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RESEARCH ARTICLE

Analysis of the Optimized Allocation of Wireless and PLC Data Concentrators in Extensive Low-Voltage Networks Considering the Increase in the Residential Electric Vehicles Charging

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ABSTRACT Several countries have recently encouraged the installation of photovoltaic (PV) systems and the adoption of electric vehicles (EVs) in urban areas to reduce dependence on carbon-based energy resources. While integrating PV systems can offer significant benefits to the network, the growing insertion of EV chargers can have a notable impact on the dynamics of low-voltage (LV) distribution networks. Therefore, to effectively leverage the advantages of PV systems and address the challenges related to the insertion of residential EV chargers, distribution companies have begun installing smart data concentrators (SDCs) at strategic points within the LV distribution network. These devices can collect and exchange information with end-users using different communication technologies, but the increased use of EVs can strongly influence the choice of the most suitable communication technologies and system optimization. In this context, this work analyzes the problem of allocating SDCs based on wireless and power line communication (PLC) technologies in extensive LV distribution networks. This analysis shows how the increasing adoption of residential EV chargers can influence the number and location of SDCs, depending on the communication technologies used. The SDCs allocation is formulated as a mixed-integer linear programming (MILP) problem, considering the penetration scenario of residential EV chargers, SDCs installation costs, and signal propagation characteristics of the communication channel as a function of distance. As a case study, SDCs are allocated in a test LV distribution network comprising 15 nodes and 45 end-users within semi-dense and dense urban environments, considering the insertion of residential EV chargers at 5%, 15%, 30%, and 50% levels. The analysis results demonstrate how the number of SDCs to be implemented can vary due to the influence of residential EV chargers. Overall, a 50% insertion of residential EV chargers requires an increase of over 80% in the number of SDCs compared to the initial requirements, and this increase applies specifically to SDCs with PLC technology. The results presented in this work may draw distribution companies' attention to the importance of selecting the right communication technology as the use of residential EV chargers increases.

INDEX TERMS Optimized data concentrators allocation, low-voltage distribution networks, wireless communication, power line communication, electric vehicles.

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NOMENCLATURE

i	SDC location index.
j	SM location index.
k	Communication technology type index.
N	Number of SDCs locations.
M	Number of SMs locations.
Z	Number of communication technology types.
D_{ij}	Distance between SDC location i and SM location j.
$Pt_{j,k}$	Transmit power of wireless SM of type k at location j.
$Pr_{ij,k}$	Receive power at wireless SDC of type k at location i.
$Gt_{j,k}$	Transmit antenna gain of wireless SM of type k at location j.
$Gr_{i,k}$	Receive antenna gain of wireless SDC of type k at location i.
γ_{ij}	Wireless propagation coefficient of the region between location i and location j.
$\mathbf{\Gamma}$	Gamma matrix.
λ	Wavelength of the transmitted wireless signal.
Z_c	Characteristic impedance of the distribution network power line.
Ψ	Propagation constant of the distribution network power line.
$Vout_{j,k}$	Output voltage of wired SM of type k at location j.
$Vin_{ij,k}$	Input voltage of wired SDC of type k at location i.
$Zout_{j,k}$	Output impedance of wired SM of type k at location j.
$Zin_{i,k}$	Input impedance of wired SDC of type k at location i.
$AC_{i,k}$	Acquisition cost of SDC of type k at location i.
$OC_{i,k}$	Operation and maintenance cost of SDC of type k at location i.
T_k	Number of SDCs of type k.
Q^{ij}	Set of intermediaries nodes between location i and j.
U^{ij}	Set of intermediaries end-user connection nodes between locations i and j.
Zr^{ij}	Set of end-user loads comprised between location i and location j.
$ZL_{q_\delta,q_{\delta+1}}$	Main line impedance between nodes q_δ and $q_{\delta+1}$.
$ZLA_{q_\delta,u_\epsilon}$	Service drop impedance between node q_δ and end-user connection node u_ϵ.
$L_{q_\delta,q_{\delta+1}}$	Length of the main line between nodes q_δ and $q_{\delta+1}$.
LA_{q_δ,u_ϵ}	Length of the service drop comprised between node q_δ and the end-user connection node u_ϵ.
$Zrm_{q_Q,j}$	Impedance of the last branch comprised between location j and node q_Q.
Zdn_{q_Q}	Resulting impedance of the electrical network downstream of node q_Q.
Zp_{q_Q}	Resulting parallel impedance between Zdn_{q_Q} and $Zrm_{q_Q,j}$, which is connected at node q_Q.
$\mathbf{A}_w$	Wireless binary coverage matrix.
$\mathbf{B}_{plc}$	PLC binary coverage matrix.
$\alpha_{ij,k}$	Element of the matrix $\mathbf{A}_w$ that indicates whether a SDC of type k at location i covers a SM installed at location j.
$\beta_{ij,k}$	Element of the matrix $\mathbf{B}_{plc}$ that indicates whether a SDC of type k at location i covers a SM installed at location j.
$x_{i,k}$	Binary variable to represent whether a SDC of type k is allocated at location i.

I. INTRODUCTION

In recent decades, there has been a significant increase in distributed generation systems based on renewable energy in urban areas, primarily photovoltaics (PVs) [1]. PV systems have allowed end-users to become active contributors to energy production, which can be integrated into low-voltage (LV) distribution networks [2]. The presence of users with PV systems offers substantial advantages to LV distribution networks, including demand curve smoothing, and deferral of network reinforcement [3]. However, realizing these benefits requires the implementation of an advanced metering infrastructure (AMI) for LV distribution network management [4]. Since many LV distribution networks worldwide are extensive, the efficient allocation of AMI resources assumes a pivotal role in shaping the future of LV distribution networks [5], [6].

Distribution companies utilize AMI for various purposes, including load monitoring, load control, and outage management [4]. These systems comprise smart data concentrators (SDCs) and smart meters (SMs). SDCs collect, store, and facilitate real-time information exchange between end-users and the distribution system operator (DSO) [5]. The data collected by these systems can be transmitted by both power line communication (PLC) and wireless technology. The selection of the appropriate technology depends on several factors, including the specific application, the load within the LV distribution network, the installation environment, and its unique characteristics [7], [8].

On the other hand, the large-scale production and commercialization of electric vehicles (EVs) continue to expand in numerous countries [1], [2], [3], [4]. The use of EVs introduces new electrical loads into the LV distribution network, such as residential EV chargers [9], which can cause problems in network operation [3]. A possible solution to this problem can be the effective management and control of demand through the use of SDC. However, the integration of these new loads can influence the performance of the SDCs, in particular, their signal coverage area [4].

Residential EV chargers could interfere with some communication technologies, being a relatively high load [10]. For example, it could cause a deficit in some SMs' coverage and require a higher number of SDCs to cover these SMs without coverage. This impact could alter the planning and result in increased costs during the implementation of the data collection system for the future LV distribution network. On the other hand, ensuring efficient collection of real-time end-user information could help the DSO to access data such as voltage, current, and energy, among others, from each end-user. Moreover, with this information, it could effectively manage energy resources and avoid unnecessary investments in network reinforcement [11]. Therefore, it is essential to analyze the influence of residential EV chargers on the number of SDCs to be installed at the LV distribution network to ensure proper planning for the deployment of these SDCs.

Several methodologies for allocating SDCs have been presented, each according to the needs of network planners or operators. Some of these methodologies address the demand aggregation point allocation problem, which can also be applied to the allocation of the SDCs. In [12] and [13], demand aggregation zones were defined using a genetic algorithm (GA) and Thevenin network reduction techniques from specific points in the distribution network. However, these works did not consider the radio propagation characteristics of urban environments in the installation area, which play an important role in the performance of SDCs. In [5], a methodology to perform the optimal allocation of SDCs and electrical charge aggregates using the particle swarm optimization (PSO) technique was proposed. In this methodology, the most critical scenario was considered, resulting in a high allocation cost. Similarly, a methodology based on PSO and graph aggregation techniques to determine the locations for installing SDCs based on Zigbee (ZB) communication technology was presented in [14]. In this methodology, the authors considered only the distance between nodes, without taking into account the additional distance in which the SM is located.

On the other hand, the feasibility of an AMI based on narrowband PLC (NB-PLC) for LV and medium voltage (MV) applications was analyzed in [10]. As a result, the authors demonstrated that implementing wired SDC could be more economical than wireless ones. In addition, a mathematical model for designing an AMI in the LV distribution network based on PLC technology was presented in [15]. The proposed model optimizes the placement of SDCs on distribution transformers to ensure reliable communication with SMs while minimizing installation costs, taking into account latency requirements. However, in these works, certain limitations were observed concerning PLC technology due to the disturbances of the communication medium caused by the LV distribution network branches and loads.

