Electrical Properties of Medium Voltage Electricity Distribution Networks

Sathsara Abeysinghe, *Member, IEEE*, Muditha Abeysekera, *Member, IEEE*, Jianzhong Wu, *Member, IEEE*, and Mahesh Sooriyabandara, *Senior Member, IEEE*

***Abstract*—An increasing amount of low carbon technologies (LCT) such as solar photovoltaic, wind turbines and electric vehicles are being connected at medium and low voltage levels to electric power networks. To support high-level decision-making processes, the impacts of the LCTs on large numbers of different types (e.g., rural, suburban, urban) of distribution networks need to be fully understood and quantified. However, detailed modeling of large numbers of real-world networks is challenging for two reasons. First, access to real-world network data is limited, and second, cleaning the data requires a significant amount of time, even before modeling of the networks. This paper offers a novel systematic methodology aimed at identifying and quantifying the key electrical properties of medium-voltage level distribution networks. The methodology allows for characterizing different types (e.g., suburban, urban) of distribution networks and obtaining 'depth' dependent electrical properties of the models of the networks. Two key sets of (electrical) data were used for the study. The first set was installed capacities of distribution substations; and the second set was the conductor cross sections of the distribution lines. In the graph models of real-world networks, 'nodes' represent the distribution substations, switchgears, busbars and consumers locations of the network. 'Links/edges' stand for the connections between the nodes through distribution lines. The results of the investigation of the real-world networks showed that, the substation capacities and the conductor cross sections could characterize the electrical properties of suburban and urban type distribution networks. The resulted probability density functions (PDF) of the electrical properties of suburban and urban type distribution networks have the potential to be directly used in generating realistic distribution network models.**

***Index Terms*—Electricity distribution networks, electrical properties, medium voltage, synthetic networks, statistically-similar networks.**

I. Introduction

ELECTRICITY distribution networks are large-scale and topologically complex systems which carry electricity from the High Voltage (HV) transmission grid to industrial, commercial and domestic users. In recent years, with a large penetration of Low Carbon Technologies (LCTs) (e.g. solar photovoltaics, wind turbines and electric vehicles) at the Medium Voltage (MV) and Low Voltage (LV) levels, electricity distribution networks are undergoing rapid changes.

A large amount of research has been carried out to analyze the impact of employing LCTs on electricity distribution networks based on either real network samples [1], [2] or standard synthetic networks, such as IEEE test cases [3], [4]. Results of such studies are usually case specific and are of limited applicability to other networks of the same type (e.g. urban/suburban).

A few researchers have identified the need of data driven/statistical studies to support the decision-making activities based on impact assessment studies on a large number of realistic electricity networks. This type of decision-making approach on the impact assessment studies of LCTs on power networks, is more robust compared to the decision-making approaches based on specific case study networks. For example, a large-scale network model based on fractal generation is used to generate LV and MV networks in [5] and [6]. The networks generated by the fractal generating tool do not correspond to any real networks but are capable to realistically mimic typical network characteristics of distribution networks of Great Britain (GB), thus allowing more general and strategic conclusions to be drawn with respect to case studies on specific networks. In [7] and [8], the impact of PV generation and EV integration is assessed on a complete distribution system of a single utility in New Zealand. Nevertheless, each distribution network is different, these types of statistical studies help to identify the common behaviors of different types (urban, suburban and rural) of distribution networks.

Robust conclusions on how different types of networks experience the impact of the LCTs, have great value for high level decision-making and policy support. However, detailed modeling of large numbers of real-world networks is challenging for two reasons. First, access to real-world network data is limited, and second, cleaning the data requires a significant amount of time, even before modeling of the networks [9].

In order to address this challenge, a number of previous studies have focused on generating random but realistic electrical power networks. As a result, a number of network models or network generating tools of electrical power networks based on well-known complex networks models [10], fractal generating methods [6], [11] and new graph models [12] have been

Manuscript received September 2, 2020; revised November 13, 2020; accepted December 4, 2020. Date of online publication November 20, 2020; date of current version February 20, 2021. This work was supported in part by the EPSRC Supergen Energy Networks Hub (EP/S00078X/1), UKRI EnergyRev Plus project (EP/S031898/1) and EPSRC-NFSC MC2 project (EP/T021969/1).

S. Abeysinghe, M. Abeysekera and J. Wu (corresponding author, e-mail: WuJ5@Cardiff.ac.uk) are with School of Engineering, Cardiff University, Cardiff CF24 3AA, United Kingdom.

M. Sooriyabandara, is with Toshiba - Bristol Research and Innovation Laboratory, Bristol BS1 4ND, United Kingdom.

DOI: 10.17775/CSEEJPES.2020.01640

developed. Identifying and quantifying the important statistical properties of different types of electrical power networks has been a key requirement when developing such random-realistic network models.

