PV Power Curtailment and BESS Management for Distribution Networks: A Practical Approach

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***Abstract*—Voltage and thermal limits in distribution feeders are the main features assessed to determine their hosting capacity (HC) due to the integration of distributed generation (DG), especially photovoltaic systems (PV). This paper proposes a PV active power curtailment control strategy combined with the management of battery energy storage systems (BESS) under high penetration of PV systems. In addition, the voltage imbalances rate is included in the evaluated operating parameters in order to reduce voltage and thermal issues and avoid or postpone the feeder reinforcement costs. The study uses Monte-Carlo and stochastic simulations to determine the HC and the PV system's random location. Also, several PV systems capacities are proposed by using statistics. Mexican standards are used for the HC estimation and to perform the power curtailment control strategy. The use of smart PV inverters is considered to reduce or increase the PV active power generation. The BESSs are capable of regulating their charge and discharge cycle independently. The results show the advantages of using strategies separately and in combination can be beneficial to improve the feeder performance.**

***Index Terms*—Active power curtailment, battery energy storage system management, thermal limits issues, voltage issues, imbalance voltage rate, stochastic simulation.**

I. INTRODUCTION

The integration of the distributed generation (DG) systems to distribution networks has increased rapidly in the last years. The photovoltaic systems (PV) are the most common DG units on distribution feeders due to the accessibility for residential customers. Due to the natural intermittence of the solar resource, some PV installations include storage systems to maintain the power supply in low generation conditions. In the special case of Mexico, the integration of PV units was promoted by regulatory electrical reform in 2013. In 2019 Mexico reported a total installed capacity of 975 MW of PV units, and is expected to be 3,201 MW in 2023. In 2019, Mexican statistics reported that the proportion of PV installed capacity units in the distribution networks with 1, 5, 10, 30, 50, 100, 250 and 500 kW was 2 %, 48 %, 39 %, 7 %, 1 %, 1 %, 1 %, and 1 %, respectively [1].

However, the increase of PV in distribution networks may lead to some consequences for the network performance; the knowing effects of the increase in PV penetration are the following: reverse power flow, feeder overvoltage, thermal issues on transformers and feeders, fault currents contribution, increasing power losses, phase imbalance, and low power factor [2]–[6]. Therefore, complementary considerations in planning and management strategies must be taken into account. Usually, it requires the network reinforcement (e.g., feeders recalibration) or improving the voltage regulation by employing On-Load Tap Changer (OLTC) transformers [7]; but this implies an increase in the electric company's costs.

The operators need to know the maximum amount of PV penetration that the distribution network can host, within the operation limits requirements. This concept is known as estimation of the hosting capacity (HC). The HC estimation determines the distributed generation penetration level ($DG_{p_{\%}}$) that the distribution network can host without infringing the normative and technical operative restrictions. The PV penetration can be determined by the total PV installed capacity respect the feeder's capacity or the number of customers with PV systems respect the total of customers, and can be described by (1).

$$DG_{p_{\%}} = \frac{Number\ of\ Customers\ with\ PV}{Total\ Number\ of\ Customers} \cdot 100\,\% \qquad (1)$$

The operative restrictions can be voltage regulation limits, feeder's thermal limits, power losses, power factor, harmonic distortion, among others. Usually, the operators use voltage regulations and thermal constraints for HC estimation because are two of the main aspects of the feeder's planification and operation. Another essential condition is the voltage imbalance because it can be increased when the DG grows [8].

In [9] addresses three fundamentally different quantification approaches for the HC estimation: deterministic, stochastic-probabilistic, and time-series. The analysis determined that due to the variability of PV generation and load demand, the stochastic approach is the most effective because implies the simulation of realistic scenarios [9].

The problems derived by PV power output variabilities, as voltage fluctuation, frequency variation, power quality issues, and harmonic distortion [10]–[14], it can require control strategies to mitigate those effects. Some mitigation proposed methods include battery energy storage systems (BESS) management, electric vehicle charging strategies, PV power derating, among others [15], [16]. Even though the storage system's cost is currently expensive, the forecasting future storage prices carried out and in [17] indicates that the cost will decrease in a short time because battery technology improves and the manufacturing cost decreases. In [18] and [19] have been carried out studies about the operative and cost-benefit rate of setting and managing a storage system based on BESS in a PV system. Reference [18] presents an economic assessment for different methods such as installing damping load, power curtailment, batteries, and a combination between power curtailment and batteries. The results showed better

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utilities for electric distribution companies when combining the power curtailment and the BESS management.

In [20] control strategies and BESS are used to avoid costly grid expansion and reinforcement solutions in low voltage feeders by stochastic simulations. Studies employ Volt-Watt, Volt-Var, and BESS controls individually and combined. The controls act in voltage regulation by reducing the active power generation or by reactive compensation. Results showed that Volt–Watt control efficiently reduces the effects of high PV penetration and increases the HC. Also, the studies showed that the Volt-Walt control can be more beneficial when is combined with the BESS management. The studies considered a PV generation profile and a different demand profile per customer, and only 5 kW of generation capacity for all the PV systems. However, this can reduce the simulation realism, and hence the results due to some feeders can host a higher diversity of PV systems capacities.