In [16], the strengths and weaknesses of using SDCs based on wireless and PLC technologies for a home area network (HAN) are analyzed and compared. However, an LV distribution network has much more complex characteristics than a HAN, and the analysis of the influence of the insertion of new loads in the distribution network is important to optimize the allocation of SDCs.

In this context, this work aims to analyze how the growth of the use of residential EV chargers in LV distribution networks can influence the allocation of SDCs. Such analysis can help in planning the installation of future SDCs, highlighting the need or not of reinforcements for data collection depending on the communication technologies employed. The main contributions of this work are described below.

- This work analyzes the influence of residential EV charger deployment on the optimized allocation of SDCs in an extensive LV distribution network. To this end, a case study was presented with up to 50% of end-users using residential EV chargers, providing valuable insights for power distribution planners. The focus is determining whether additional SDCs need to be installed to ensure that information from all SMs is appropriately collected. The study uses a test LV distribution network with 45 end-users in semi-dense and dense urban environments. The results show a direct correlation between the increase in residential EV chargers and the increased number of SDCs.
- A methodology is proposed to analyze the optimal allocation of SDCs using wireless and PLC technologies in extensive LV distribution networks. The methodology can help power distribution planners determine the optimal placement of SDCs, ensuring effective information collection and minimizing installation costs. Contrary to the specialized literature, this approach combines the installation of SDCs with wireless and PLC technologies, overcoming the limitations of using these technologies independently. The integration of wireless and PLC technologies will ensure communication between SDCs and SMs, allowing the creation of a useful database to improve energy distribution planning and operation studies.

The remainder of this paper is organized as follows. Section II describes the basic concepts of the communications technologies used by SDCs. Section III presents the proposed methodology for analyzing the influence of residential EV chargers' insertion on SDC allocation. Section IV presents a case study to analyze the proposed methodology, considering the technical characteristics of the LV distribution network, different types of SDCs, and varying levels of residential EV charger insertion. Section V presents the results obtained from the application of the proposed methodology, and finally, Section VI provides a summary of the main conclusions.

II. COMMUNICATION TECHNOLOGIES

In the current scenario of LV distribution network modernization, SDCs enable real-time information collection and exchange between the end-users SMs and the distribution company [15]. Collecting and exchanging information from SMs can be carried out over the air using SDCs based on wireless technology or through power lines employing SDCs based on PLC technologies [10]. A generic topological structure of the communication network between the SDCs

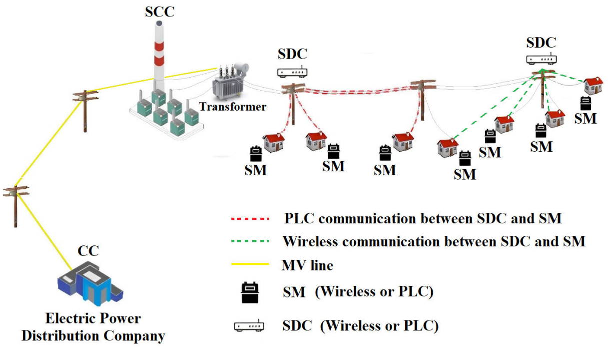

FIGURE 1. Generic network topology for the collection and exchange of information through the SDCs.

and the SMs for information collection and exchange can be shown in Fig. 1. The SMs are installed at users' residences, while the SDCs are strategically installed at potential nodes within the LV distribution network. Each SDC collects information from a group of SMs and sends it to the smart central concentrator (SCC), which helps to exchange information with the control center (CC) of the electric power distribution company.

A. WIRELESS TECHNOLOGY

The use of SDCs based on wireless communication technologies has demonstrated great promise due to their versatility, fine granularity, and cost-effectiveness in terms of installation and maintenance [17]. Among the available wireless technologies, ZB (both ZB and ZB Pro) have attracted attention for their attributes, such as low power consumption, mid-range capability, and high network capacity (supporting up to 64,000 nodes) [18]. Moreover, their flexible network structure allows the implementation of various topologies including mesh operation, offering suitable data rates (up to 500 kbps), low latency, and robust security (AES-128 encryption with 3 levels of security) [17]. These devices also exhibit good immunity to interference, thanks to their spread spectrum technique [5].

ZB is based on the IEEE 802.15.4 standard that specifies the physical (PHY) and medium access control (MAC) layers for wireless personal area networking (WPAN). It has been determined to operate in 3 different industrial, scientific, and medical (ISM) bands (868 MHz, 915 MHz, and 2.4 GHz), each with distinct specifications [19]. In this work, the standardization for the 2.4 GHz band (ranging from 2.4 to 2.4835 GHz) will be analyzed, as it is the most commonly used band in Brazil. This band offers 16 channels and employs the direct sequence spread spectrum technique (DSSS/SS) with quasi-orthogonal modulation and offset quaternary phase shift keying (OQPSK) mapping, reaching data rates of around 250 kbps [20]. The analysis of the SDC allocation problem based on wireless technologies within regions with different radio propagation characteristics is currently a major concern [5], which is discussed below.

1) WIRELESS DATA TRANSMISSION

When employing SDCs based on wireless communication technology for data collection and exchange, it is important to evaluate the maximum coverage that can be achieved by these devices. The maximum coverage evaluation can be performed by applying the modified free-space propagation equation, as detailed in [5]. This equation relates the received power ($Pr_{ij,k}$) that guarantees communication between a SDC of type k allocated at location i and a SM of type k installed at location j, and the distance ($D_{ij,k}$) between these devices. Furthermore, this equation considers both the propagation characteristics in the region between locations i and j and the technical specifications of the devices and is expressed as follows:

$$Pr_{ij,k} = Pt_{j,k} \cdot Gt_{j,k} \cdot Gr_{i,k} \cdot \left(\frac{\lambda}{4\pi}\right)^2 \cdot \left(\frac{1}{D_{ij}}\right)^{\gamma_{ij}} \quad (1)$$

where $Pt_{j,k}$ and $Gt_{j,k}$ are, respectively, the transmit power and antenna gain of the SM of type k installed at location j and $Gr_{i,k}$ is the antenna gain of the SDC of type k allocated at location i. γ_{ij} is the propagation coefficient of the region between location i and location j. λ is the wavelength of the transmitted wireless signal.

From (1), the SDC coverage can be evaluated based on the minimum receive power that guarantees correct communication between a SDC of type k allocated at location i and a SM of type k installed at location j within the LV distribution network. The detailed formulation of wireless data transmission is proved in Appendix A.

B. PLC TECHNOLOGY

The use of SDCs based on PLC communication technologies has also proven to be an interesting and economically viable solution. These technologies leverage existing electrical lines for information transmission, resulting in significant reductions in infrastructure deployment costs, similar to when wireless technologies are employed [21]. However, LV distribution networks were not originally designed to serve as a communication medium. As a result, their use must overcome certain challenges, including distortions caused by inherent characteristics of the electrical network (e.g., mismatches leading to high levels of reflections and fading) and interferences generated by various loads and the integration of PV systems [22], [23]. These factors can drastically reduce the coverage area of SDCs [24].

In this context, the third generation PLC (G3-PLC), which falls under narrowband PLC (NB-PLC) technology, has gained recognition for offering a substantial increase in range compared to broadband PLC (BB-PLC) [25]. Although this extended range does involve a trade-off with a reduction in data rates, it still proves sufficient to meet the requirements of AMI. G3-PLC employs a forward error correction (FEC) scheme composed of an inner Reed Solomon code and an outer convolutional code, followed by two-dimensional interleaving [26]. If the Robust Operation (ROBO) mode is enabled, a repeat code with a factor of four is added to improve error correction capabilities. Orthogonal frequency division multiplexing (OFDM) is employed to increase the robustness of the communication system to multipath fading effects [25]. Each OFDM subchannel can utilize various phase shift keying mapping schemes, including differential (DBPSK, DQPSK, and D8PSK) or coherent (BPSK, QPSK, and 8PSK) schemes. In its less robust operating mode, G3-PLC can operate with data rates of up to 500 kbps at the PHY layer [27].

According to regional regulations, the G3-PLC can operate in different frequency bands between 10 and 490 kHz [28]. This work will employ G3-PLC devices operating within the 154.6875 to 487.5 kHz band specified by the Federal Communications Commission (FCC). Thus, the SDC allocation problem based on PLC technologies within LV distribution networks is analyzed below, considering the propagation characteristics of the power line and the effect of loads and branches.

