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# Short-Term Distribution System Planning Using a System Reduction Technique

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**ABSTRACT** Given the necessity of developing more efficient electric distribution systems (EDSs) and providing a continuous energy service for active and passive users, distribution system planners are constantly seeking for more robust planning strategies that can address the complexities of large-scale EDSs. In this regard, the proposed work investigates the implementation of a novel strategy that is based on two stages to tackle the short-term planning problem in large-scale EDSs. In the first stage, a system reduction technique is developed to remove all non-desired buses and circuits from the original large-scale EDS, while in the second stage an optimization model is formulated to represent the EDS expansion planning problem. The planning stage is designed using a multi-period formulation, which defines, in the most cost-effective way, actions such as the allocation of voltage regulators (VRs) and capacitor banks (CBs) to improve the EDS operation, considering the demand growth and new requests for distributed generation (DG) connections. The objective function of this optimization model minimizes the expected cost of energy purchased from the market and charges due to carbon emission taxes, while the energy purchased from DG developers is maximized. For simulation purposes, a real 1080-bus EDS is reduced to an equivalent 54-bus system and implementing the developed optimization model, results show that a set of planning actions can be obtained to improve the EDS operation. These obtained planning actions are projected to the 1080-bus EDS and using an optimal power flow tool, the accuracy of the proposed planning strategy is estimated.

**INDEX TERMS** Short-term distribution system planning, stochastic mixed-integer linear programming model, system reduction technique.

## NOMECLATURE

### SETS

| | |
|---|---|
| $\Gamma_n / \Gamma_s$ | Set of buses / substations. |
| $\Gamma_t / \Gamma_y / \Gamma_C$ | Set of time periods / planning years / scenarios. |
| $\Gamma_{ca} / \Gamma_{cb}$ | Set of CBs capacities / locations to install CBs. |
| $\Gamma_{dg}$ | Set of candidate locations for DG. |

### PARAMETERS

| | |
|---|---|
| $\gamma$ | Parameter that multiplies the results obtained for $\Gamma_t$ to obtain results for the whole year $y$ ($8760/\|\Gamma_t\|$). |
| $\lambda^{vr}$ | regulation range of a VR. |
| $\Phi^{dg}$ | Power factor for a renewable-based DG unit. |
| $\overline{\tau}$ | Maximum number of steps of a VR. |
| $\zeta^{ct}$ | Prices of charges due to carbon emission taxes. |
| $\zeta^{dg} / \zeta^{pm}_{t,y}$ | Prices of purchasing energy from DG / energy market at time $t$, year $y$. |
| $\zeta^{fx/sw}$, $\zeta^{vr}$ | Allocation cost of CBs and VRs. |
| $\hat{\xi}^{d}_{t,c}$, $\hat{\xi}^{dg}_{t,y,c}$ | Demand relative to the peak demand level and DG power production relative to the rated power capacity at time $t$, year $y$, and scenario $c$. |
| $e^{co2}$ | Emission intensity related to the energy purchased form the market. |
| $\rho_c$ | Probability of occurrence of a scenario $c$. |
| $IL$ | Maximum investment limit. |
| $\overline{I}_{ij}$ | Maximum thermal capacity of circuit $ij$. |

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| | |
|---|---|
| $P^d_{i,y}$, $Q^d_{i,y}$ | Peak demand at node $i$ and year $y$. |
| $\overline{Q}_{b,a}$ | Reactive power of a CB with capacity $a$ at bus $b$. |
| $\overline{P}^{dg}$, $\overline{x}^{dg}_m$ | Nominal capacity and maximum photovoltaic module or wind turbine to be installed at bus $m$. |
| $R_{ij}$, $X_{ij}$ | Resistance, and reactance of circuit $ij$. |
| $Z_{ij}$ | Parameter that represents the magnitude of the impedance of circuit $ij$. |
| $\overline{V}$, $\underline{V}$ | Upper and lower limits for the voltage magnitude. |
| $\overline{I}_{ij}$ | Maximum thermal limit of circuit $ij$. |
| $\overline{x}^{dg}_m$ | Maximum number of DG units to be installed at bus $m$. |

### VARIABLES

| | |
|---|---|
| $\tau_{j,t,y}$ | Integer variable to define the tap position of an VR located at bus $j$, time $t$, year $y$. |
| $C_{b,a,t,y}$ | Integer variable to define the CB modules at bus $b$ with capacity $a$, time $t$, year $y$. |
| $\overline{C}_{b,a}$ | Integer variable to define the maximum modules of a CB to be installed at bus $b$ with capacity $a$. |
| $[I, P, Q]_{ij,t,y,c}$ | Current flow magnitude, and power flow at circuit $ij$, time $t$, year $y$, scenario $c$. |
| $P^{dg}_{m,t,y,c}$, $Q^{dg}_{m,t,y,c}$ | Power supplied by a renewable-based DG unit located at bus $m$, time $t$, year $y$, and scenario $c$. |
| $P^S_{s,t,y,c}$, $Q^S_{s,t,y,c}$ | Power supplied by the substation localized at bus $s$, time $t$, year $y$, and scenario $c$. |
| $Q^{cb}_{b,t,y}$ | Reactive power delivered by a CB at bus $b$, time $t$, year $y$. |
| $V_{i,t,y,c}/\hat{V}_{i,t,y,c}$ | Voltage magnitude / Auxiliary variable to control the voltage at bus $i$, time $t$, year $y$, and scenario $c$. |
| $x^{dg}_m$ | Integer variable to define the number of renewable-based DG units to be installed at bus $m$. |
| $x_{b,a}$ | Binary variable that defines the allocation of a fixed CB at bus $b$ with capacity $a$. |
| $w_{b,a}$ | Binary variable that defines the allocation of a switchable CB at bus $b$ with capacity $a$. |
| $z^{vr}_j$ | Binary variable that defines the allocation of a VR at bus $j$. |

## I. INTRODUCTION

In the last decades, the restructuration of the electricity markets has changed the traditional philosophy of electric distribution system (EDS) planning problems, this condition has encouraged distribution system operators (DSOs) to seek new strategies for providing a safe and discrimination-free energy service to passive and active users. The most common planning strategies are based on the management of operational resources to effectively improve the EDS performance and provide network access for new demand and requests for new connections of distributed generation (DG) [1]. However, the applicability of these strategies depends directly on the number of decision variables considered in the problem formulation and its scalability is compromised when large-scale EDSs are studied.

In order to provide more flexibility in the EDS planning studies, some strategies have been developed based on new trends towards a carbon-free energy service. For example, in [2] is developed a stochastic mixed-integer linear programming (SMILP) model for the expansion EDS planning problem that considers multiple planning options simultaneously with the planning of renewable-based DG. The authors in [3] develop a stochastic mixed-integer conic programming model, where its solution should determine the type, capacity, and location of DG and energy storage systems while carbon emissions are mitigated via the carbon tax policy. Latter, as an alternative to overcome the limitations of such formulation, the strategy proposed in [3] was updated to explore the advantages of implementing a mateheuristic approach in [4]. *Melgar-Dominguez et al.* [5] propose a planning strategy based on two-stage robust formulation, where planning actions are optimized considering the effects of a demand response program and the cap-and-trade policy.

The authors in [6] present an adaptive robust optimization approach that promotes investments in low-emission technologies such as renewable-based DG units, energy storage systems, and electric vehicle charging stations. To analyze the relationship of carbon emissions, investment costs, and generation costs, multiple planning decisions are optimized through a multi-objective strategy in [7]. In [8], a strategy of multiple investment options based on Markov decision process has been developed. The problem is formulated as an intractable multistage stochastic programming model; however, using an approximate dynamic programming approach, the original problem is decomposed into sequential subproblems.