Approaches as in [21] study the control coordination between OLTC, bank capacitors, and BESS storage for voltage regulation. The results show that the fast and local BESS response combined with the global OLTC effect ensures a fast response for voltage regulation and reduction of BESS stress; the proposed approach can be suitable as long as the feeder has voltage regulation support elements (such as the OLTC). However, if the feeder does not previously have this kind of support, it can represent a significant investment.

In [22], it is proposed the use flexible AC transmission system (FACTS) concept in distribution networks in order to manage the renewable energy resources and BESS storage by a flexible AC power flow control system (FACPFCS). The results show that achieving proper renewable energy resources and BESS selection and coordination can be possible. The approach is feasible as long as DG and BESSs penetration is enough to provide the required control response.

The proposed approach in [23] studies the use of a coordinated optimal Volt-Var control by phasor measurement units in distribution networks (D-PMU) and electric vehicles (EV) parking lots management. The proposed control can regulate the voltage at all grid buses during disturbances, even when the D-PMUs and parking lots are located at different buses and geographical locations. Similar to [21] and [22], the approach is suitable if EV parking lots' power supply capacity (such as DG penetration) is adequate to perform the Volt-Var control and the D-PMUs are previously placed.

The approaches in [21]–[23] are practical but can implicate a significant inversion from the distribution company due to it requiring advanced metering systems or voltage regulation support; it also, a previous inversion from the customers is necessary because the DG, EV chargers, or BESS penetration must be considered for control requirements. So, these approaches are feasible for distribution feeders with high distributed resources (e.g., DG, BESS, or EV) penetration and not for low penetration.

Several approaches have been proposed to increase the HC maintaining the voltage regulation and without distribution network reinforcement by using voltage control techniques and power curtailment [24]–[26]. The power curtailment is performed when the PV negative effects are severe. This usually may occurs when the power generation is maximum, and the load demand is minimum.

PV inverters and BESS must have the ability to regulate their active output power so that the control works correctly. Also, it is suggested that the BESS management be employed to mitigate or smooth the variability of PV power and load demand. The power fluctuation mitigation can reduce the voltage issues caused by the PV generation intermittency. The most used methods are the moving average control (MAC) [27]–[30] and ramp-rate control [31], [32].

Several approaches require a metering system and a communication infrastructure between the system elements and the distribution network operator (DNO). The communication infrastructures are necessary because they report the feeder's status to the DNO, and according to the requirements (standards), the performance can be adjusted [33]. However, the grid reinforcement measured represents a significant cost increase, and in most cases, the cost-benefit rate is unreasonable, as is analyzed in [34]. As an alternative in [35] and [36], it is assumed that each PV inverter is equipped with wireless communication and is capable of reporting to the DNO their status, as is shown in Fig. 1; then an assessment of low-cost wireless communication (as cellular communication) performance is carried out; the results show that performance and cost-rate are convenient employing cellular communication for the network management.

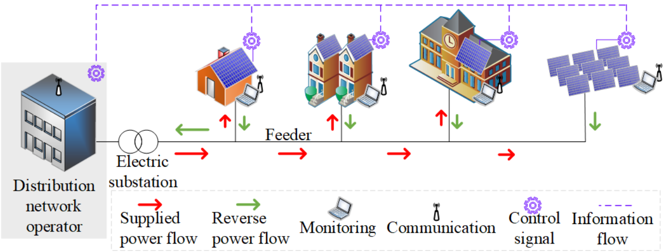

Fig. 1. Communication between DNO and PV systems.

This paper will employ stochastic simulations by Monte-Carlo in an OpenDSS-Python environment to obtain the HC in medium voltage feeders with PV and energy storage systems. The control strategy combines active power curtailment and BESS management in each customer. The energy storage systems employ the MAC to mitigate the PV variability and a drop control algorithm for managing the state of charge (SoC). Also, it is considered an infrastructure of low-cost communication between the PV inverters and the DNO to carry out the generation curtailment.

The novelty of this work is to use realistic scenarios to achieve a more objective analysis. Variable daily load and irradiance profiles are used. Different capacities of PV units and storage systems are considered following the statistics of units installed in the feeder. In addition to voltage regulation and thermal issues, the imbalanced voltage is adopted as another constraint for HC estimation.

II. Battery Energy Storage System

A. *Mitigation Approach*

The MAC is used to smooth the PV power output ($P_{PV}(t)$) variability as is shown in Fig. 2 by using a BESS connected in parallel with a PV unit [30].

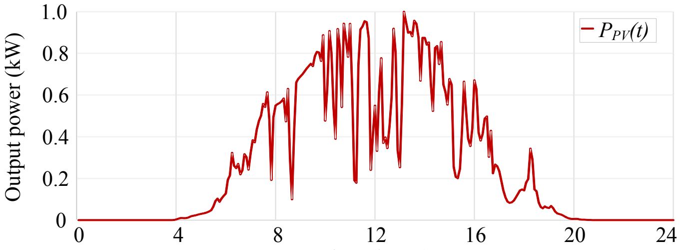

Fig. 2. PV power output variability.