1) PLC DATA TRANSMISSION

The modeling of the LV distribution network is performed using the principles of line transmission (LT) theory, which helps to describe the behavior of power lines as a communication channel [29]. It is well-known that power lines were not designed for communication, making them very hostile and susceptible to high attenuations. The primary attenuation of the PLC signal is due to losses in the lines and loads [30]. Consequently, a power line can be effectively modeled using key parameters such as characteristic impedance (Zc) and propagation constant (Ψ) [30]. These parameters are dependent on fundamental line properties (R, C, L, G) and can be computed by (2) and (3).

$$Z_c = \sqrt{\frac{R + jwL}{G + jwC}} \tag{2}$$

$$\Psi = \sqrt{(R + j\omega L) \cdot (G + j\omega C)} \tag{3}$$

On the other hand, the PLC communication channel between a SDC of type k allocated at location i and SM of type k installed at location j is represented by a two-port network, defined by an equivalent transfer matrix described in ABCD parameters, as follows:

$$\begin{bmatrix} Vin_{ij,k} \\ Iin_{ij,k} \end{bmatrix} = \begin{bmatrix} A^{ij} & B^{ij} \\ C^{ij} & D^{ij} \end{bmatrix} \begin{bmatrix} Vout_{j,k} \\ Iout_{j,k} \end{bmatrix} \tag{4}$$

where $Vout_{j,k}$ and $Iout_{j,k}$ are the output voltage and current values of a SM of type k installed at location j. $Vin_{ij,k}$ and $Iin_{ij,k}$ are the input voltage and current values of a SDC allocated at location i. Each ABCD parameter is calculated considering the influence of branches and loads between locations i and j [23], [31].

Note that the input voltage of the SDC of type k allocated at location i depends on the output voltage of the SM of type k installed at location j. Therefore, the relationship between these voltages can be determined as follows [25]:

$$\frac{Vin_{ij,k}}{Vout_{j,k}} = \frac{Zin_{i,k}}{Zin_{i,k}A^{ij} + B^{ij} + Zin_{i,k}Zout_{j,k}C^{ij} + Zout_{j,k}D^{ij}} \tag{5}$$

where $Zin_{i,k}$ is the input impedance of the SDC of type k at location i, and $Zout_{j,k}$ is the output impedance of the SM of type k at location j.

From (5), the SDC coverage can be evaluated based on the minimum input voltage that guarantees correct communication between a SDC of type k allocated at location i and a SM of type k installed at location j. The detailed formulation of the PLC data transmission is proved in Appendix B.

III. PROPOSED METHODOLOGY TO ANALYZE THE INFLUENCE OF RESIDENTIAL EV CHARGERS' INSERTION ON SDC ALLOCATION

The proposed methodology consists of two steps. In the first step, the optimal locations at the LV distribution network to install the SDCs are determined. In the second step, the influence of the insertion of residential EV chargers on the SDC installation planning is analyzed. The LV distribution network is modeled as a communication medium, allowing for determining the constraints of each communication technology (wireless and PLC). Then, a mathematical optimization model is developed to determine the optimal locations for SDC installation. This model ensures both the data collection and exchange between the SDCs and the SMs and the minimization of the costs related to the allocation of these SDCs. In addition, the proposed model considers the joint use of SDCs based on wireless and PLC technologies.

On the other hand, in the second step, the proposed mathematical model must be applied for each level of residential EV charger insertion to determine if this insertion will result in a variation in the number of SDCs needed. Depending on the type and technology of the SDCs utilized, it may be possible that the points previously defined do not need to be altered for each new level of residential EV charger insertion. The results obtained from the proposed methodology allow us to analyze the influence of the increasing insertion of residential EV chargers on studies related to the installation of SDCs.

A. OPTIMAL SDC ALLOCATION PROBLEM

The stages required to allocate the SDCs at the LV distribution network using wireless and PLC technologies are shown below. First, we delimited the LV distribution network and identified the location of SMs, PV systems, and residential EV chargers utilizing geographic information. Then, we model this LV distribution network for data transmission according to the type of technology.

1) NETWORK MODELING FOR DATA TRANSMISSION CONSIDERING THE USE OF WIRELESS TECHNOLOGY

We consider the geographical location and urban environment characteristics of the LV distribution network for wireless technology. The geographical location allows us to determine the distances (D_{ij}) between SDCs locations i and the SMs locations j. On the other hand, the propagation characteristics of the region under study can be represented by the gamma matrix ($\mathbf{\Gamma}$) composed of the elements γ_{ij}, obtained from databases or through field measurements [5]. In addition, the technical specifications of the devices to be used SDCs and SMs are obtained [14]. Then, we use the modified free-space model (1), considering the variation of the γ_{ij}, to determine the minimum $Pr_{ij,k}$ that guarantees the communication between the SDC and the SM. Finally, we determine the wireless binary coverage matrix $\mathbf{A}_w$, indicating whether a given SDC located at i covers a SM located at j. The computation of each of these parameters and the sequence of steps to construct the $\mathbf{A}_w$ matrix are detailed in Appendix A.

2) NETWORK MODELING FOR DATA TRANSMISSION CONSIDERING THE USE OF PLC TECHNOLOGY

We determine the basic parameters of the lines and the end-user loads. Then, we segment the LV distribution network to model it considering the effect of branches and loads. Utilizing LT theory, we compute the ABCD parameters of the transfer matrices of each network segment. Subsequently, we obtain the equivalent transfer matrix which describes the PLC communication channel between the SDC location i and SM location j. This equivalent matrix helps us to determine the minimum $Vin_{ij,k}$ that guarantees the communication between the SDC and the SM. Finally, we perform the calculation of the PLC binary coverage matrix $\mathbf{B}_{plc}$ to evaluate whether a given SDC located at i provides coverage to a SM located at j. The computation of each of these parameters and the sequence of steps to construct the $\mathbf{B}_{plc}$ matrix are detailed in Appendix B.

3) MATHEMATICAL OPTIMIZATION MODEL

The binary coverage matrices $\mathbf{A}_w$ and $\mathbf{B}_{plc}$ are used to formulate the optimization problem. The binary variable $x_{i,k}$ is defined to indicate whether a SDC of type k is allocated at location i. As noted in [5], SDCs are relatively expensive to install and maintain. Therefore, we have defined the objective function to minimize the SDC allocation cost by determining the minimum number of SDCs required to ensure the full coverage of all SMs. Thus, the SDCs allocation problem for an LV distribution network with N SDCs locations, M SMs locations, and Z types of communication technology available, can be written as:

$$\min \sum_{k=1}^{Z} \sum_{i=1}^{N} (AC_{i,k} + OC_{i,k}) \cdot x_{i,k} \tag{6}$$

where $AC_{i,k}$ is the acquisition costs, and $OC_{i,k}$ is the maintenance and operation costs, for installing a SDC of type k at location i. The index k denotes the type of communication technology used by the SDC, which can be wireless (ZB or ZB Pro) or PLC (G3-PLC).

To ensure a minimum SDC allocation cost through the use of wireless and PLC communication technologies and to guarantee data collection from each of the SMs at the LV distribution network, the objective function defined in (6) is subject to the following constraints:

$$\sum_{i=1}^{N} x_{i,k} \leq T_k, \quad \forall k = 1, \ldots, Z \tag{7}$$

$$\sum_{k=1}^{Z} \sum_{i=1}^{N} \alpha_{ij,k} \cdot x_{i,k} + \sum_{k=1}^{Z} \sum_{i=1}^{N} \beta_{ij,k} \cdot x_{i,k} \geq 1$$
$$\forall i = 1, \ldots, N, \quad \forall j = 1, \ldots, M \tag{8}$$

In constraints (7), and (8), T_k is the maximum number of SDCs of type k available for installation, and $\alpha_{ij,k}$ and $\beta_{ij,k}$ are elements of the binary coverage matrices $\mathbf{A}_w$ and $\mathbf{B}_{plc}$, respectively.

In (7), it is indicated that the number of SDCs to be allocated must not exceed N or the number that the distribution company is willing to install. The first part of (8) ensures data collection from SMs when a wireless technology SDC is allocated, while the second part ensures data collection from SMs, if a PLC technology SDC is allocated. The sum of both parts guarantees the use of both technologies in the SDC allocation problem.

The optimization problem is a mixed-integer linear programming (MILP) problem since the objective function (6) and all constraints are linear functions of the binary variable $x_{i,k}$. Therefore, considering that our problem is a MILP problem with a small number of constraints and variables, it can be solved efficiently using algorithms such as Branch and Bound or Branch and Cut [32]. In this work, we have employed the LPSolveAPI optimization solver, which uses a Branch and Bound algorithm to solve efficiently MILP problems [33].