As shown in the discussed papers [2]–[8], the complexity of formulating planning problems for EDSs has been increased due the need to develop strategies that address multiple investment options with an emphasis on achieving economic, technical, and environmental targets. When these planning strategies are based on classical optimization approaches, their efficiency could be impaired when large-scale EDSs are studied. As an alternative, the authors in [9] present a decomposition approach, based on variable neighborhood search algorithm, to solve a planning problem of large-scale EDSs, which involves the medium and low-voltage network.

Such complexities bring new challenges to be considered in the formulation of a planning problem of large-scale EDS. This condition shows the need of exploring new approaches based on techniques for system reduction. These techniques seek to remove all non-desired buses and circuits to lessen the number of decision variables to be considered. The authors in [10] develop a simplification technique applied to EDSs to assess the impacts of integrating photovoltaic (PV)-based DG. In [11], the authors present a reduction method for a feeder dynamic analysis with a high penetration level of PV-based DG. In [12], the approaches proposed in [10] and [11] are enhanced to cope with imbalances in circuits and loads. Later, the methodology presented in [12] is generalized to consider the aggregation of load and generation [13], and the aggregation of voltage regulator (VR) devices [15]. In the literature can be found other reduction techniques, for example, a method based on segment substitution [14], a backward-forward graph navigation technique for radial systems [16], and a decomposition technique into upstream and downstream systems [17].

In most works related to the development of EDS planning strategies [2]–[8], their applicability have been limited to medium-scale EDSs (up to hundreds of buses), where only [9] presents a metaheuristic-based approach to solve large-scale EDSs. On the other hand, the application of system reduction techniques has been scarcely investigated, where only the authors in [18] propose a simplification technique for determining an equivalent EDS and by solving a deterministic optimization model, planning decisions are carried in such reduced system. However, this approach is limited to a medium-scale 135-bus EDS and its application in large-scale EDSs has not investigated. In this context, the present work aims to fill the existing gap in the literature by taking advantages of a system reduction technique to solve the short-term planning problem in large-scale EDS. Therefore, based on the above review, where the main drawbacks of the existing literature are discussed, the contributions of the proposed work are:

- Proposing a novel strategy to tackle the short-term planning problem in large-scale EDSs. The problem is viewed from the DSO point of view, and consists of determining the most suitable planning actions to improve the EDS operation, considering the demand growth and new DG connections. Traditional planning actions, such as the allocation of VRs and CBs, are optimized to effectively control the voltage profile and reactive power support. Therefore, the strategy consists of two stages, where a system reduction technique for removing all non-desired buses and circuits is designed in the first stage. Meanwhile, the second stage presents a stochastic optimization model, where its solution defines the planning actions to be carried out.
- Implementing a system reduction technique to estimate a reduced EDS that can be used in planning studies. This technique allows, by removing non-desired buses and circuits, reducing the number of variables to be considered in the problem solution without losing the relevant characteristics of a large-scale EDS.
- Proposing a SMILP formulation that addresses, via a multi-period representation, a planning horizon composed by several years, where each year captures the variability and uncertainties of demand and DG power production. The solution obtained from this model, using the reduced EDS, can be projected to the original system, as an alternative to solve planning problems in large-scale EDSs via classical optimization techniques.

## II. PROBLEM DESCRIPTION

DSOs is an entity responsible for efficiently operating an EDS and providing a continuous power supply with acceptable quality to their users. When demand increases over the years and the current EDS infrastructure cannot meet the new demand with quality standards, the DSO should implement some planning actions to provide a quality energy service maximizing the EDS efficiency. Some common actions, implemented in a short-term planning period, consist of the coordination of some devices to the effective management of voltage profiles, reactive power injections, energy losses, and power factor [19]. Nevertheless, the emergence of renewable-based DG has encouraged the DSO to seek new strategies to integrate such projects in their EDS planning studies.

In this work, the problem is studied from the DSO perspective that consists of implementing planning actions such as the allocation of VRs and CBs to improve the EDS operation, guaranteeing the quality of the energy service for all users. In the formulation, the problem involves requests for renewable-based DG connections, where it is considered that the DSO encourages the DG developers to integrate their projects by purchasing the energy produced by these sources. Therefore, DG developers should integrate their projects in a cooperative way, for which the DSO establishes the suitable capacity to be installed in EDS locations predefined by the DG developers. It is considered that DG developers have evaluated the economic and technical benefits of connecting to such EDS locations.

From the mathematical perspective, the complexity of the presented problem increases when large-scale EDSs are studied. To overcome these challenges, this work proposes a strategy that consists of implementing a system reduction technique while a SMILP model is used to represent the expansion planning problem of EDSs. The system reduction technique seeks to estimate an approximate EDS, where some characteristics such as buses and circuits classified according to the DSO criteria or by physical conditions due to EDS infrastructure should be retained in the reduced system. Finally, the decision-making process is assisted by solving the SMILP model that should define, in the most cost-effective way, the planning actions to be carried out in the EDS and the proper renewable-based DG installed capacity to be connected.

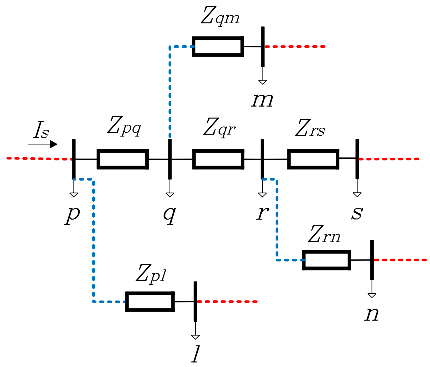


**FIGURE 1. Illustrative diagram for a generic system configuration.**

## III. SYSTEM REDUCTION TECHNIQUE

The implementation of this technique consists of developing four algorithms to remove all non-desired buses and circuits from a radial large-scale EDS. For planning purposes, imbalances in both load and generation are outside the scope of the proposed work.

### A. SYSTEM IDENTIFICATION

Prior to develop the reduction technique, the following steps should be carried out:

1) Identify the radial EDS topology and storing the data information into the matrix $L$, where each circuit with its respective impedance is associated. Similarly, identify the matrix $N$ that contains all the buses with their respective active and reactive power demand.
2) Considering the matrix $N$, each bus is categorized as presented in in Fig. 1. In this illustrative 7-bus system, buses $p$, $q$ and $r$ are denoted as main buses and other buses $s$, $m$, $n$ and $l$ show some configurations that can appear during the reduction process. From this figure, the red dotted lines represent the existence of more circuits, the blue dotted lines represent the existence or not of additional circuits, this information is conveniently exemplified as needed.
3) Define the bus $p$ as the reference or root point.
4) Considering $p$ as the reference bus, $q$ is defined as middle bus, $r$ as adjacent bus and $l, m, n$ and $s$ are denoted as extreme buses.
5) Finally, define the matrix $N_i$ that contains the desired buses established by the DSO criteria.