The MAC estimates a smoothed curve $P_{MA_T}(t)$ given by (2) where T is the smoothing window time. The curve can be smoother when the window time is increased, as is shown in Fig. 3.

$$P_{MA_T}(t) = \frac{1}{T}\sum_{\tau=1}^{T} P_{PV}(t-\tau) \tag{2}$$

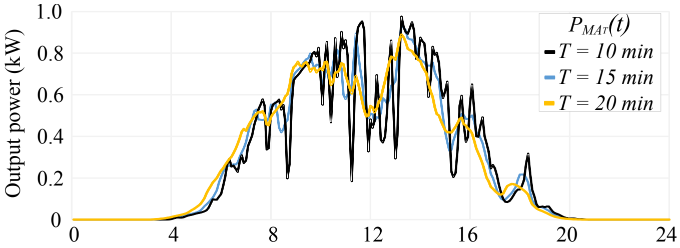

Fig. 3. Smoother curves with several windows time.

Finally, the power supplied by the BESS $P_{BESS}(t)$ is calculated as in (3). Fig. 4 shows an example of a smoothing curve with several windows time. A smoother curve will require more energy from the BESS but results in better mitigation [27].

$$P_{BESS}(t) = P_{PV}(t) - P_{MA_T}(t) \tag{3}$$

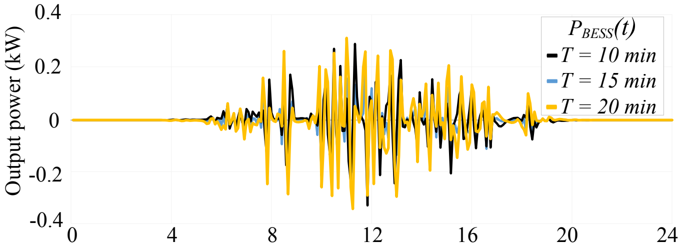

Fig. 4. BESS power output to smooth the PV variability.

B. *State of Charge Management*

The drop control algorithm determines the required power from the BESS to maintain the SoC near from the reference value SoC_{ref} (established by the customer) between the minimum SoC (SoC_{min}) and the maximum (SoC_{max}) (established by the manufacturer). The BESS charging and discharging periods are shown in Fig. 5.

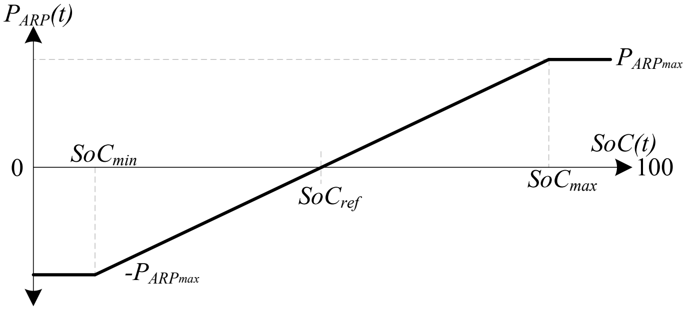

Fig. 5. BESS state of charge and discharge.

The $P_{ARP}(t)$ is established for the maximum allowed recovery power $P_{ARP_{max}}$ according to with the BESS output/input power capacity or the net instantaneous power $P_{net}(t)$ between the PV power output and the load demand ($P_{net}(t) = P_{load}(t) - P_{PV}(t)$). The $P_{ARP}(t)$ is estimated as is given by (4).

$$P_{ARP}(t) = \begin{cases} P_{ARP_{max}} & |P_{net}(t)| \geq P_{ARP_{max}} \\ |P_{net}(t)| & |P_{net}(t)| < P_{ARP_{max}} \end{cases} \tag{4}$$

Then the power of the drop control algorithm is estimated as indicated in (5).

$$P_{drop}(t) = -P_{ARP}(t)\beta(t) \tag{5}$$

The drop parameter $\beta(t)$ determinate the BESS charge or discharge state. If the value of $\beta(t)$ is -1 the BESS is in discharge state, opposite ($\beta(t) = 1$) the BESS is in charge state. It is proposed, that the charging state is restricted only in PV power generation hours, i.e. $P_{PV}(t) > 0$. The value of β can be determinate by (6).

$$\beta(t) = \begin{cases} -1 & SoC(t) \geq SoC_{ref} \\ -1 & SoC_{min} < SoC(t) < SoC_{ref} \text{ and } P_{PV}(t) = 0 \\ +1 & SoC(t) < SoC_{ref} \text{ and } P_{PV}(t) > 0 \end{cases} \tag{6}$$

C. *Proposed BESS Power Estimation*

At last, the proposed smoothed power $P_{sp}(t)$ is calculated by the combination of (2) and (5) [27], as is given in (7). Then, the power must be supplied by the BESS $P^{sp}_{BESS}(t)$ is calculated by subtracting the instantaneous PV power output $P_{PV}(t)$, as in (8).

$$P_{sp}(t) = P_{MA_T}(t) + P_{drop}(t) \tag{7}$$

$$P^{sp}_{BESS}(t) = P_{PV}(t) - P_{sp}(t) \tag{8}$$

III. PV Generation Curtailment

A. *Control Logic for PV Generation Curtailment*

The maximum power point tracker ($MPPT$) on PV inverters can be adjusted to set the active power output according to the maximum PV power generation available [37]. The aforementioned is employed to reduce or increase the generation. Considering that the feeders can be more sensitive to voltage or current changes, the restrictions must be unified. The maximum voltage regulation V_{max} and the minimum V_{min} are compared with the voltage limits V_{limit_1} and V_{limit_2}, the maximum current $I_{max_{\%}}$ is compared with the feeder thermal limit $I_{TL_{\%}}$ and the maximum imbalance voltage $VIR_{max_{\%}}$ is compared with the voltage imbalance rate limit $VIR_{limit_{\%}}$. The applied standards give the value of the limits. A voltage band

