voltage sensitivity analysis

Considering that the penetration of DG will cause voltage impact in the operation, an analysis of the sensitivity of the most sensitive nodes to voltages changes was done by calculating the voltage stability values as shown in Table VIII.
Voltage Sensitivity base case overhead.

Node	Sensitivity %V/Mvar		
	13.2kV	**20 kV**	**24.9 kV**
039	1.5	0.829	0.646
037	1.5	0.827	0.644
038	1.5	0.826	0.644
035	1.5	0.810	0.634
041	1.5	0.808	0.633

Table to XI. The voltage sensitivity is calculated for different nodes when reactive power is added. The tables below show selected results for nodes which were obtained for the overhead and undergrounded cases of circuits for the cases base case, increased demand and Grid Extension respectively.

Table VIII.
Voltage Sensitivity base case overhead.

Node	Sensitivity %V/Mvar		
	13.2kV	**20 kV**	**24.9 kV**
039	1.5	0.829	0.646
037	1.5	0.827	0.644
038	1.5	0.826	0.644
035	1.5	0.810	0.634
041	1.5	0.808	0.633

Table IX.
Voltage Sensitivity base case underground.

Node	Sensitivity %V/Mvar		
	13.2kV	**20 kV**	**24.9 kV**
039	1.502	0.823	0.65
037	1.4969	0.821	0.649
038	1.4934	0.820	0.648
035	1.4549	0.804	0.638
041	1.4513	0.803	0.637

Table X.
Voltage Sensitivity for increased demand.

Node	Sensitivity %V/Mvar	
	20 kV	**24.9 kV**
039	0.8509	0.665
037	0.8487	0.664
038	0.8472	0.663
035	0.8307	0.653
041	0.8292	0.652

TABLE XI.
VOLTAGE SENSITIVITY FOR EXTENDED NETWORK.

Node	Sensitivity %V/Mvar	
	20 kV	24.9 kV
039	0.8549	0.668
037	0.8523	0.667
038	0.851	0.666
035	0.8339	0.655
041	0.8321	0.654

VI. HOSTING CAPACITY ANALYSIS

A HC calculation was done to evaluate the situation with the challenge of integrating the DG into distribution grids. This analysis was done using the NEPLAN function for Hosting capability.

The following parameters were applied:

- Network model: modeling IEEE network;
- Load Model: constant current
- Voltage & thermal capacity constraints

Evaluation was done using a repetitive process for different Scenarios: DG Location, DG Capacities, DG Integration levels (10%, 20%, …, 100%, etc). Number of Scenarios: 50 with steps of 2%.

Additionally, for the hosting calculation, it was assumed as maximal individual DG per node, an available capacity assuming the installation of distribution transformers according to the Colombian Standard NTC 819. In the example, six load levels were implemented. For each load level a specific transformer was defined. This is, loads of 304, 259, 172, 129, 82 and 44 kVA, for transformers of 750, 630, 400, 225 and 112,5 kVA nominal capacity were selected. The results of the simulations are diagrams that illustrate network operation below the maximum voltage allowed (green zone), when half operate above and half below (yellow zone) and when all exceed the limits (red zone). Additionally, the voltage limit is the red line, as can be observed in Fig. 4.

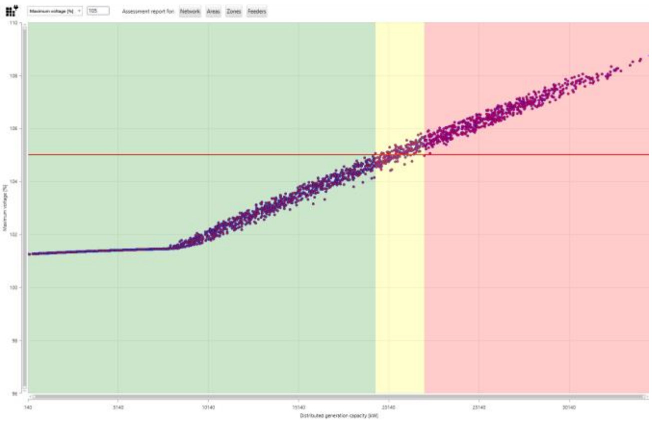

Fig. 4. Hosting capacity chart for the 24.9 kV case with 5% of maximum voltage limit.

The following tables compilates maximum capacity for DG for the 13.2 kV, 20 kV and 24.9 kV overhead (OHL) base cases, added to the 13.2 kV undergrounded (UG) case. Ones without system improvement (WI) and others with system improvement (SI) (allowing change of transformer sizes as required by the load increase).

TABLE XII. HOSTING CAPACITY SIMULATION RESULTS WI.

Voltage [kV]	ΔV [%]	Limit	OHL/ UG	Max. DG [kW]
13.2	3	WI	OHL	8956
20	3	WI	OHL	8751
24.9	3	WI	OHL	8891
13.2	5	WI	OHL	8956
20	5	WI	OHL	8751
24.9	5	WI	OHL	8891
13.2	3	WI	UG	8651
13.2	5	WI	UG	8651

TABLE XIII. HOSTING CAPACITY SIMULATION RESULTS WITH SI.

Voltage [kV]	ΔV [%]	Limit	OHL/ UG	Max. DG [kW]
13.2	3	I	OHL	10777
20	3	I	OHL	13784
24.9	3	I	OHL	12793
13.2	5	I	OHL	13078
20	5	I	OHL	18652
24.9	5	I	OHL	19412
13.2	5	I	UG	11922
13.2	3	I	UG	9937

As it can be observed, in the 13.2 kV undergrounded case the DG decrease around to 3.5% as a result of the cable capacitance. If improvements are not included, DG for the three voltages remain similar as result of the distribution transformer limited capacity. This is, in this example, the maximal capacity of the transformer has been achieved, limiting the DG. Implementing improvements in the distribution transformers of the 13.2 kV's net the injected power DG can be increased approximately 20.3%. For the overhead networks if the voltage increases from 13.2 kV to 20 kV and if improvements are implemented, allowing an overvoltage of 3%, it is possible to install around 27,9% of DG.

Moreover, if the improvements are not done, the DG is the same without depending on the overvoltage limits. These results can be different in another network. This work shows that any network must be analyzed separately in order to determine its HC and the improvements that shall be implemented for an optimal decision.

VII. CONCLUSIONS

With the important challenges of the DG penetration and the expected addition of e-mobility and storage capacity, new measures to achieve the balance between utilities and consumers with installed DG must be adopted.

To improve drastically the flexibility in the integrations of DG and others in the future of the grid expansion, increase the reserve capacity, amplify the Hosting Capacity and avoid bottlenecks that can affect the grid flexibility, it is imperative when planning new feeders to consider seriously the advantages of changing the medium voltages from 11,4 kV; 13,2 kV 13,8 kV to a voltage in the range of 20- 25 kV, as adopted in Europe.

The results presented in this paper provide the basis of the analysis that shall be done to support the decision of increasing the voltage levels currently employed in Latin America to the higher suggest ones with important improvements such as power losses reduction and improved operating conditions.

Actually, the installed base in Medium voltage in Colombia are designed for nominal voltages of 17,5 and 20 kV but operated at lower voltages, because most of the medium voltage switchgears are coming from European suppliers, use a BIL of 95 kV / 125 kV.

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