To remove all non-desired busses, some special conditions that depend on the bus location are considered to maintain the relevant characteristics of the original EDS. These conditions are explained in detail in the following subsections:

#### 1) REMOVING ALL NON-DESIRED MIDDLE BUSES

From Fig. 1 considers the circuits formed by the buses $p$, $q$ and $r$, where $p$ is the reference bus, $q$ is a middle bus and $r$ is an adjacent bus. To remove $q$ from the original configuration, it is necessary that this bus is an unbranched and non-desired bus, in other words, there is no $q-m$ circuit. Initially, the loads are modeled as constant current, according to *Kirchhoff*'s first law, the current of the bus $q$, given by $I_q$, is divided into two parts as shown in (1). In (2), each part of the current is affected by the impedances $Z_{pq}$ and $Z_{qr}$. Finally, expression (3) determines the equivalent currents $I_p^{eq}$ and $I_r^{eq}$, where the respective part of $I_q$ is added to the current of buses $p$ and $r$.

$$I_q = I'_q + I''_q. \tag{1}$$

$$I'_q = \frac{Z_{qr}}{Z_{pq}+Z_{qr}} I_q; \quad I''_q = \frac{Z_{pq}}{Z_{pq}+Z_{qr}} I_q. \tag{2}$$

$$I_p^{eq} = I_p + I'_q; \quad I_r^{eq} = I_r + I''_q. \tag{3}$$

Multiplying the previous expressions (1)-(3) by its respective voltage ($V_p$, $V_q$, and $V_r$), equivalent expressions for the demand for each bus are obtained as shown in (4)-(6). Note that in (5), the demand $S_q$ is obtained considering that $V_q - V_p \approx 0$ and $V_r - V_q \approx 0$, where each part of this demand is affected by the impedances $Z_{pq}$ and $Z_{qr}$. In (6), these parts are added to the demand of buses $p$ and $r$, resulting in equivalent demands $S_p^{eq}$ and $S_r^{eq}$. Expression (7) ensures that the initial system demand (with buses $p$, $q$ and $r$) must be equal to the equivalent demand (resulting from removing bus $q$). Finally, (8) establishes that the impedance of the equivalent circuit is the total impedance of circuits $p-q$ and $q-r$.

$$S_q = S'_q + S''_q. \tag{4}$$

$$S'_q = \frac{Z_{qr}}{Z_{pq}+Z_{qr}} S_q; \quad S''_q = \frac{Z_{pq}}{Z_{pq}+Z_{qr}} S_q. \tag{5}$$

$$S_p^{eq} = S_p + S'_q; \quad S_r^{eq} = S_r + S''_q, \tag{6}$$

$$S_p + S_q + S_r = S_p^{eq} + S_r^{eq}, \tag{7}$$

$$Z^{eq} = Z_{pq} + Z_{qr}. \tag{8}$$

#### 2) REMOVING ALL NON-DESIRED END BUSES AND BUSES WITH DEMAND EQUAL ZERO

This step is implemented for those non-desired buses that appear at the end of each EDS branch. To illustrate this condition, consider in Fig. 1 the circuit $r-s$, where $s$ is an extreme bus to be removed. In this situation, the demand of such end-bus must be transferred to the adjacent bus; For example, the demand of the bus $r$ is modified by the demand transferred from the bus $s$ as shown in (9). When the equivalent demand $S_r^{eq}$ is determined, the impedance of the circuit $r-s$ is simply removed.

$$S_r^{eq} = S_r + S_s. \tag{9}$$

Another situation that can appear in the reduction process is non-desired buses with a demand equal to zero. When end buses, for example, $l$, $m$, $n$ and $s$, are non-desired buses and have no demand, the procedure consists of removing these buses and also their connection impedances.

### B. REDUCTION PROCEDURE

The procedure consists of a sequence of steps, which are carried out until all non-desired buses and circuits are removed. These steps are detailed as follows:

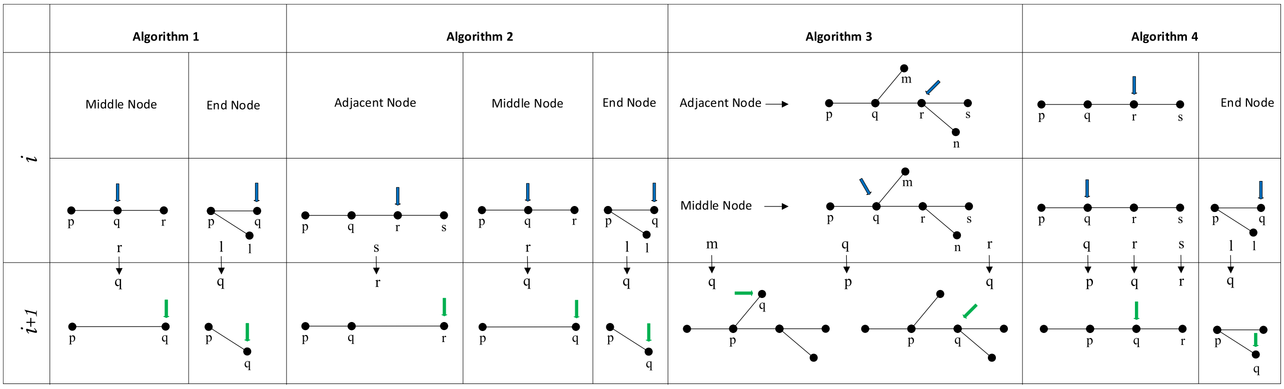


**FIGURE 2.** Illustrative diagram of the reduction process for the algorithms 1, 2, 3, and 4.

1) Find and sort the elements of the matrix $L$ in descending order. Identify all buses contained in this matrix and start the process with the root bus (generally denoted as $p$).
2) The matrix of desired buses $N_i$ is added to the matrix $N$. These desired buses must remain in the reduced EDS.
3) Identify special buses such as locations of substations, control devices, DG units and added to $N_i$.
4) Eliminate all non-desired buses and circuits, using four algorithms:
   a) Algorithm 1: Reduction by bus location.
   b) Algorithm 2: Reduction by characteristic bus.
   c) Algorithm 3: Identification of branching bus.
   d) Algorithm 4: Identification of desired bus.
5) To maintain the topological characteristics of the system, the algorithm determines automatically a subset $N_u$ that contains all the junction buses, which are added to the set $N_i$ ($N_i \leftarrow N_i + N_u$).
6) The reduction process ends when the number of rows ($N_f$) in the matrix $N$ is equal to the number of elements in $N_i$ ($N_f = N_i$).

The implementation of the reduction technique is studied considering four circumstances, each one with its corresponding algorithm as shown in the bus diagram in Fig. 2 and based on Fig. 1. From Fig. 2, the upper part shows the current iteration identified by $i$ and the lower part the next iteration $i+1$. Note that Algorithms 3 and 4 simultaneously analyze two buses with different characteristics in the current iteration. In each algorithm the analysis is carried out by columns with shifts from left to right, blue arrows indicate the analysis of the possible bus to be removed from the original system, while green arrows identify the new position of the bus $q$. Each algorithm is presented the following subsections:

### 1) ALGORITHM 1: REDUCTION BY BUS LOCATION

The process used in this algorithm is presented in Algorithm 1 and illustrated using Fig. 2. The loop is executed only when $q$ is a middle or extreme bus, in both cases $q$ should not be a desired or a branched bus. When $q$ is a middle bus, the elimination is carried out using (4)-(8), where in the next iteration, part of the demand of $q$ is transferred to the buses $p$ and $r$, and the equivalent impedance is calculated. For algorithm implementation purposes, the bus $r$ takes the position of the bus $q$ in the next iteration, while the reference bus $p$ remains. Considering $q$ as an end bus, this case is illustrated in the second column of Fig. 2, for the next iteration this bus and the impedance of the circuit $p$—$q$ are simply removed from the EDS. Note that, the position of the bus $p$ is retained and, in the iteration $i$+1, the bus $l$ is parsed as $q$.

**Algorithm 1** Reduction by Bus Location

Initiate $i = 0$;
**while** $N_f \neq N_i$ **do**
  **if** $q$ is: Middle, unbranched and non-desired bus **then**
    $q^{i+1} \leftarrow r^i$;
    $S_p^{i+1} \leftarrow S_p^i + \frac{Z_{qr}^i}{Z_{pq}^i + Z_{qr}^i} S_q^i$;
    $S_r^{i+1} \leftarrow S_r^i + \frac{Z_{pq}^i}{Z_{pq}^i + Z_{qr}^i} S_q^i$;
    $Z_{pq}^{i+1} \leftarrow Z_{pq}^i + Z_{qr}^i$;
  **else if** $q$ is: Extreme and non-desired bus **then**
    Remove $Z_{pq}^i$
    $S_p^{i+1} \leftarrow S_p^i + S_q^i$;
  **end if**
  $i \leftarrow i+1$
**end while**

### 2) ALGORITHM 2: REDUCTION BY CHARACTERISTIC BUS

For this Algorithm 2, three possibilities are considered and exemplified using Fig. 2. This type of reduction occurs when $r$ is an adjacent bus, $q$ is a middle or end bus, where the reduction process depends on whether their demand are zero, without circuits connecting them with others buses, and these buses are non-desired buses. The algorithm starts removing the adjacent bus $r$ and the impedance of the circuit $p$—$s$ is determined as the sum of the impedances of the circuits $q$—$r$ and $r$—$s$. In the next iteration ($i$+1), the bus $s$ takes the position of the bus $r$ and the previous procedure is applied. Note that if the bus $r$ cannot be removed, the bus $q$ is analyzed and removed considering the same conditions applied to bus $r$. Similarly, in the next iteration, the bus $r$ takes the position of $q$, if none of these possibilities were found, then $q$ is removed as an end bus as shown in the third column of Algorithm 2, where this bus and its impedance $p$–$q$ are removed from the system and, the bus $l$ takes the position of $q$ for the next iteration.