V_{band} is proposed to anticipate the abrupt change in voltage magnitudes. In this sense, the reduction of $MPPT$ ($Red_{MPPT_{\%}}$) will carry out if any restriction is not fulfilled, no matter if the other restrictions are within limits. The increase of $MPPT$ ($Inc_{MPPT_{\%}}$) will only be carried out if all are within limits. The logic is given as in (9) and as an example, Fig. 6 illustrates these logic.

$$MPPT = \begin{cases} MPPT - Red_{MPPT_{\%}} & V_{max} \geq (V_{limit_1} - V_{band}) \\ & or\ V_{min} \leq (V_{limit_2} + V_{band}) \\ & or\ I_{max_{\%}} \geq I_{TL_{\%}} \\ & or\ VIR_{max_{\%}} \geq VIR_{limit_{\%}} \\ MPPT + Inc_{MPPT_{\%}} & V_{min} > (V_{limit_2} + V_{band}) \\ & and\ V_{max} < (V_{limit_1} - V_{band}) \\ & and\ I_{max_{\%}} < I_{TL_{\%}} \\ & and\ VIR_{max_{\%}} < VIR_{limit_{\%}} \end{cases} \tag{9}$$

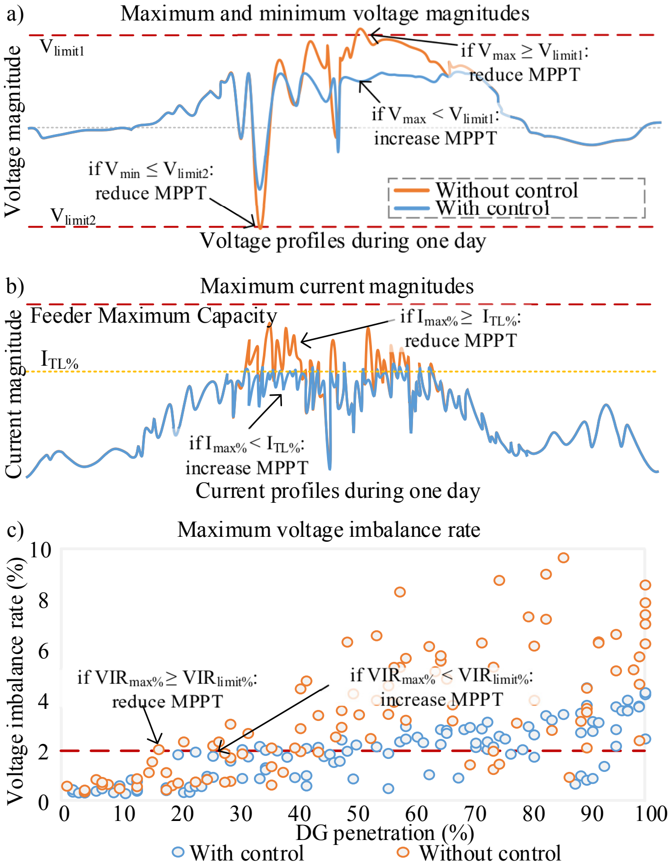

Fig. 6. Power curtailment criteria by: a) voltage magnitudes, b) feeder overload, and c) voltage imbalance rate.

IV. Proposed Methodology

A. Stochastic Simulation

Monte-Carlo simulations provide realistic scenarios with different PV systems and BESS capacities, random location, and PV penetration values. In Fig. 7 the methodology flowchart is shown. On 1^{st} all the random scenarios are generated. The same scenarios are employed for different study cases on the feeder. Followed, in 2^{nd} step first Monte-Carlo scenario is selected, and in the 3^{rd} step, the daily simulations start. Then, in the 4^{th} step, the BESS management is made by each customer. After, the 5^{th} step evaluates the voltage regulation, imbalanced voltage, and thermal overloading issues. If some issue is reported, the curtailment control is performed (6^{th} step), otherwise not. The generation curtailment and the BESS management will be applied in the next simulation step in 7^{th}. Once the daily simulation is finished, the next Monte-Carlo scenario will be evaluated (8^{th} step). The standards are assessed after the daily simulation; the PV penetration value is saved if some standard is not satisfied. Finally, 9^{th} step, the HC is determinate. The final HC is established by the minimum PV penetration value saved.