B. ANALYSIS OF RESIDENTIAL EV CHARGER INSERTION

Once the installation locations are determined, we insert the residential EV chargers into the LV distribution network in a tiered mode. The flowchart in Fig. 2 should be applied for each insertion level to determine if a greater number of SDCs are needed. Finally, we determine the location, number, and type of SDCs required for each insertion level. Fig. 2 has been created to illustrate each stage and analyze the influence of the insertion of residential EV chargers in the SDC installation planning.

IV. CASE STUDY

In this section, the input data necessary to analyze the allocation of wireless and PLC SDCs considering the insertion of residential EV chargers are defined. A test LV distribution network inspired by [13] is used. This LV distribution network consists of 15 nodes, with 45 end-users,

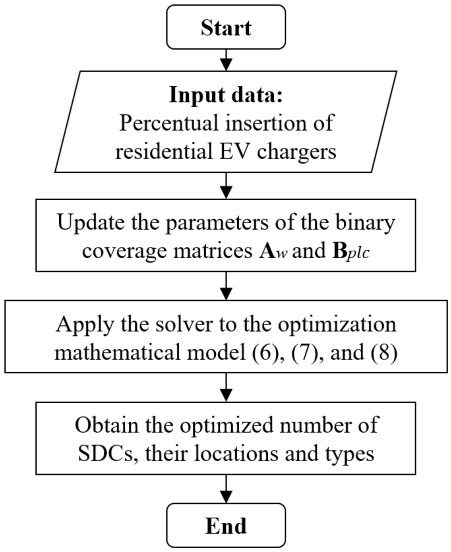

FIGURE 2. Flowchart to analyze the impact of the insertion of residential EV chargers.

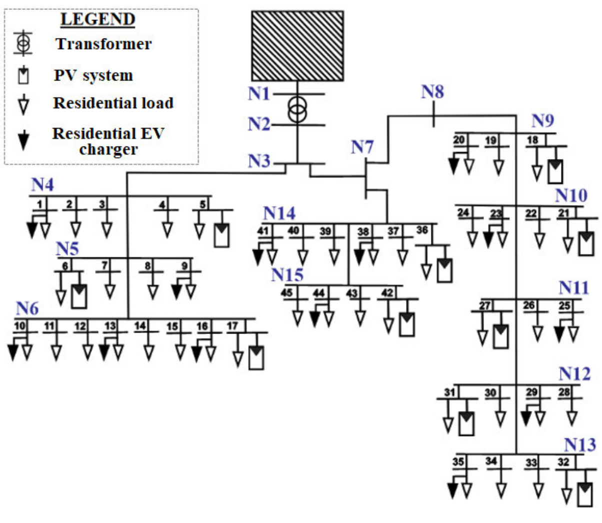

FIGURE 3. LV distribution network test (adapted from [13]).

each of which has a SM installed. Furthermore, all end-users have connected residential loads; some have PV systems and residential EV chargers installed, as illustrated in Fig. 3. The parameters of the LV distribution network were obtained from [14].

On the other hand, Fig. 4 provides an overview of the urban environment where the test LV distribution network is geographically situated. This urban environment is composed of relatively tall residences, each equipped with a SM, along with sports areas and numerous trees. These urban environment characteristics are important considerations in the SDC allocation process, as they can significantly affect the propagation coefficient γ_{ij}. Consequently, each region between locations i and j will present unique γ_{ij} values, which will influence SDC coverage.

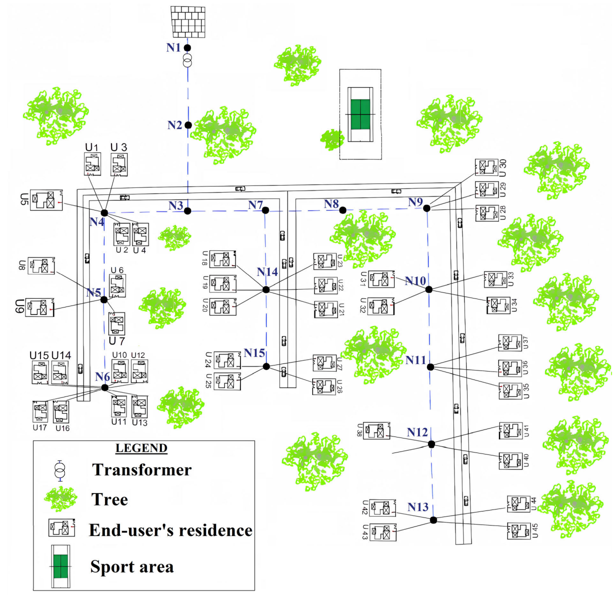

FIGURE 4. Characteristics of the urban environment where the test LV distribution network is situated.

A. TECHNICAL SPECIFICATIONS OF SDC AND SM DEVICES

The technical specifications of the devices employed for the application of the methodology are as follows:

- Wireless technology: The ZB and ZB Pro devices were employed, whose technical specifications were based on those of the ZB Xbee-S2C and ZB Xbee-S2C Pro devices, respectively, without loss of generality [14].
- PLC technology: The technical specifications of G3-PLC devices have been derived from the specifications of EVALKITST8500-1 devices without loss of generality. These devices are configured to operate with the G3-PLC standard in the FCC band ranging from 154.6875 to 487.5 kHz [31].

The price estimate used in the presented analysis was determined by averaging the values of different SDC and SM found on the Internet. Tables 1 and 2 present the main technical characteristics of each technology.

TABLE 1. Technical specifications of ZB-Type SDC and SM devices.

Device Type	ZB	ZB Pro
Range Frequency	2.4 to 2.4835 GHz (ISM)	
Modulation	Quasi-Orthogonal (OQPSK)	
Number of Channels	16	15
Maximum Data Rate	250 kbps	
Transmission Power	+ 5dBm / + 8dBm (boost mode)	+ 18dBm
Receive Sensitivity (1% PER)	-100 dBm / -102 dBm (boost mode)	-101 dBm
Acquisition Cost	\$ 53.87	\$ 71.25
Maintenance and Operation Cost	\$ 0.54	\$ 0.71

B. RESIDENTIAL EV CHARGER INSERTIONS AND CHARGING TIME ZONES.

The insertion of residential EV chargers was analyzed by considering the level 2 residential charger with a power

TABLE 2. Technical specifications of PLC-Type SDC and SM devices.

Device Type	G3-PLC
Frequency Range	150.6875 to 487.5 kHz
Modulation	OFDM (BPSK, QPSK, 8PSK, DBPSK, DQPSK, D8PSK)
Encoding	Reed-Solomon and Convolutional (optional ROBO mode)
Subchannels	72
Data Rate	240 kbps (D8PSK)
Transmission Power (network) for Vcc = 15V	1.15W to 2 Ω
RMS Transmission Voltage (network) for Vcc = 15V	123.92 dBuV to 2 Ω 126.85 dBuV to 51 Ω
Receive Sensitivity	33 dBuV (DBPSK ROBO)
	38 dBuV (DBPSK)
	42 dBuV (DQPSK)
	45 dBuV (D8PSK)
Input Impedance	136 to 68 Ω
Output Impedance	2 to 9 Ω
Acquisition Cost	$ 85,25
Maintenance and Operation Cost	$ 0,85

of 6.6 kW, which can be achieved within a LV distribution network 240 V. This type of residential charger has a moderate charging speed [34]. Fast and ultrafast chargers are not included in this analysis because they are not economical for the end-user as they require additional wiring [9].

1) INSERTION LEVELS OF RESIDENTIAL EV CHARGERS

The insertion levels of residential EV chargers are the proportion of users with residential EV chargers installed in relation to the total number of users of the LV distribution network. These levels will be 5%, 15%, 30%, and 50% [9]. Furthermore, the roulette wheel method is employed to randomly determine the installation of residential EV chargers within the LV distribution network, as shown in Table 3.

TABLE 3. Insertion levels of residential EV chargers.

Insertion levels	Number of Users	Users with residential EV charger
5%	2	21 ,37
15%	7	21 ,37 3 , 26, 27, 29, 45
30%	14	3, 21, 26, 27, 29, 37, 45 15, 25, 28, 32, 34, 35, 40
50%	23	3, 21, 26, 27, 29, 37, 45 15, 25, 28, 32, 34, 35, 40 6, 7, 10, 14, 18, 22, 31, 38, 44

2) CHARGING TIMES OF ELECTRIC VEHICLES

The charging activity is restricted within the hourly distribution 17:00h-22:00h, and a Poisson distribution randomly determines the connection times [4]. This time interval is representative of EV users, who charge their vehicles as soon as or shortly after arriving home in the evening. This hourly distribution coincides with a significant part of the hour of peak residential demand, as shown in Fig. 5.