**Algorithm 2** Reduction by Characteristic Bus

Initiate $i = 0$ ;
**while** $N_f \neq N_i$ **do**
  **if** $r$ is: Adjacent, unbranched, demand equals to zero and non-desired bus **then**
    Remove bus $r$
    $Z_{qr}^{i+1} \leftarrow Z_{qr}^{i} + Z_{rs}^{i}$;
  **else if** $q$ is: middle, unbranched, demand equals to zero and non-desired bus **then**
    Remove bus $q$
    $p^{i+1} \leftarrow p^{i}$;
    $q^{i+1} \leftarrow r^{i}$;
    $Z_{pq}^{i+1} \leftarrow Z_{pq}^{i} + Z_{qr}^{i}$;
  **else if** $q$ is: end, demand equals to zero and non-desired bus **then**
    Remove bus $q$
    Remove $Z_{pq}^{i}$
    $p^{i+1} \leftarrow p^{i}$;
    $q^{i+1} \leftarrow l^{i}$;
  **end if**
  $i \leftarrow i+1$
**end while**

### 3) ALGORITHM 3 AND 4

Algorithms 3 and 4 are used to identify some characteristic of each bus under study and their implementation is simultaneously carried out with Algorithms 1 and 2. The Algorithm 3, procedure illustrated in Fig. 2, considers that the bus $r$ is adjacent and $q$ is a middle bus, both identified as branched buses. This procedure starts analyzing the buses $r$ and $q$ in the same iteration, if no bus is removed, then in the next iteration ($i$+1), all the bus positions including the reference bus $p$ are moved to the next position as shown in Fig. 2. Similarly, the Algorithm 4 considers $r$ as an adjacent bus and $q$ as a middle or end bus. The procedure starts analyzing the bus $r$ and the middle bus $q$ in the same iteration. For the next iteration, the positions of all the buses to be analyzed are shifted when no bus is removed. Other possibility is that $q$ is an end bus, where the new position of $q$ is the position of bus $l$ as illustrated in the last column of Fig. 2.

**Algorithm 3** Identification of Branching Bus

Initiate $i = 0$ ;
**while** $N_f \neq N_i$ **do**
  **if** $r$ and $q$ are:Branched buses **then**
    **if** $r$ is: Adjacent bus **then**
    **end if**
    **if** $q$ is: Middle bus **then**
      $p^{i+1} \leftarrow q^{i}$;
    **end if**
    $i \leftarrow i+1$
  **end if**
**end while**

## IV. PLANNING PROBLEM FORMULATION

In previous section, a system reduction technique was presented to reduce a large-scale EDS to an equivalent system. In this regard, the mathematical formulation of a SMILP model to represent the short-term planning problem is proposed in

**Algorithm 4** Identification of Desired Bus

Initiate $i = 0$ ;
**while** $N_f \neq N_i$ **do**
  **if** $r$ and $q$ are: desired buses **then**
    **if** $r$ is: Adjacent bus **then**
    **end if**
    **if** $q$ is: Middle bus **then**
      $p^{i+1} \leftarrow q^{i}$;
      $q^{i+1} \leftarrow r^{i}$;
      $r^{i+1} \leftarrow s^{i}$;
    **else if** $q$ is: End bus **then**
      $p^{i+1} \leftarrow p^{i}$;
      $q^{i+1} \leftarrow l^{i}$;
    **end if**
  **end if**
  $i \leftarrow i+1$
**end while**

this section. The problem formulation considers the optimal allocation and coordination of VRs and CBs to provide an effective control of the voltage profile and the reactive power support. In addition, the capacity for new connections of DG units in predefined locations should be defined.

### A. UNCERTAINTY CHARACTERIZATION FOR DEMAND AND GENERATION

The distribution planning problem involves some uncertain parameters, which are related to the demand, wind speed and irradiance level in the location where the DG units can be installed. The uncertain behavior is characterized using probability density functions (PDFs). The realizations of conventional demand are modeled through the normal PDF, where these realizations are assumed to be normally distributed around the prediction value with a standard deviation of 2%.

The uncertainty of solar irradiance can be modeled using several PDFs such as Beta, Weibull and Log-Normal. In this work, the Weibull PDF is used to model the solar irradiance [20]. To properly model the uncertain behavior of wind speed, the Rayleigh PDF is a common expression to characterize such behavior [21]. With the information obtained from the Weibull PDF, for a given wind speed, the normalized wind power relative to the installed capacity is determined using a linear approximation of the wind curve [22].

### B. GENERATION PROCESS FOR REPRESENTATIVE SCENARIOS

Increasing the number of scenarios can improve the accuracy of the PDFs that models the uncertainties. However, a large number of scenarios lead to a great computational effort to solve optimization problems. In this regard, implementing a scenario reduction technique, which allows determining the most representative scenarios, could be crucial to determine the solution of the proposed SMILP model. This process is carried out in two steps described as follows:

- Step 1: To predict a certain number of probable scenarios, the first step consists of randomly generating a large number of scenarios. These scenarios are generated using the PDFs for conventional demand, wind speed and solar irradiance presented in the previous section.

- Step 2: Using the scenarios generated in the previous step, here the k-means technique is used to determine representative scenarios in order to reduce the problem complexity and obtain a more tractable problem. This scenario reduction technique classifies and clusters the scenarios into a certain number of groups, depending on their characteristics [23].

### C. OPTIMIZATION MODEL

The objective function given in (10) minimizes the expectation of energy purchased from the market and charges due to carbon emission taxes while the energy purchased from renewable-based DG is maximized. The planning horizon is composed of a predefined number of years contained in the set $\Gamma_y$, each year $y$ is represented by a set of time intervals $\Gamma_t$ to capture the variability in the demand and renewable power production. It is worth noting that the components of (10) are calculated as present values considering the planning years and the interest rate $r$.

$$\min \sum_{s\in\Gamma_s}\sum_{t\in\Gamma_t}\sum_{y\in\Gamma_y}\sum_{c\in\Gamma_{sc}} \frac{\rho_c\left[\zeta^{pm}_{t,y}\gamma P^S_{s,t,y,c}+\zeta^{ct}e^{co2}\gamma P^S_{s,t,y,c}\right]}{(1+r)^y} - \sum_{m\in\Gamma_{dg}}\sum_{t\in\Gamma_t}\sum_{y\in\Gamma_y}\sum_{c\in\Gamma_{sc}} \frac{\rho_c\zeta^{dg}\gamma P^{dg}_{m,t,y,c}}{(1+r)^y} \quad (10)$$

This objective function is subject to the EDS steady-state operating constraints (11a), technical limits (12a), constraints of allocation of CBs and VRs (13a) and (14a), operation and location of renewable-based DG units (15), and the predefined investment budget (16).