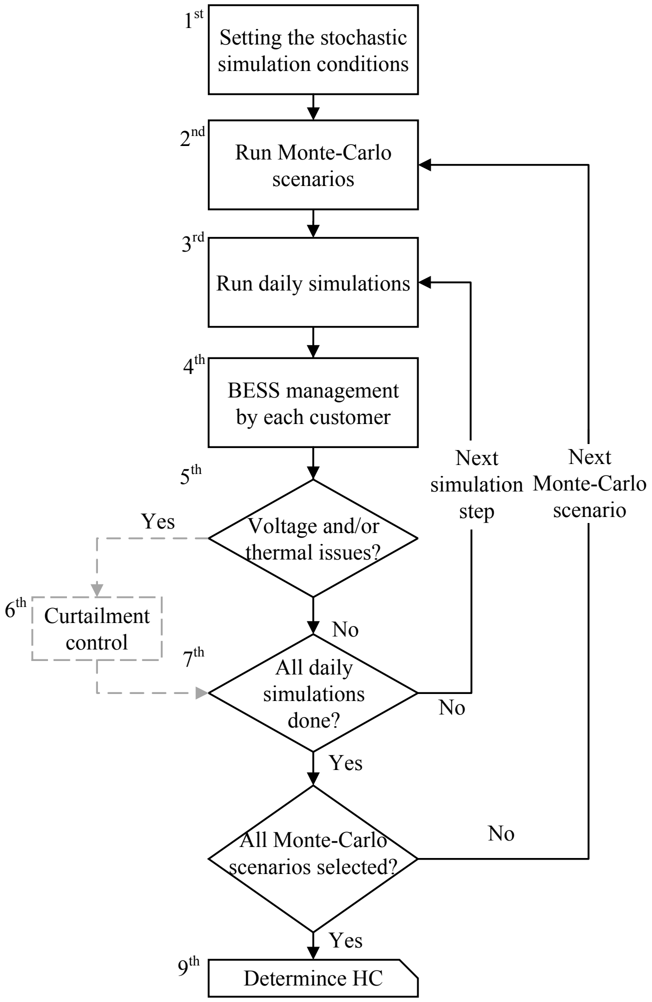

Fig. 7. Flowchart of the proposed methodology.

B. Selection of the Standardization

As an example, Mexican standards were adopted. In this paper, the handbook [38] is used to set the maximum of the total PV power units installed and the thermal feeder limit. The grid code [39], and the standard [40] to set the voltage regulation range, the maximum voltage imbalance rate, as well as the permissible voltage magnitudes for both voltage regulation and imbalance rate. The resolution data of the measuring must be 10 minutes, with 95 % of the measured magnitudes regarded as acceptable. The admissible voltage magnitude operation range is 0.93 to 1.05 p.u. The maximum voltage imbalance rate is 2 %, and the maximum utilization for feeders and the electric substation is 80 % of their capacities. The PV systems with capacities greater than 50 kW are restricted to be connected in three phases buses. The standardization has been continuously updated since 2013. Hence, the reference values can be modified for future studies.

V. Tested Feeders

This work employs two feeders for studies. The first is the IEEE 123 node test feeder, and the other is a real Mexican distribution feeder. Both operate in MV.

In each feeder are performed simulations without and with a combination of management strategies. The simulation conditions are classified as follows.

- No Control: installed PV generation without active power curtailment and no installing BESS.
- Control: installed PV generation with active power curtailment and no installing BESS.
- BESS: installed PV generation with BESS management and without active power curtailment.
- Control + BESS: installed PV generation with active power curtailment and BESS management.

All simulations provide their respective HC achieved. The initial HC gets by "No Control" simulation (NC).

A. IEEE 123 Node Test Feeder

The control strategies described above were implemented and tested on the IEEE 123 node test feeder, as shown in Fig. 8, with a total of 91 load nodes, which operate in imbalanced conditions and with a nominal voltage of 4.16 kV, this feeder can present voltage regulation issues. The electrical substation (orange circle) has a capacity of 5 MVA; the total charge is ≈ 80 % of its capacity. The feeder has 118 sections of three-phase, bi-phases, and single-phase lines. The size of the PV are bases on the follows statistics where the proportion of PV systems with 1, 5, 10, 30, 50 and 100 kW is 3 %, 11 %, 24 %, 52 %, 9 % and 1 %, respectively. In the same way, the storage systems will have storage capacities of 4, 4, 8, 24, 36 and 48 kWh with maximum power inputs/outputs of 1.6, 1.6, 3.2, 9.6, 14.4 and 19.2 kW, respectively. The 100 % of connected PVs is ≈ 43.66 % of the electric substation capacity ($ES_{\%}$). The maximum voltage regulation is approximately 1.05 p.u., so the V_{band} will be fixed in 0.01 p.u.

It is considered that the feeder is in a geographical area of 3.61 km^2. Therefore, the same irradiance profile was used for all customers and a different load profile for each customer. However, it is beneficial to use different irradiance profiles in the photovoltaic systems in larger geographical areas. The load and PV profiles were developed by Electricity North West and The University of Manchester and are available in [41]. In Fig. 9 the normalized irradiance profile is shown and the Fig. 10 shows a typical normalized load profile. Each profile represents a daily shape with 5 minutes step (288 points in 24 hours). The normalization in each PV and load profile considers the plant capacity factor for PVs and the coincidence factor for the loads.