In addition, Fig. 6 shows the net charge curves increase when considering the insertion of residential EV chargers [14].

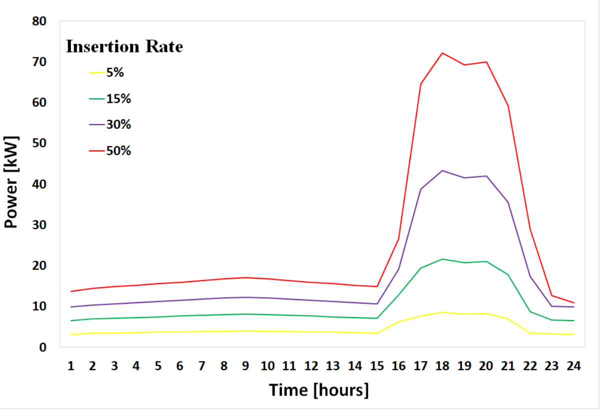

FIGURE 5. Electric vehicle charging demand curve, considering the period from 17:00 to 22:00 hours.

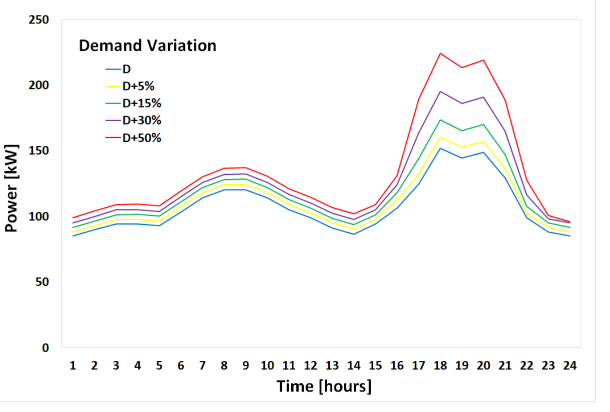

FIGURE 6. Net load curves considering the insertion of residential EV chargers (adapted from [14]).

C. SIMULATION SCENARIOS

The following scenarios were considered to illustrate the performance of the proposed methodology:

- Scenario S0: The allocation of SDCs within the LV distribution network without considering the insertion of residential EV chargers is determined.
- Scenario S1: A 5% insertion of residential EV chargers within the LV distribution network is considered.
- Scenario S2: A 15% insertion of residential EV chargers within the test LV distribution network is considered.
- Scenario S3: The presence of 30% of residential EV chargers within the LV distribution network is considered.
- Scenario S4: A 50% insertion of residential EV chargers is considered within the LV distribution network.

The peak hour energy consumption for each of the scenarios is considered. During the scenarios considered, the PV systems within the test LV distribution network remain stationary.

V. SIMULATION RESULTS AND DISCUSSION

In this section, we apply our SDC allocation model, considering that the index k can take three different values:

$k = 1$ (ZB technology device), $k = 2$ (ZB Pro technology device), and $k = 3$ (G3-PLC technology device). The SDC location index i, represents a possible LV distribution network node where SDCs can be allocated. The SM location index j, represents a SM installed at an end-user of the LV distribution network. Furthermore, since the presented optimization problem is a MILP that can be solved by exact methods, we use the LpSolveAPI optimization solver to solve such a problem [33]. Finally, we present the SDC installation planning solutions within the LV distribution network for the different scenarios considered.

A. RESULTS OF OPTIMAL ALLOCATION OF SDC WITHIN LV DISTRIBUTION NETWORKS

Table 4 shows the nodes determined for SDCs allocation, considering the independent use of wireless technology SDCs, the independent use of PLC technology SDCs, and the combined use of wireless and PLC technology SDCs. The mathematical model was subjected to relaxation to obtain solutions under scenarios considering the independent use of wireless SDCs and PLC SDCs.

Considering the use of wireless SDCs, the proposed methodology has determined the allocation of 7 SDCs: 3 SDCs based on ZB technology at nodes N6, N9, N13, and 4 SDCs based on ZB Pro technology at nodes N3, N5, N11, and N15. In addition, considering SDCs based on PLC technology, a methodology has determined the allocation of 2 SDCs based on G3-PLC at nodes N4 and N11. When the possibility of installing PLC and wireless SDCs is considered, 1 SDC based on ZB Pro at node N12, and 1 SDC based on G3-PLC is installed at node N4, guaranteeing communication with all installed SMs.

Initially, it was perceived that an advantage existed for PLC technology over wireless, since the installation of SDCs based on PLC technology is cheaper than wireless SDCs. Furthermore, it was observed in Table 4 that the most viable solution is obtained considering the joint use of wireless and PLC technologies, so it will be considered for the proposed analysis as reference scenario S0.

TABLE 4. Optimal SDC allocation results for scenario S0.

Type and technology		Node	Cost ($)
Wireless	ZB	N6, N9, N13	451.07
	ZB Pro	N3, N5, N11, N15	
PLC	G3-PLB	N4, N11	172.20
Wireless and PLC	ZB	-	158.06
	ZB Pro	N12	
	G3-PLC	N4	

On the other hand, Fig. 7 shows the coverage of allocated SDC, specifically from the reference scenario, which employs both wireless and PLC technologies. 1 SDC based on G3-PLC were allocated at nodes N4, covering 35 SMs. In addition, 1 SDC based on ZB Pro was allocated at node N12, covering 10 SMs.

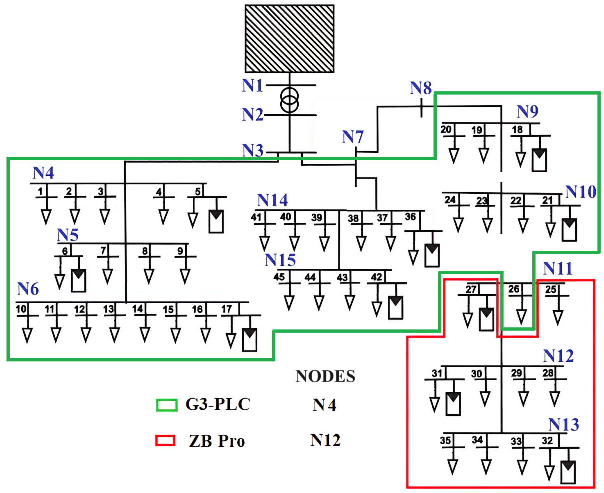

FIGURE 7. SDC coverage for reference scenario S0. SDC coverage considering wireless and PLC technologies.

B. RESULTS OF ANALYSIS OF RESIDENTIAL EV CHARGER INSERTION ON THE ALLOCATION OF SDC

Table 5 shows the results for each proposed insertion scenario when only SDCs based on PLC technology are used.

In scenario S1, the methodology has determined the allocation of 2 SDCs based on G3-PLC, which are allocated at nodes N4 and N11. Scenario S2 required the deployment of 1 additional SDC based on G3-PLC at node N1. The methodology determined the allocation of 4 SDCs based on G3-PLC at nodes N5, N9, N12, and N14 for Scenario S3. Finally, scenario S4 identified the allocation of 1 extra SDC based on G3-PLC at node N1. The analysis reveals that installing residential EV chargers significantly influences the number of SDCs to be deployed when utilizing PLC technology.

TABLE 5. Optimal allocation of SDC based on PLC technology.

Scenario	G3-PLC	
	Node	Cost ($)
S1	N4, N11	172.20
S2	N1, N4, N11	258.30
S3	N5, N9, N12, N14	344.40
S4	N1, N6, N9, N12, N14	430.50

Although the initial installation costs may seem relatively low, the analysis shows that adding residential EV chargers significantly increases the number of required SDCs based on PLC technology. As the number of residential EV chargers increases, more SDCs are needed, leading to higher installation costs. Notably, if the EV insertion rate exceeds 30%, over 100% additional SDCs would be necessary, resulting in more than double the initial costs. Hence, it is important to consider the influence of residential EV chargers when planning the allocation of SDCs based on PLC technology. Table 6 exhibits the variation in SDCs number and installation costs concerning reference scenario S0.

TABLE 6. Effects of residential EV chargers on SDC allocations based on PLC technology.