The active and reactive power balance are presented in (11a) and (11b), respectively. The voltage drop at circuit $ij$ is determined in (11c) while the magnitude of the current flow is calculated using (11d). Note that these expressions contain quadratic terms and the non-convex constraint given by (11d); thus, some reformulations are implemented as presented in [24]. In (11d), the left-hand side term is approximated using the nominal voltage while the right-hand side is linearized using piecewise linear functions [25]. Technical limits and quality requirements of an EDS are defined in (12a) and (12b), where (12a) define the lower and upper bound for the voltage magnitude and (12b) defines the thermal capacity for each circuit $ij$.

$$\sum_{ij\in\Gamma_l} P_{ij,t,y,c}-\sum_{ji\in\Gamma_l}(P_{ji,t,y,c}+R_{ij}I^2_{ij,t,y,c})+\sum_{s\in\Gamma_s|_{s=i}} P^S_{s,t,y,c} + \sum_{m\in\Gamma_{dg}|_{m=i}} P^{dg}_{m,t,y,c} = P^d_{i,y}\hat{\xi}^d_{t,c},\ \forall(i,t,y,c), \quad (11a)$$

$$\sum_{l\in\Gamma_l} Q_{ij,t,y,c}-\sum_{ji\in\Gamma_l}(Q_{ji,t,y,c}+X_{ij}I^2_{ij,t,y,c})+\sum_{s\in\Gamma_s|_{s=i}} Q^S_{s,t,y,c} + \sum_{m\in\Gamma_{dg}|_{m=i}} Q^{dg}_{m,t,y,c}+\sum_{b\in\Gamma_{cb}|_{b=i}} Q^{cb}_{b,t,y} = Q^d_{i,y}\hat{\xi}^d_{t,c}, \quad \forall(i,t,y,c), \quad (11b)$$

$$V_{i,t,y,c}-\hat{V}_{j,t,y,c} = \frac{(R_{ij}P_{ij,t,y,c}+X_{ij}Q_{ij,t,y,c})}{V^o}, \quad \forall(i,j,ij,t,y,c), \quad (11c)$$

$$I^2_{ij,t,y,c}V^2_{i,t,y,c} = P^2_{ij,t,y,c}+Q^2_{ij,t,y,c},\ \forall(i,ij,t,y,c), \quad (11d)$$

$$\underline{V} \le V_{i,t,y,c} \le \overline{V}, \quad \forall(i,t,y,c), \quad (12a)$$

$$0 \le I_{ij,t,y,c} \le \overline{I}_{ij}, \quad \forall(ij,t,y,c), \quad (12b)$$

where the indices $(i,j), ij, b, c, m, s, t, y$ correspond to the sets $\Gamma_n, \Gamma_l, \Gamma_{cb}, \Gamma_C, \Gamma_{dg} \subset \Gamma_n, \Gamma_s \subset \Gamma_n, \Gamma_t, \Gamma_y$, respectively.

Planning actions are performed to improve the EDS operation and to avoid violations of technical constraints under the expectation of the demand growth during the short-term horizon. In this work, fixed and switchable CBs and VRs are considered as planning options. The allocation and operation of these devices are modeled by expressions (13) and (14), respectively. The reactive power injection for a CB installed at bus $b$ with capacity $a$ is defined by (13a). To determine the capacity and type (fixed or switchable) of a CB, expression (13b) is used. From this expression, $ax_{b,a}$ and $aw_{b,a}$ represent the capacity of a fixed and switchable CB, respectively. If a CB to be installed is determined to be fixed, then $C_{b,a,t,y} = \overline{C}_{b,a}$; otherwise, (13c) and (13d) are used to optimally choose a switchable CB. Logical constraints in (13e) define that only one capacity of a fixed and a switchable CB can be installed at bus $b$. When a VR is located at bus $j$, the voltage magnitude is regulated in (14a), which depends on the step voltage variation ($\frac{\lambda^{vr}}{\overline{\tau}}$) and the tap position $\tau$. In (14b), the available tap steps are limited by the lower and upper bound, which depend on the maximum tap step position ($\pm\overline{\tau}$). Note that a VR is located when $z^{vr} = 1$ in (14b); otherwise, the VR is not installed and the voltage magnitude in (14a) is not regulated ($V = \hat{V}$).

$$Q^{cb}_{b,t,y} = C_{b,a,t,y}\overline{Q}_{b,a}, \quad \forall(b,a,t,y), \quad (13a)$$

$$0 \le \overline{C}_{b,a} \le \sum_{a\in\Gamma_{ca}} ax_{b,a}+\sum_{a\in\Gamma_{ca}} aw_{b,a},\ \forall(b,a), \quad (13b)$$

$$\overline{C}_{b,a} \le C_{b,a,t,y}+\sum_{a\in\Gamma_{ca}} aw_{b,a}, \quad \forall(b,a,t,y), \quad (13c)$$

$$0 \le C_{b,a,t,y} \le \overline{C}_{b,a}, \quad \forall(b,a,t,y), \quad (13d)$$

$$\sum_{a\in\Gamma_{ca}} x_{b,a} \le 1;\ \sum_{a\in\Gamma_{ca}} w_{b,a} \le 1, \quad \forall b, \quad (13e)$$

$$V_{j,t,y,c} = \hat{V}_{j,t,y,c}+\frac{\lambda^{vr}}{\overline{\tau}}\tau_{j,t,y}, \quad \forall(j,t,y,c), \quad (14a)$$

$$-\overline{\tau}z^{vr}_j \le \tau_{j,t,y} \le \overline{\tau}z^{vr}_j \quad \forall(j,t,y), \quad (14b)$$

where the indices $a, b, c, j, t, y$ correspond to the sets $\Gamma_{ca}, \Gamma_{cb}, \Gamma_C, \Gamma_n, \Gamma_t, \Gamma_y$, respectively.

Renewable-based DG units are considered to be integrated in the formulation of the short-term planning problem. In this approach, the DG developers define locations where their projects should be connected to the EDS; however, the DSO determines the most appropriate DG capacity to be connected to the system. The DG operation model is given