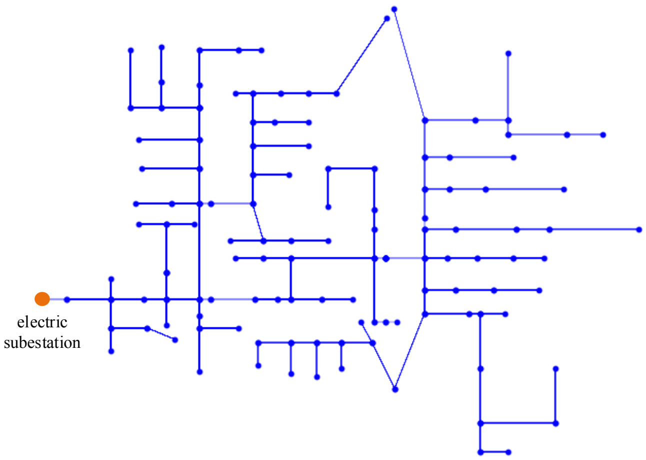

Fig. 8. Topology of the IEEE 123 node test system.

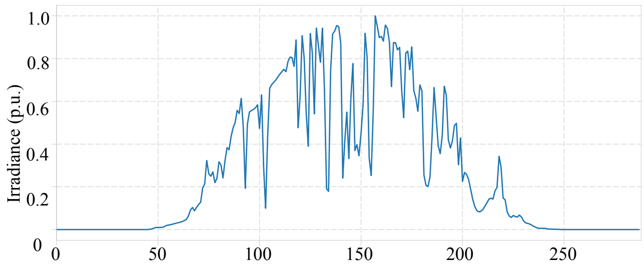

Fig. 9. PV shape profile.

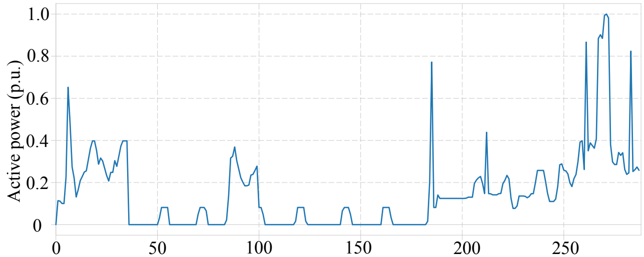

Fig. 10. Load shape profile.

The PV generation curtailment requires setting a $Red_{MPPT_{\%}}$ value. In [42], are proposed several reduction $Red_{MPPT_{\%}}$ values up to 10 % for generation curtailment assessment. In this case, the power reduction performed $Red_{MPPT_{\%}}$ is 1% and the increase $Inc_{MPPT_{\%}}$ is 1%. The generation cut will be limited by a minimum $MPPT$ ($MPPT_{\%_{min}}$) in the PV inverters, which will be 80%. The voltage band for the control will be V_{band} = 0.01 p.u. To evaluate the feeder performance, the strategies will be tested individually and combined.

A1. IEEE 123 Node Test Feeder Results: this section presents the results and analysis for IEEE 123 feeder. The number of simulations was 1033 to have several PV location possibilities. Each analysis employed the same scenarios. The simulation results are shown in Table I, which are presented according to the HC obtained in each simulation case. The HC feeder in "No Control" is 29 % of PV penetration by imbalance issues (this is ≈ 27 customers with PV units), total PV kW installed is 13.10 % of the electrical substation capacity ($ES_{\%}$); the feeder reported no voltage issues, and the thermal issues may occur when $DG_{p_{\%}}$ is 43 % and $ES_{\%}$ is 19.10 %. In "Control," an increase in hosting capacity was observed by 6 % ($DG_{p_{\%}}$ from 29 % to 35 %) limited by imbalance issues, this represents ≈ 5 additional PV units and 2.1 % more of substation utilization ($ES_{\%}$ from 13.10 % to 15.20 %); the thermal issues may occurs when $DG_{p_{\%}}$ = 61 % and not 43 %. For “BESS” control, no HC increase was achieved; but the feeder utilization improves because issues present until $DG_{p_{\%}} > 61$ % instead at 43 % as in “No Control”. The “Control + BESS” approach shows a more significant increase than other strategies from 29 % to $DG_{p_{\%}}$ = 43 % and also limited by imbalancing conditions; this is approximately 13 more extra customers and 6 % more of ES utilization ($ES_{\%}$ from 13.10 % to 19.10 %). While the feeder utilization has better performance, presenting thermal issues until $DG_{p_{\%}} > 63$ %.

TABLE I
HC Estimation for IEEE 123 Node Test Feeder

Management	Voltage		Voltage Imbalance		Thermal	
	$ES_{\%}$	$DG_{p_{\%}}$	$ES_{\%}$	$DG_{p_{\%}}$	$ES_{\%}$	$DG_{p_{\%}}$
No Control	43.66	100	13.10	29	19.1	43
Control			15.20	35	26.9	61
BESS			13.10	29	26.9	61
Control + BESS			19.10	43	28.4	63

In this feeder, performed simulations showed that the employed or combination of management strategies could increase the HC. As detailed in [6], the combination of management approaches provides the greatest HC improvement is better than when are used individually. Furthermore, in [6], the HC was determined in terms of the substation capacity according to Brazilian standard NBR 5416: 1997. This establishes that the transformer must withstand an overload for a certain time and not exceed 150 % of its nominal capacity. However, in this case, this consideration is not adapted to the feeders since the feeders are limited to not accommodating more than 80 % of its nominal capacity. Also, the % of voltage out of limits must be < 5 % of all measurements in a time-lapse; although limited by voltage imbalance problems, this feeder showed a behavior according to [6].