Scenario	SDCs allocated	Percentage increase in SDCs number	Percentage increase in costs
S1	2	0.00%	8.21%
S2	3	50.00%	38.81%
S3	4	100.00%	54.11%
S4	5	150.00%	63.28%

In scenario S1 there is no variation in the number of SDCs, but there is a variation in the cost, this is due to the change in the technology used, since in this case only SDCs based on PLC technology are used.

On the other hand, Table 7 shows the results for each of the proposed insertion scenarios when only wireless SDCs are used.

The analysis reveals that for each of the proposed insertion scenarios the same number of SDCs is required. Specifically, the results demonstrate that installing residential EV chargers does not influence the number of SDCs allocated when utilizing wireless technology. This finding indicates that wireless communication could provide a reliable and efficient solution for integrating EV charging infrastructure with SDCs, without requiring additional infrastructure.

TABLE 7. Optimal allocation of SDC based on Wireless technology.

Scenario	Wireless		Cost ($)
	ZB	ZB Pro	
S1	N6, N9, N13	N3, N5, N11, N15	451.07
S2	N6, N9, N13	N3, N5, N11, N15	451.07
S3	N6, N9, N13	N3, N5, N11, N15	451.07
S4	N6, N9, N13	N3, N5, N11, N15	451.07

However, although there are no changes in the number of wireless SDCs to be installed, the initial installation cost of such SDCs is very high. Compared to the reference scenario S0, the exclusive installation of wireless SDCs exceeds 100% of the required SDC, resulting in a cost of over 65.0%.

Table 8 presents the results of the proposed scenarios involving the joint use of wireless and PLC technology SDCs. In scenario S1, the methodology has determined the allocation of 2 SDCs: 1 SDC based on ZB Pro at node N12 and 1 SDC based on G3-PLC allocated to node N4. Scenario S2 3 SDCs are required, 1 SDC based on ZB at node N15, 1 SDC based on ZB Pro at node N12, and 1 SDC based on G3-PLC allocated to node N4. Scenario S3 required the deployment of 1 additional SDC based on G3-PLC at node N1. Finally, the proposed methodology for insertion of 50% residential EV chargers determined the allocation of 2 SDCs based on ZB at nodes N6 and N10, 2 SDCs based on ZB Pro at nodes N5 and N12, along with 1 SDC based on G3-PLC at node N14.

TABLE 8. Results optimal of wireless and PLC SDCs allocation.

Scenario	Wireless and PLC			Cost ($)
	ZB	ZB Pro	G3-PLC	
S1	-	N12	N4	158.06
S2	N15	N12	N4	212.47
S3	N10	N12	N1, N14	298.57
S4	N6, N10	N5, N12	N14	338.84

TABLE 9. Effects of residential EV chargers on wireless and PLC SDCs allocations.

Scenario	SDCs allocated	Percentage increase in SDCs number	Percentage increase in costs
S1	2	0.00%	0.00%
S2	3	50.00%	25.61%
S3	4	100.00%	47.06%
S4	5	150.00%	53.35%

Moreover, Table 9 shows the influence of residential EV charger insertion on SDCs allocation. Notably, if the EVs insertion rate exceeds 50%, 100% more SDCs would be required, resulting in a cost 53,35% higher than the initial costs. However, the joint use of wireless and PLC SDCs is an alternative worth considering when planning SDC installation. This approach presents a lower cost than using only wireless or PLC SDCs. Table 9 exhibits the variation in the number of SDCs and installation costs relative to reference scenario S0.

Fig. 8, and Fig. 9 provide valuable insight into the influence of residential EV charger insertion on SDCs.

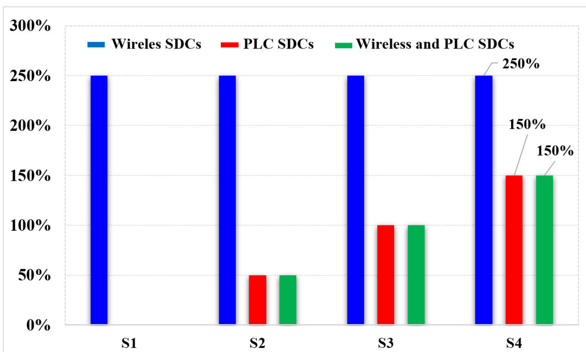

FIGURE 8. Percent increase in the number of SDCs by proposed scenarios.

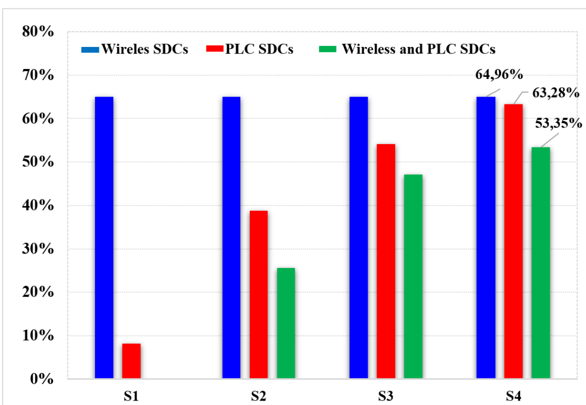

FIGURE 9. Percentage increase of the SDCs installation cost to the proposed scenarios.

Initially, utilizing PLC technology alone may result in lower implementation costs. However, as the number of residential EV chargers increases, more SDCs may be required, driving up installation costs. Additionally, the high cost associated with employing SDCs equipped solely with wireless technology, mainly due to the challenges posed by densely populated urban environments, cannot be ignored. Therefore, it is imperative to consider the joint use of both communication technologies to reduce installation costs and ensure comprehensive coverage of SMs located at the end-user's premises.

Moreover, Table 10 shows the results when considering the insertion of 50% of residential EV chargers within the LV distribution network, which is S4. It is observed that the most viable solution is obtained considering the joint use of wireless and PLC technologies.

TABLE 10. Optimal SDC allocation results with residential EV charger insertion - Scenario S4.

Type and technology		Node	Cost ($)
Wireless	ZB	N6, N9, N13	451.07
	ZB Pro	N3, N5, N11, N15	
PLC	G3-PLC	N3, N4, N8 N12, N15	430.50
Wireless and PLC	ZB	N6, N10	338.84
	ZB Pro	N5, N12	
	G3-PLC	N14	

Fig. 10 shows the coverage of each type of installed SDC, considering the results of the most viable solution which is given by considering both wireless and PLC technologies. 1 SDC based on G3-PLC were allocated to nodes N14, covering 13 SMs. In addition, 2 SDCs based on ZB were allocated at nodes N6, and N10, covering 8 and 5 SMs, respectively. Finally, 2 SDCs based on ZB Pro were allocated to nodes N5, and N12, covering 9, and 10 SMs, respectively.

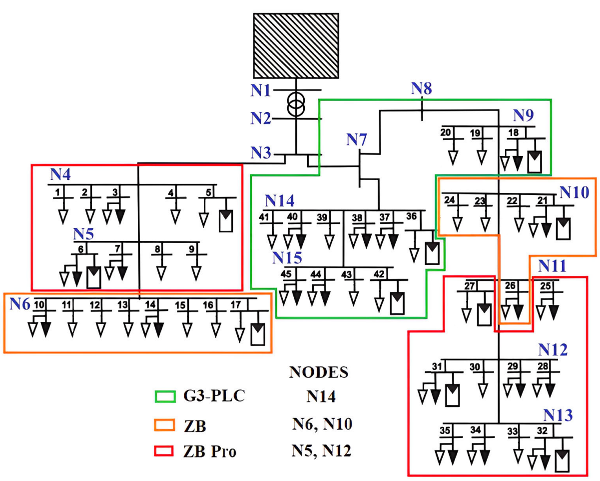

FIGURE 10. SDC coverage for scenario S4. SDC coverage considering wireless and PLC technologies.

VI. CONCLUSION

This work solves the problem of SDC allocation within the LV distribution network by considering the joint use of wireless and PLC technologies. The allocation is conducted to ensure information collection from SMs, and simultaneously, the required number of SDCs is minimized. Furthermore, the influence of the increase in residential EV chargers on the number of SDCs required is also analyzed as part of such a problem. The allocation problem is formulated using a MILP model, which is solved using the LPSolveAPI optimization solver. The problem is applied in a test LV distribution network with 15 nodes and 45 end-users. The analysis of the proposed scenarios demonstrates how the number of SDCs to be installed may vary due to the influence of residential EV chargers on wireless and PLC communication technologies. It is also observed that as the insertion of residential EV chargers increases, the number of SDCs increases, mainly PLC technology SDCs. It is expected that some of our results can help distribution company planners in planning and implementing SDC for monitoring and data collection in future LV distribution networks.