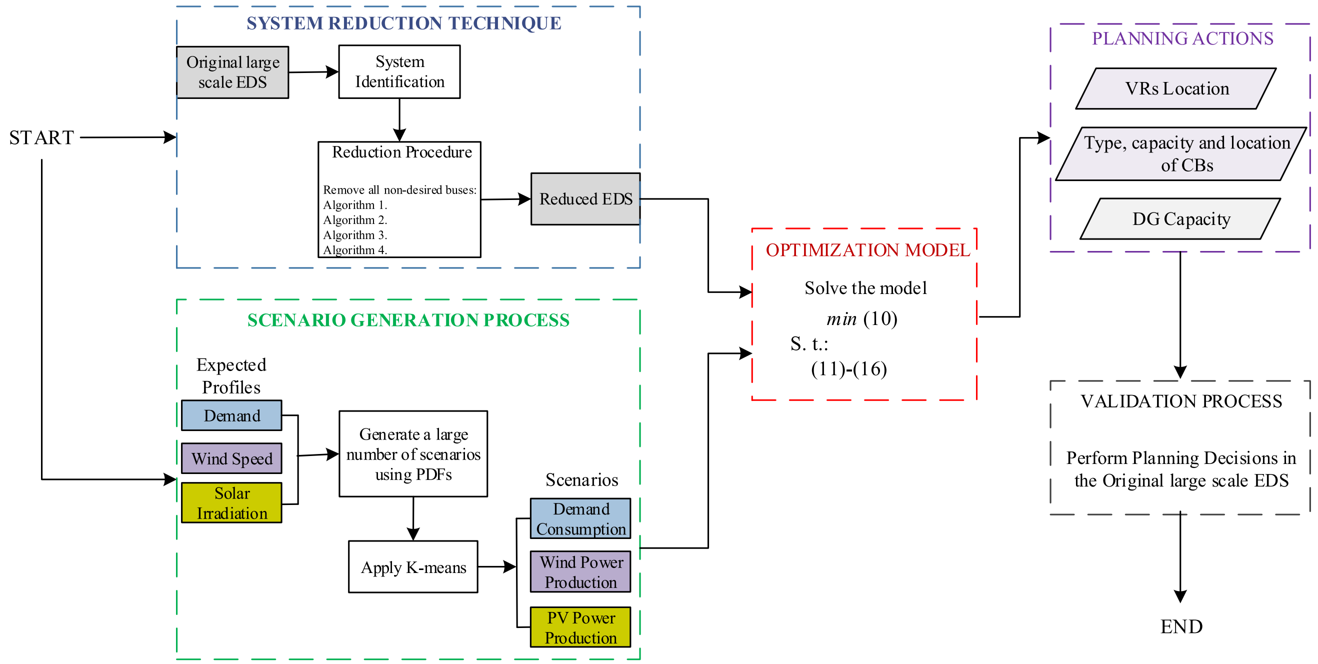


**FIGURE 3.** **Flowchart of the proposed solution framework.**

by (15), where the active power injection at bus $m$ is modeled by (15a) that depends on the installed capacity ($x_m^{dg}\overline{P}_m^{dg}$) and the generation factor $\hat{\xi}^{dg}$. This factor $\hat{\xi}^{dg}$ represents the variability of the available power relative to the installed DG capacity and depends directly on the technology considered (wind or PV), for which their values are generated by using PDFs. The capacity of a DG unit located at bus $m$ is determined by the integer variable $x_m^{dg}$ in (15b). It is considered in (15c) that DG units can provide reactive power support to the system. The DG reactive power support is controlled by a predefined power factor $\Phi^{dg}$ and the active power injection $P^{dg}$.

$$P_{m,t,y,c}^{dg} = x_m^{dg}\overline{P}_m^{dg}\hat{\xi}_{t,y,c}^{dg}, \quad \forall(m,t,y,c), \tag{15a}$$

$$0 \leq x_m^{dg} \leq \overline{x}_m^{dg}, \quad \forall m, \tag{15b}$$

$$-P_{m,t,y,c}^{dg} tg(cos^{-1}\Phi^{dg}) \leq Q_{m,t,y,c}^{dg} \leq P_{m,t,y,c}^{dg} tg(cos^{-1}\Phi^{dg}), \quad \forall(m,t,y,c), \tag{15c}$$

where the indices $c, m, t, y$ correspond to the sets $\Gamma_C, \Gamma_{dg} \subset \Gamma_n, \Gamma_t, \Gamma_y$, respectively.

Finally, (16) defines the maximum investment budget established by the DSO for the allocation of CBs and VRs.

$$\sum_{b\in\Gamma_{cb}}\sum_{a\in\Gamma_{ca}} \zeta_a^{fx} x_{b,a} + \sum_{b\in\Gamma_{cb}}\sum_{a\in\Gamma_{ca}} \zeta_a^{sw} w_{b,a} + \sum_{j\in\Gamma_n} \zeta^{vr} z_j^{vr} \leq IL \tag{16}$$

### *D. SOLUTION SCHEME FOR THE SHORT-TERM PLANNING PROBLEM*

For illustrative purposes, the proposed strategy to solve the short-term planning problem in real large-scale EDS is divided in five steps, where it is identified the system reduction technique, scenario generation process, optimization model, planning actions as the output of the strategy, and the validation process. Each step, presented in Fig. 3, is explained as follows:

- In the first step, the system reduction technique requires the information of the original EDS, where the EDS topology, power demand, impedances of circuits, and desired nodes and circuits are identified and stored. Using this information, the reduction process starts removing all non-desired buses and circuits using the strategies presented in Algorithms 1-4.
- Prior to solve the planning problem, uncertainties in demand and DG power production are captured by an scenario generation process in the step two. A large number of scenarios are generated using PDFs and, to reduce the problem complexity, the K-means technique is implemented to determine a representative number of scenarios.
- Once the original EDS is reduced to an equivalent simplified system and uncertainties are captured by a representative number of scenarios, this information is the input data used to solve the optimization model in the third step.
- The solution of the optimization model defines the VRs location, type, capacity, and location of CBs and

the renewable-based DG capacity, being these planning actions the output data of the proposed strategy.

- In the final step, all the planning decisions are projected to the original EDS. To validate the planning results, an optimal power flow tool is used to perform simulations using both systems (original and reduced), where its solution allows to estimate the accuracy of the developed reduction technique.

## V. CASE STUDIES

To evaluate the performance of the developed planning strategy, a real 1080-buses EDS [26] is studied under different test conditions. Prior to assess the performance of the strategy, this section describes assumptions, case studies, technical information of the 1080-buses EDS, and technical and economic information of each planning options.

### A. DATA INFORMATION

The system reduction technique is implemented in the real 1080-bus distribution system. This system contains a substation, 1079 circuits and 1080-buses, the peak demand for this system is 4,136 MW and 1,758 MVAr, the nominal voltage is 13.8 kV, where upper and lower limits are defined to 1.05 and 0.95 pu, respectively. An emission intensity of 0.80 kg-$CO_2$/kWh and a carbon emission tax of \$45/ton-$CO_2$ are adopted. The solution of the planning problem should provide the localization, size and determine the type of planning option to be carried out. The planning problem considers options such as the allocation of VRs and CBs (fixed and switchable), in addition, the operation of these devices is optimally coordinated to provide more flexibility in the operation stage of the EDS.

The economic information regarding to installation cost of CBs and VRs can be found in [27]. For these devices, an investment limit is defined to \$30k, it is worth mentioning that this budget can be defined by the DSO prior to solve the optimization problem. Independent projects of DG based on PV and wind technologies are considered in this work. It is assumed that the DG developers define specific locations for connecting their projects. For test purposes, locations at buses 183, 483, and 563 are defined for PV-based DG while 487, 791, and 805 for wind-based DG. It is worth mentioning that these DG locations do not affect the performance of the proposed planning strategy, which is implemented based on the DSO criteria.

It is considered that DG units can provide reactive power support by controlling the power factor of each unit, which is set to 0.98. The prices of energy purchased from renewable-based DG ($\zeta^{dg}$) are assumed to be \$60/MWh.

### B. ASSUMPTIONS AND CASES

In order to validate the proposed strategy is assumed a planning horizon of 3 years, where the demand is expected to increase annually by 3% and an interest rate of 2% is adopted. In the planning horizon of 3 years, each year is divided into 48 time intervals ($t$) to capture the variability of demand and DG power production. For these 48-$t$s, prices of energy purchased from the market, and the expected profiles for demand and DG power injections are presented in Fig.4.

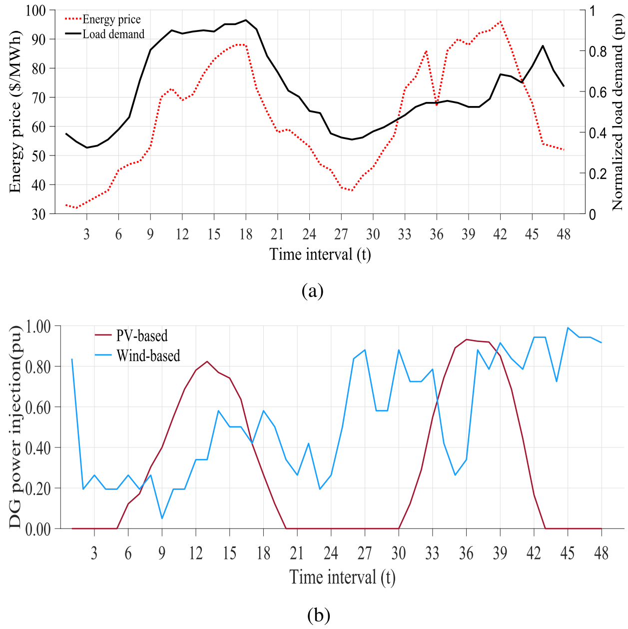


**FIGURE 4.** Expected value for a) demand and price of energy purchased from the market, and b) DG power injections.

Prior to implement the planning strategy, the initial condition of the 1080-bus EDS is determined using a power flow tool. The results show, in Fig. 5, an infeasible EDS operation with a voltage magnitude profile below the predefined lower limit when at peak loading scenario is assessed. Therefore, in order to overcome this infeasible EDS operation, three cases are studied and presented as follows:

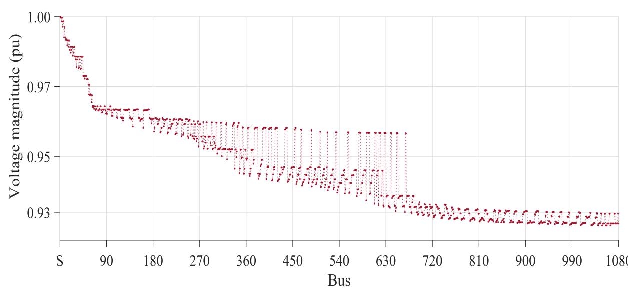


**FIGURE 5.** Voltage profile at peak loading scenario for the initial condition.

- Case I: Considering only the optimal allocation of fixed and switchable CBs.
- Case II: The CB location is simultaneously optimized with the capacity planning for renewable-based DG.
- Case III: Considering the optimal allocation of VR and capacity planning for renewable-based DG units.

## VI. SIMULATION RESULTS AND DISCUSSION

The strategy consists of implementing a system reduction technique to determine an equivalent EDS, and an optimization model to represent the short-term planning problem. In this regard, the system reduction technique has been implemented in Matlab, while the optimization model in the mathematical language AMPL and solved using CPLEX. A computer with an Intel i7-7700 processor and memory RAM of 16 GB is used for carried out the simulations.

Therefore, numerical results are categorized into three subsections, where the first one shows the equivalent reduced EDS. In the second subsection, results of the planning actions to be carried out on such system are presented and, finally, the last one validates via a comparative analysis, the performance and applicability of the proposed planning strategy.

### A. SYSTEM REDUCTION TECHNIQUE

The system reduction technique is implemented on the 1080-bus system, where the diagram of this system is shown in Fig. 6.a. Based on results obtained for the initial condition, where Fig.5 reveals that the 1080-bus EDS does not meet the power quality standards, buses with voltage magnitude below to the lower bound are defined as desired buses. These buses, presented in black in Fig. 6.b, are defined as candidate locations to install fixed and switchable CBs, and VRs. In addition, buses for allocating wind- and PV-based DG units are also included in this figure. This figure also shows additional buses identified in red and blue as those that host the substation and topological points (junction buses), respectively. From this identification, the original system is reduced to equivalent EDS by implementing the develop system reduction technique, for which the equivalent EDS must maintain relevant characteristics of the original 1080-bus system. Therefore, as a result of applying the system reduction technique, the 54-bus system is obtained and illustrated in Fig. 6.b, where desired buses are retained from the 1080-bus EDS.

### B. SHORT-TERM PLANNING IN THE EQUIVALENT 54-BUS EDS

From expected profiles for demand and DG power injection, presented in Fig. 4, a set of 1000 scenarios are generated using their corresponding PDFs and, applying the scenario reduction technique K-means, this large number of scenarios is reduced to 10. Therefore, the equivalent reduced 54-bus EDS and the obtained 10 scenarios are used to solve the SMILP under each condition proposed for each case. Results for each case are presented as follows:

#### 1) RESULTS OF CASE I

When only the option of installing CBs is considered to overcome the initial infeasible EDS operation, the solution of the proposed planning model determines that an investment cost of $29.35k is needed. As the option of renewable-based DG connection is disregarded for this case, a higher expected cost of $4498k due to the energy purchased from the market is obtained. In addition, the DSO should pay a high charge of $2418.19k due to the carbon emission taxes.

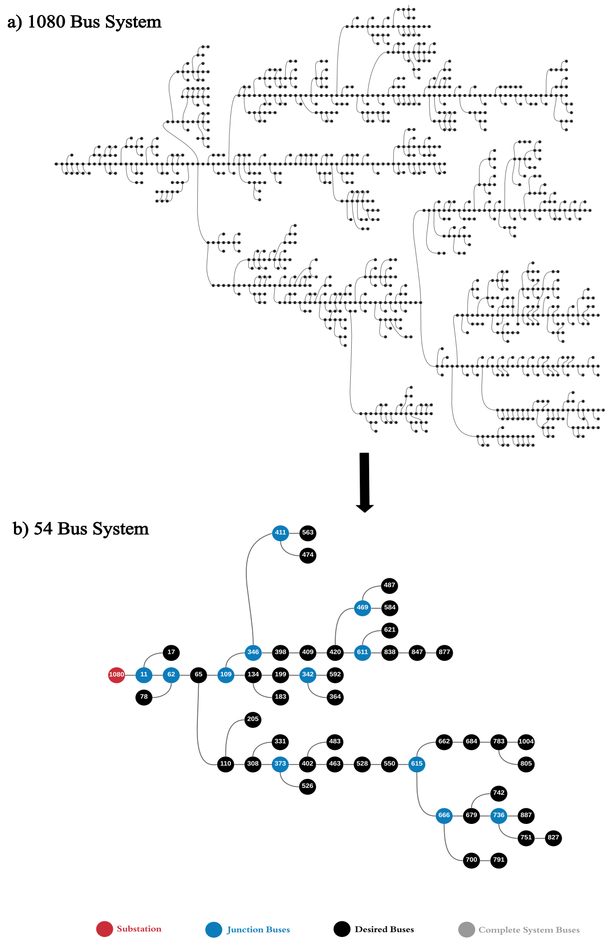


**FIGURE 6. Diagram of the a) original 1080-bus EDS and b) reduced 54-bus EDS, identifying desired buses and junction buses.**

#### 2) RESULTS OF CASE II

When the option of determining the DG capacity in the predefined locations is available, the expected cost of the energy purchased from the market is reduced to $2348.715k, which implies in a reduction of 47.78% when compared to the value obtained from Case I. Similarly, charges due to carbon emission taxes are decreased to $1282.61k, which results in a reduction of 46.96%. However, these reductions are a consequence of purchasing energy from the renewable-based DG with a total expected cost of $1832.08k. With a total investment cost of $27.40k to install a switchable and three fixed CBs, a total installed DG capacity of 2.8 MW can be connected to the EDS, where 1.6 MW and 1.2 MW represent the installed capacity for wind- and PV-based technology, respectively.

#### 3) RESULTS OF CASE III

In the solution of this case, two VRs must be installed with a investment cost of $30k to improve the EDS operation

**TABLE 1.** **Proposed planning actions for each case studied in the reduced 54-bus distribution system.**

| Case | CBs $b$ (kVar) | VRs $j$ | DG units $m$ (MW) |
|---|---|---|---|
| I | Switch.: 109 (1500); 736 (1200); 877 (300) | - | - |
| II | Fixed: 65, 199, 736 (300); Switch.: 109 (600) | - | Wind-based: 487 (0.6); 791 (0.2); 805 (0.8) PV-based: 183 (0.4) 483 (0.6); 563 (0.2) |
| III | - | 62, 463 | Wind-based: 487 (0.4); 791 (0.2); 805 (0.8) PV-based: 183 (0.6) 483 (0.8); 563 (0.2) |

considering the DG connection. When this planning option is carried out, the total DG installed capacity increases to 3 MW and compared to the DG capacity obtained from Case II, this increase is around 6.67%. From the DSO perspective, such increase reduces the expected cost of the energy purchased from the market in 2.012%, which results in a value of \$2301.463k. As expected, charges due to carbon emission taxes have a lower expected cost of \$1278.258k, while the expected cost of the purchased of energy from the DG is \$1849.77k.