B. *Mexican Feeder*

Studies also were performed in a Mexican 13.8 kV imbalanced three-phase distribution feeder. Fig. 11 shows the feeder configuration; the network consists of a total of 265 customers, of which 5 are classified as large customers. The electric substation (orange circle) has 10.5 MVA, which is a typical capacity for distribution networks. The feeder has 200 sections of a three-phase, bi-phases, and single-phase lines. The total load is 23.57 % of the electric substation capacity. On this feeder, statistics used in the “IEEE 123 Node Test Feeder” did not result in serious enough impact for the studies; hence, the proportion of the PV sizes are proposed with 3 %, 18 %, 24 %, 52 %, 0 %, 0 %, 2 %, and 1 %, but keeping the same PV capacities. In addition, the same battery data is used. The 100 % of connected PVs is ≈ 75.88 % of the electric substation capacity; the V_{band} will be fixed in 0.02 p.u.

Fig. 11. Three-phase Mexican tested feeder.

The same irradiance profile in Fig. 9 is used in this feeder; different load profiles were employed for each customer. The power reduction performed is keep in $Red_{MPPT_{\%}} = 1$ % and the increase is $Inc_{MPPT_{\%}} = 1$ %.

B1. Mexican Feeder Results: the simulations were carried out in the same way as in the IEEE feeder. The simulation results are shown in Table II. The HC feeder in “No Control” is 26 % (this represents ≈ 69 customer with PV) in imbalancing conditions, the feeder reported a voltage $DG_{p_{\%}}$ of 36 %, and the thermal $DG_{p_{\%}}$ is 43 %. In “Control,” an increase in hosting capacity was observed at 8 % ($DG_{p_{\%}}$ from 26 % to 34 %), both limited by imbalance issues, which represents ≈ 22 additional customers and 6.2 % more generation added ≈ 651kW ($ES_{\%}$ from 19.63 % to 25.83 %), while the thermal $DG_{p_{\%}}$ increased from 57 % to 75 % and the voltage $DG_{p_{\%}}$ improves to 50 %. For the “BESS” strategy, the HC was also increased by 34 %; the $DG_{p_{\%}}$ voltage and thermals increased from 36 % to 47 %, and 57 % to 61 %, respectively. Just with storage systems managed to improve the voltage and current conditions in the feeder. In “Control + BESS”, the same HC obtained from the other strategies was achieved, while the voltage $DG_{p_{\%}}$ was the same that obtained in “Control” and the thermal $DG_{p_{\%}}$ increased to 84 %. In this feeder, the highest HC increase was not achieved when combining the strategies. This is because a higher number of customers wich operate under imbalanced conditions joined at PV increase can produce important imbalanced conditions.

TABLE II
HC Estimation for Mexican Feeder

Management	Voltage		Voltage Imbalance		Thermal	
	$ES_{\%}$	$DG_{p_{\%}}$	$ES_{\%}$	$DG_{p_{\%}}$	$ES_{\%}$	$DG_{p_{\%}}$
No Control	21.93	36	19.63	26	44	57
Control	35.84	50	25.83	34	54.81	75
BESS	29.7	47	25.83	34	45.8	61
Control + BESS	35.84	50	25.83	34	59.3	84

Still, there are remarkable advantages in reducing voltage problems (increasing voltage $DG_{p_{\%}}$) and increasing the current injection capacity of photovoltaic generation (increasing thermal $DG_{p_{\%}}$). That can be interpreted as a more significant amount of energy exported from the customer to the feeder.

VI. Discussion of the Results

This section discusses the performance of the management strategies applied in each of the feeders. In Table III, a comparison is shown between the HCs achieved with "No Control" (NC), with "Control" (C), by "BESS" (B), and "Control + BESS" (C + B) in IEEE 123 feeder; for which is showing the $DG_{p\%}$ of the HC achieved, the total of customers with PV connected ("Customers with PV"), the total installed power of PV ("Total PV in kW"), the maximum % of voltage out of limits and voltage imbalance ("$V_{issues\%}$" and "$VI_{issues\%}$", respectively), the maximum current registered in the feeder in % of its nominal capacity ("$I_{max\%}$") and the total energy exported by electric substation in MWh ("Exported Energy in MWh"). The three strategies C, B, and C + B, will be compared with NC and each other. Their respective advantages will be mentioned.

The strategies to reduce active power (C and C + B) achieved the highest increases in HC, with 35 % and 43 %, respectively. In contrast, in B, no increase in HC was achieved. In B, the same PV capacity installed in NC was maintained; in C, the total installed PV capacity increased by 105 kW, while C + B increased 300 kW. No voltage out of limits was reported in any of the strategies. On the other hand, the voltage imbalances $VI_{issues\%}$ in all management strategies were out of limits (maximum imbalance voltage of all measures is 5 % per customer); in NC is 16.66 % and presented a not very significant reduction in B. Whereas, in C, a more significant number of connected customers was achieved with imbalance of 6.94 %.

While in C + B, 15.27 % of imbalance was achieved with the highest number of customers with PV of all the strategies. The maximum current in B decreased 4.34 % compared to NC. In C, the maximum current was 2.81 % lower with additional customers. In C + B, the maximum current was 65.06 % with 40 clients with PV. Finally, the energy exported in B was reduced due to the use of storage systems, while in C, an additional 391 MWh were exported. In C + B, with the highest amount of exported energy, it was possible to export 1957 MWh more concerning the 929 MWh of NC. In this feeder, the C + B control was the best performance, as it allowed more significant PV integration.