APPENDIX

In this section, the calculation of the binary coverage matrices $\mathbf{A}_w$ and $\mathbf{B}_{plc}$, which allow us to define the coverage of each SDC allocated within the LV distribution network, is described.

A. WIRELESS DATA TRANSMISSION FORMULATION

1) MODELING FOR WIRELESS DATA TRANSMISSION

The geographical location of the LV distribution network to be evaluated is established. This geographical location allows us to calculate the distance D_{ij} between the SDC to be allocated at location i and the SM installed at location j, according to:

$$D_{ij} = \sqrt{(i_x - j_x)^2 + (i_y - j_y)^2} \tag{9}$$

where (i_x, i_y) are the coordinates of the SDC allocated at location i, and (j_x, j_y) are the coordinates of the SM installed at location j.

On the other hand, the propagation characteristics of the urban environment of the LV distribution network between location i and location j can be represented by the coefficients γ_{ij}. These coefficients can be classified as follows: metropolitan areas with free spaces ($\gamma_{ij} = 2$), urban areas with medium-sized residences ($\gamma_{ij} = 3$), and densely populated urban areas with tall residences, trees, and large obstacles ($\gamma_{ij} = 4$) [5]. So, each communication channel formed between a SDC located at i and a SM located at j will have a different γ_{ij}, consequently, each SDC will have different coverage, as can be observed in Fig. 11:

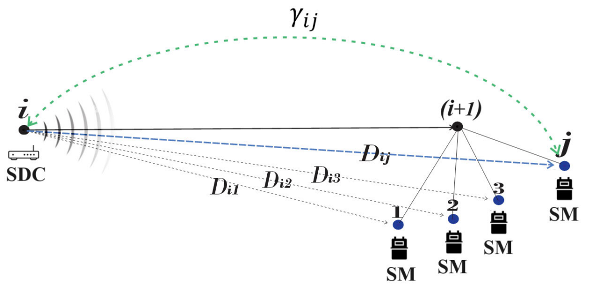

FIGURE 11. Generic communication channel between a SDC located at *i* and a SM located at *j*.

Moreover, the $\mathbf{\Gamma}$ matrix corresponding to the LV distribution network is defined as follows:

$$\mathbf{\Gamma} = \begin{bmatrix} \gamma_{11} & \gamma_{12} & \cdots & \gamma_{1j} & \cdots & \gamma_{1M} \\ \gamma_{21} & \gamma_{22} & \cdots & \gamma_{1j} & \cdots & \gamma_{2M} \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ \gamma_{i1} & \gamma_{i2} & \cdots & \gamma_{ij} & \cdots & \gamma_{iM} \\ \vdots & \vdots & \vdots & \vdots & \ddots & \vdots \\ \gamma_{N1} & \gamma_{N2} & \cdots & \gamma_{Nj} & \cdots & \gamma_{NM} \end{bmatrix} \tag{10}$$

Furthermore, from (1) we can obtain the minimum received power that guarantees communication between a SDC at location i and a SM at location j, as follows:

$$Pr_{ij,k} = Pt_{j,k} \cdot Gt_{j,k} \cdot Gr_{i,k} \cdot \left(\frac{\lambda}{4\pi}\right)^2 \cdot \left(\frac{1}{D_{ij}}\right)^{\gamma_{ij}} \tag{11}$$

From (11), it is possible to evaluate the coverage of the SDC based on the relation between $Pr_{ij,k}$ and the minimum operation power ($P_{min_{op}}$). This $P_{min_{op}}$ represents the receive sensitivity value of the device, which can be obtained from its technical specifications, detailed in Table 1.

2) WIRELESS BINARY COVERAGE MATRIX

The binary coverage matrix $\mathbf{A}_w$ is defined to ensure the collection of SM information considering the limitations of wireless technology. Each element of the matrix $\mathbf{A}_w$ is determined as follows:

$$\alpha_{ij} = \begin{cases} 1, & \text{if } P_{min_{op}} \leq Pr_{ij,k} \\ 0, & \text{if } P_{min_{op}} > Pr_{ij,k} \end{cases} \tag{12}$$

where $\alpha_{ij} = 1$ represents the correct exchange of information between the SDC allocated at location i and the SM installed at location j; otherwise α_{ij}=0.

Finally, Fig. 12 summarizes the sequence of steps to be followed to obtain the binary coverage matrix, denoted as $\mathbf{A}_w$

B. PLC DATA TRANSMISSION FORMULATION

1) MODELING FOR PLC DATA TRANSMISSION

The behavior of a LV distribution network as a communication channel is described employing an equivalent circuit composed of its corresponding impedances. Fig. 13 shows the path comprised between a SDC located at i and a SM located

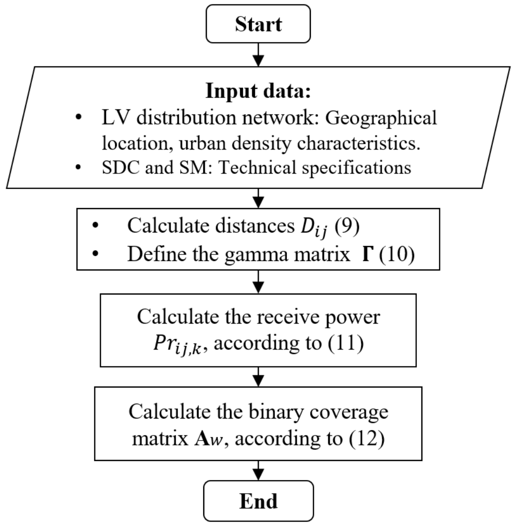

FIGURE 12. Flowchart of modeling the LV distribution network for data transmission using Wireless technology.

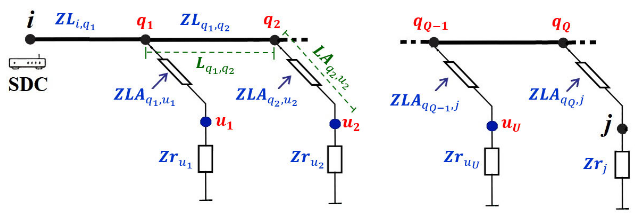

FIGURE 13. Path comprised between a SDC located at *i* and a SM located at *j*.

at j. To facilitate the representation of this path, the following sets were defined: $Q^{ij} = \{q_1, q_2, \ldots, q_\delta, \ldots, q_Q\}$, which represents the set of intermediaries nodes between location i and j. $U^{ij} = \{u_1, u_2, \ldots, u_\epsilon, \ldots, u_U, j\}$, which represents the set of intermediaries end-users connection nodes between locations i and j, including the last end-user connection node j. $Zr^{ij} = \{Zr_{u_1}, Zr_{u_2}, \ldots, Zr_{u_\epsilon}, \ldots, Zr_{u_U}, Zr_j\}$, which represents the set of end-user loads comprised between location i and location j, including the last end-user load Zr_j. Note, for simplicity of notation the indices ij of each element of the sets (Q^{ij}, U^{ij}, and Zr^{ij}) will be omitted.

Where ZL_{q_1,q_2} represents the impedance of the main line between nodes q_1 and q_2, and ZLA_{q_2,u_2} represents the impedance of the service drop comprised between node q_2 and end-user connection node u_2. L_{q_1,q_2} is the length of the main line between nodes q_1 and q_2. LA_{q_2,u_2} is the length of the service drop between node q_2 and end-user connection node u_2. Zr_{u_1} represents the end-user's residential load u_1, some of which have residential PV systems and residential EV chargers.

It can be seen from Fig. 13 that the path comprised between locations i and j is composed of multiple branches and connected loads. For a more detailed analysis, this path is divided into segments to facilitate its modeling and help to take into account the effect of branches and loads, as shown in Fig. 14.

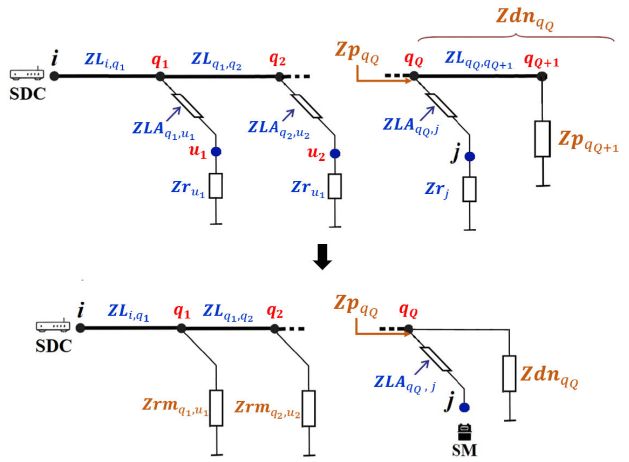

FIGURE 14. Impedances of the segments corresponding to the path comprised between locations *i* and *j*.