#### 4) DISCUSSION

The implementation of the proposed strategy in the 54-bus EDS assists to the DSO in the decision-making process to determine the most suitable plan to be carried out. As discussed in previous subsection, these actions improve the EDS operation and, consequently, the DSO economy because the costs of purchasing energy from the market and charges for carbon taxes are reduced and, in contrast, the participation of the renewable-based DG is increased by purchasing their production. Each plan is presented in Table 1, identifying the location ($j$) of VRs, location ($b$), type (Fixed/Switch.), and capacity (kVar) of CBs, and location ($m$) and capacity (MW) for each DG unit.

As expected, the implementation of the proposed strategy in the reduced 54-bus system requires less computational effort, with a maximum solution time of 2104.49 seconds. It is worth mentioning that when the proposed strategy is implemented using the original 1080-bus EDS (without applying the system reduction technique), no solution can be found as CPLEX ran out of memory.

### C. VALIDATION OF PLANNING ACTIONS IN 54-BUS TO 1080-BUS EDS

To validate the accuracy of the system reduction technique, each planning solution (solutions of Cases I-III) obtained for the reduced 54-bus EDS is projected to the original 1080-bus system. For a comparative analysis, decisions such as a) location and tap position of VRs; b) location, type (fixed/switchable), installed capacity, and modules in operation of CBs; and c) installed capacity of DG units are fixed for both 54- and 1080-bus system. Fig. 7 illustrates the implementation of all planning actions, obtained from the solution

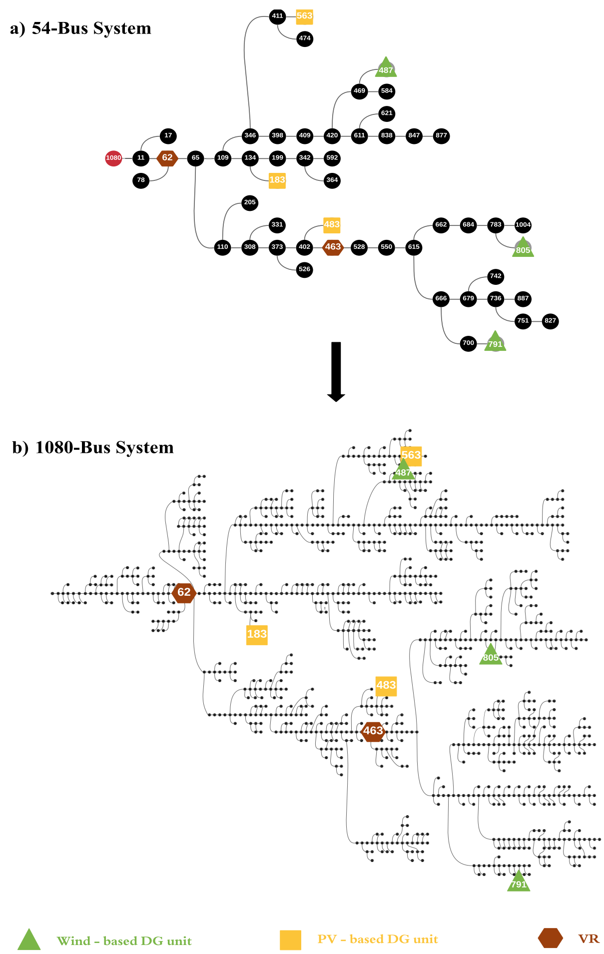


**FIGURE 7.** **Illustrative procedure to implement the obtained planning actions from the a) 54-bus EDS on the original b) 1080-bus EDS.**

of Case III for the 54-bus EDS, on the original system. It worth mentioning that this procedure was implemented for Cases I and II, however, for illustrative purposes only Case III is shown in this figure. Finally, once that all planning actions for both systems are fixed, an optimal power flow tool is used to perform simulations, considering only an expected scenario for demand and DG power production.

Solutions show that using the reduced 54-bus EDS, the planning actions can be implemented in the original 1080-bus system, where lower approximation errors are obtained. Table 2 shows percentage differences between each components of the objective function. For clarity, results for the original 1080-bus system are identified by the extensions denoted as Cases I-III.o, while for the 54-bus system as Cases I-III.r. Comparing the results for all cases, it is observed that the maximum difference for cost of energy purchased from the market and charges due to carbon taxes were obtained for Case III with values of 0.8344% and 0.8139%, respectively. Note that, for all solutions, the cost of energy purchased from the renewable-based DG was the same.

After simulations, voltage magnitude profiles for both systems are compared, considering only the voltage level of

**TABLE 2.** Validation of proposed plans for each case in the original 1080-bus and in the reduced 54-bus EDS.

| EDS | Case | Cost of energy purchased from market ($10^3$ \$) | Charges due to carbon taxes ($10^3$ \$) | Cost of energy purchased from DG ($10^3$ \$) |
|---|---|---|---|---|
| 1080-bus | I.o | 4522.22 | 2431.84 | 0 |
| | II.o | 2333.19 | 1274.18 | 1866.77 |
| | III.o | 2284.93 | 1269.92 | 1881.90 |
| 54-bus | I.r | 4503.52 | 2421.68 | 0 |
| | II.r | 2314.93 | 1264.25 | 1866.77 |
| | III.r | 2265.86 | 1259.59 | 1881.90 |
| | | Percentage differences (%) | | |
| Cases | I.o-I.r | 0.4136% | 0.4178% | 0% |
| | II.o-II.r | 0.7828% | 0.7797% | 0% |
| | III.o-III.r | 0.8344% | 0.8139% | 0% |

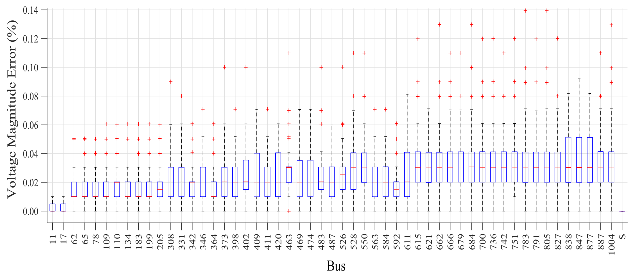


**FIGURE 8.** Errors of comparing, for all 48 time intervals, the voltage magnitude for each bus of the 54-bus system contained in the 1080-bus EDS.

retained buses. Fig 8 shows the voltage magnitude error for the Case III, where each box-plot summarizes the obtained error comparing the voltage level, for all 48 time intervals, of the reduced and the original system. From this figure, it is observed that the maximum error found is around 0.14%. In general, the obtained errors, when comparing solutions for both systems, result smalls enough to be insignificant during the decision-making process and, consequently, validate the accuracy of the reduction technique developed in this work.

## VII. CONCLUSION

The necessity to address the complexities of large-scale electric distribution systems (EDSs) encourages distribution system operators (DSOs) to seek new planning strategies. In this regard, this work presented a planning strategy that depends on a system reduction technique and optimization model. The strategy was tested in a real 1080-bus EDS, for which the system reduction technique estimated an equivalent 54-bus system by removing all non-desired buses and circuits. Using this reduced EDS, planning actions were carried out, solving a stochastic mixed-integer linear programming model.

Numerical results showed that the proposed strategy provided several investment options to improve the EDS operation. When the most suitable plan was carried out, costs of purchasing energy from the market and charges due to carbon taxes were reduced around 48% and 47%, respectively. In contrast, the participation of the renewable-based DG was maximized by purchasing their energy production. Planning actions were projected to the original EDS and using an expected scenario in demand and DG power production, simulations were carried out. Results showed that, by comparing the components of the objective function under this condition for each system, maximum percentage differences of 0.83% and 0.81% were achieved. Additionally, comparing the voltage magnitude profile between both systems, a maximum error of 0.14% was determined. Based on these results, it is concluded that the strategy can be used as an effective tool to assist the DSO in the decision making process. Future work will address the incorporation of others planning actions (e. g. conductor replacement) and address further advances in the development of the system reduction technique, for example considering imbalances in loads.

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