TABLE III
Comparison of the Management Strategies for IEEE 123 Node Test Feeder

Management strategy	NC	C	B	C + B
$DG_{p\%}$	29	35	29	43
Number of customers with PV	27	32	27	40
Total PV in kW	655	760	655	955
$V_{issues\%}$	0	0	0	0
$VI_{issues\%}$	16.66	6.94	15.97	15.27
$I_{max\%}$	65.03	62.22	60.69	65.06
Exported Energy in MWh	929	1320	730	2866

Similarly, Table IV, shows the HC obtained. In this feeder the strategies C, B, and C + B achieved the same HC of 34 %, equivalent to 22 additional customers and additional 651 kW compared to NC. In C and C + B no voltage out of limits were reported ($V_{issues\%} = 0$), while in B 1.38 % was reported which does not represent important voltage regulation problems in this HC. Different voltage imbalance problems were obtained $VI_{issues\%}$ in each of the drives, where B had the highest $VI_{issues\%}$ with 16.66 %, followed by C with 11.11 % and C + B the smallest imbalance with 8.33 %. According to what was reported, $VI_{issues\%}$ in C + B is reduced by up to 50 % with respect to B and ≈ 25 % with respect to C. With respect to the maximum current $I_{max\%}$ in C + B presented the lowest current, while B the highest. The exported energy was lower in the strategies that use active power curtailment; the combination between storage systems and active power curtailment reported the lowest amount of exported energy in C + B. The exported energy difference between C and C + B is due to the active power provided by the BESS when the generation is low or null.

TABLE IV
Comparison of the Management Strategies for Mexican feeder

Management strategy	NC	C	B	C + B
$DG_{p\%}$	26	34	34	34
Number of customers with PV	69	91	91	91
Total PV in kW	2062	2713	2713	2713
$V_{issues\%}$	0	0	1.38	0
$VI_{issues\%}$	6.25	11.11	16.66	8.33
$I_{max\%}$	50.41	54.03	59.04	53.99
Exported Energy in MWh	20042	24299	26083	22905

The two cases presented similar behaviors, in both the maximum current $I_{max\%}$ was lower with the combination of storage systems and active power reduction (C + B); also, no voltage out of limits $V_{issues\%}$ was significant, which indicates that the strategies used can help to control the voltage regulation of the feeder; in both feeders, the active power reduction managed to reduce the voltage imbalance especially when combined with the use of BESS. The same trends were not obtained regarding the HC increase because the two feeders have different characteristics: the number of connected clients, topology, the proportion of PVs, electrical substation capacity, feeder capacity, etc. The exported energy did not report the same trend because one of the feeders was less restricted to HC increase. Also, the additional customers allow a greater active power generated and consequently more energy exported.

The voltage imbalance limited the HC increase in both feeders. The imbalance is because most of the connected PVs are < 50 kW. According to the connection restrictions, the PVs < 50 kW can be connected to one or two phases, producing serious imbalance issues on both feeders. Therefore, voltage imbalance is an aspect that must be considered. In addition, particular characteristics of each feeder do not allow generalizing a behavior pattern when using management strategies; rather, they allow identifying their technical advantages over other strategies.

After performed the respective management strategy, the operator can assess if the feeder performance improves or remains, i.e., for example, if the thermal $DG_{p\%}$ value increase, means that feeder maximum current decreased, which allowed an increase in the generation current injection capacity. In this context, the increase of $DG_{p\%}$ is considered as improving performance. On the other hand, if the $DG_{p_{\%}}$ remains, the operator can evaluate particular operative aspects, as the % of voltage or imbalance over the limits, voltage regulation, and maximum current.

Although the management strategy may not increase the HC in particular situations, it is possible to determine its advantages. This allows the operator to decide which is the most suitable management strategy. Additionally, the approach can help to postpone or avoid the distribution network reinforcement cost.

VII. Conclusions

In this paper, a realistic approach was proposed that evaluated HC in different management strategies. The approach contemplated the natural intermittency of the PVs, random connection, and different PVs capacities distributed through statistics. This allows the estimated HC to be used by the network operator as the reference margin to add PVs without violating the operating restrictions.

Studies have shown more advantages when combined management strategies than when used individually. When just power curtailment is used (C), the feeder performance improves significantly compared with just the BESS management (B); this is because the reverse power flows reduction in the B strategy is limited by the BESS storage capacity. The generation reduction using BESS (C + B) presented the most significant benefits because C and B strategies complement each other.

The exported energy differences when BESS is employed are because the batteries stores part of the PV generation excess; hence, overcurrent and voltage issues reduce because the reverse power flows are decreased. Thus, the management of storage systems can complement other control strategies.

The voltage imbalance in both feeders restricts the increase in HC; however, the management strategies' advantages were mainly favorable. Controls with generation reduction, C and C + B, can allow more users to connect PVs without violating the thermal limit of the feeder and also present fewer imbalance voltages issues, especially with the C + B strategy.

Despite the advantages of using management strategies, the increase in HC is not an obligatory advantage. Moreover, since not all feeders will have the same response, some benefits may be more noticeable depending on their characteristics. So the cost-benefit could be insufficient.

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