Where the impedances of the branches between location i and location j, as Zrm_{q_1,u_1} (without considering the last branch comprised between node q_Q and location j), can be calculated from the following equation:

$$Zrm_{q_1,u_1} = \frac{ZLA_{q_1,u_1}[Zr_{u_1} + ZLA_{q_1,u_1}\tanh(\phi_{LA_{q_1,u_1}})]}{ZLA_{q_1,u_1} + Zr_{u_1}\tanh(\phi_{LA_{q_1,u_1}})} \quad (13)$$

Furthermore, the impedances connected to the last node q_Q, such as Zdn_{q_Q}, which is the resulting impedance of the electrical network downstream of node q_Q, $Zrm_{q_Q,j}$, which corresponds to the impedance of the last branch comprised between node q_Q and location j, and Zp_{q_Q} which represents the resulting parallel impedance between Zdn_{q_Q} and $Zrm_{q_Q,j}$, can be calculated according to the bottom-up approach using (14) to (16) [10], [28].

$$Zdn_{q_Q} = \frac{ZL_{q_Q,q_{Q+1}}[Zp_{q_{Q+1}} + ZL_{q_Q,q_{Q+1}}\tanh(\phi_{L_{q_Q,q_{Q+1}}})]}{ZL_{q_Q,q_{Q+1}} + Zp_{q_{Q+1}}\tanh(\phi_{L_{q_Q,q_{Q+1}}})} \quad (14)$$

$$Zrm_{q_Q,j} = \frac{ZLA_{q_Q,j}[Zr_j + ZLA_{q_Q,j}\tanh(\phi_{LA_{q_Q,j}})]}{ZLA_{q_Q,j} + Zr_j\tanh(\phi_{LA_{q_Q,j}})} \quad (15)$$

$$Zp_{q_Q} = \frac{Zrm_{q_Q,j}Zdn_{q_Q}}{Zrm_{q_Q,j} + Zdn_{q_Q}} \quad (16)$$

where $\phi_{L_{q_Q,q_{Q+1}}} = \Psi_{L_{q_Q,q_{Q+1}}} \cdot L_{q_Q,q_{Q+1}}$, and $\phi_{LA_{q_Q,j}} = \Psi_{LA_{q_Q,j}} \cdot LA_{q_Q,j}$.

2) TRANSFER MATRIX

Considering the impedances obtained through (13) to (16), it is possible to calculate the transfer matrices of each segment of the path comprised between the locations i and j. These matrices can vary depending on the segment's characteristics and are categorized as follows:

- Line transfer matrix: This matrix describes the attenuations caused by each of the main line segments comprised between path i and j. For example, the calculation of the line transfer matrix between nodes q_1 and q_2 can be performed by the following equation:

$$\mathbf{TL}_{q_1,q_2} = \begin{bmatrix} \cosh(\phi_{L_{q_1,q_2}}) & ZL_{q_1,q_2}\sinh(\phi_{L_{q_1,q_2}}) \\ \frac{1}{ZL_{q_1,q_2}}\sinh(\phi_{L_{q_1,q_2}}) & \cosh(\phi_{L_{q_1,q_2}}) \end{bmatrix} \quad (17)$$

- Branch transfer matrix: This matrix describes the attenuations caused by the branches comprised between path i and j. For example, the calculation of the transfer matrix of the branch comprised between the node q_1 and the end-user u_1 can be performed by the following equation:

$$\mathbf{TRM}_{q_1,u_1} = \begin{bmatrix} 1 & 0 \\ \frac{1}{Zrm_{q_1,u_1}} & 1 \end{bmatrix} \quad (18)$$

- Resulting downstream transfer matrix: This matrix describes the attenuations caused by the electrical network downstream of node q_Q. The calculation of this matrix can be performed by the following equation:

$$\mathbf{TDN}_{q_Q} = \begin{bmatrix} 1 & 0 \\ \frac{1}{Zdn_{q_Q}} & 1 \end{bmatrix} \quad (19)$$

- Service drop transfer matrix: This matrix describes the attenuations caused by the last service drop ($ZLA_{q_Q,j}$) within the path i and j, and can be obtained by the following equation:

$$\mathbf{TLA}_{q_Q,j} = \begin{bmatrix} \cosh(\phi_{LA_{q_Q,j}}) & ZLA_{q_Q,j}\sinh(\phi_{LA_{q_Q,j}}) \\ \frac{1}{ZLA_{q_Q,j}}\sinh(\phi_{LA_{q_Q,j}}) & \cosh(\phi_{LA_{q_Q,j}}) \end{bmatrix} \quad (20)$$

Finally, the equivalent transfer matrix describing the communication channel between a SDC allocated at node i and a SM installed at location j can be obtained by multiplying the matrices of each segment placed in serial, through the following equation:

$$\begin{aligned} \mathbf{T}_{ij} &= \mathbf{TL}_{i,q_1} \cdot \mathbf{TRM}_{q_1,u_1} \cdot \mathbf{TL}_{q_1,q_2} \cdot \mathbf{TRM}_{q_2,u_2} \cdots \\ &\quad \cdots \mathbf{TL}_{q_{Q-1},q_Q} \cdot \mathbf{TDN}_{q_Q}\mathbf{TLA}_{q_Q,j} \\ &= \begin{bmatrix} A^{ij} & B^{ij} \\ C^{ij} & D^{ij} \end{bmatrix} \end{aligned} \quad (21)$$

Each ABCD parameter of the $\mathbf{T}_{ij}$ matrix considers the effect of branches and loads between location i and location j. Furthermore, from (6) we can obtain the minimum input voltage that guarantees communication between a SDC at location i and a SM at location j, as follows:

$$Vin_{ij,k} = \frac{Vout_{j,k} \cdot Zin_{i,k}}{Zin_{i,k}A^{ij} + B^{ij} + Zin_{i,k}Zout_{j,k}C^{ij} + Zout_{j,k}D^{ij}} \quad (22)$$

From (22), it is possible to evaluate the coverage of the SDC based on the relation between $Vin_{ij,k}$ and the minimum operation voltage ($V_{min_{op}}$). This $V_{min_{op}}$ represents the receive sensitivity value of the device, which can be obtained from its technical specifications, detailed in Table 2.

3) PLC BINARY COVERAGE MATRIX

To ensure the collection of SM information considering the limitations of PLC technology, the binary coverage $\mathbf{B}_{plc}$ matrix is defined. Each element of the $\mathbf{B}_{plc}$ matrix is determined as follows:

$$\beta_{ij} = \begin{cases} 1, & \text{if } V_{min_{op}} \leq Vin_{ij,k} \\ 0, & \text{if } V_{min_{op}} > Vin_{ij,k} \end{cases} \tag{23}$$

where $\beta_{ij} = 1$ represents the correct exchange of information between the SDC allocated at location i and the SM installed at location j; otherwise $\beta_{ij} = 0$.

Finally, Fig. 15 summarizes the sequence of steps to be followed to obtain the binary coverage matrix, denoted as $\mathbf{B}_{plc}$.

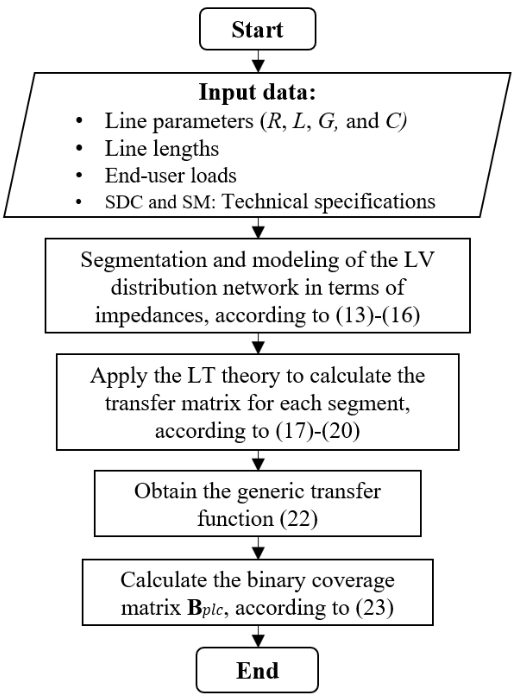

FIGURE 15. Flowchart of modeling the LV distribution network for data transmission using PLC technology.

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