Statistical properties of electric power networks can be categorized into two groups: topological properties and electrical properties. Topological properties of a distribution networks describe how different network components are located and connected. Electrical properties of a distribution network describe its electrical characteristics, such as impedances of the transmission and distribution line conductors, impedances of the electrical equipment (e.g., transformers), thermal ratings of conductors, protection devices and other electrical equipment, and installed capacities of the primary and secondary substations.

In literature, most of the related research on generating random-realistic power networks is carried out for HV transmission networks and the studies carried out at the MV and LV levels are limited [10]. However, with rapid changes happening at the distribution levels, developing large numbers of realistic MV and LV distribution networks are of increasing importance.

A majority of the related previous studies have focused on developing realistic topology models for power networks followed by comprehensive investigations on topologies of real-world networks [13]. However, network topologies by themselves are not sufficient to describe the performance of electrical power networks. Electrical properties together with their topological structures are critical for the evaluation of the network performance including power losses, voltage drop, reliability and costs, etc.

The typical assumptions used in some of the previous studies to assign electrical properties to network topologies, such as uniform distributions of the consumer load and uniform cross sections and cable types for all the distribution lines are not sufficiently accurate to describe the realistic electrical behavior of the distribution networks. Distribution of the consumer load is usually different from one network type to the other and difficult to predict without sufficient information from the real networks. Moreover, the guidelines and recommendations for network planning and design are also different from region to region and may not be followed exactly in practice due to various reasons such as geographical constraints, policies, regulations and financial factors. Hence, planning and design guidelines of distribution networks by their own, are also not sufficient to provide realistic representations of the electrical properties of distribution networks.

Investigations of electrical properties of power networks in literature primarily refer to the investigations related to the distribution of transmission and distribution line impedances of the networks. Weighted graphs of power networks with weights of the edges representing the impedance of the transmission or distribution lines are used to derive the electrical properties of the power networks in such studies. The concept of electrical distance has also been used in the references [9], [14] and [15] when studying the electrical characteristics of power networks. The most common measure of electrical distance has been the absolute value of the inverse of the system admittance matrix (this is the same admittance matrix that is used in power flow analysis in electrical power system studies) [16]. Most of those previous studies were carried out at the HV level. A number of studies at the distribution level were carried out to obtain the optimal conductor selection for radial type distribution networks [17], [18]. But it was common in such previous studies to assume that distribution of the consumer loads is a known factor for the study. Then, general network planning and design guidelines were adapted to meet technical and financial constraints.

By reviewing the literature, it is evident that a wider statistical analysis on the electrical properties of distribution networks, supported by a large amount of real-world data is required. Therefore, followed by the topological investigation in [13], an investigation of the electrical properties of real-world, MV electricity distribution networks is carried out in this paper. The motivation of this study is to identify and quantify the key electrical properties which will later be useful in generating random synthetic-realistic distribution network models with electrical properties similar to those of real distribution networks.

The main contributions of this paper include: (1) identifying the key electrical properties that are useful to characterize the real world MV distribution networks; (2) quantifying the electrical properties of real world MV urban and suburban networks using techniques from graph theory and the concepts from power system analysis; and (3) introducing a novel, 'depth dependent' approach to better characterize the electrical properties of the MV distribution networks. The proposed methodology of the study is shown in Fig. 1.

II. Methodology

Real world data for this study was collected from a Chinese power grid. The selected set of data includes the technical and geographical information about MV suburban and urban distribution networks. Networks were categorized as urban

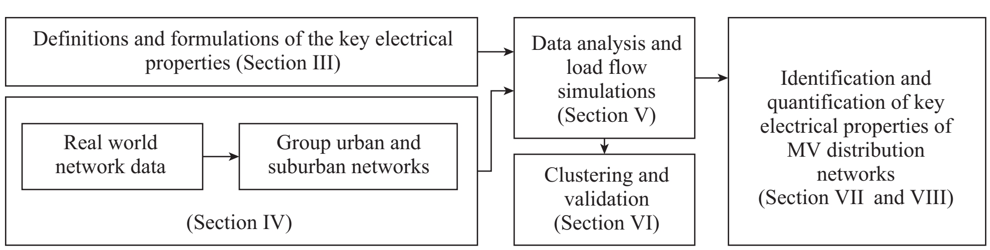


Fig. 1. Proposed methodology of the study.

and suburban networks according to their population densities. Networks with population densities over 1,500 people per km2 were classified as urban areas [19]. Radial network structures with one main-grid supply point were considered. All selected suburban networks have radial structures. Most urban networks are meshed networks but operated in radical structures. In such cases, the operational radial structures with only one main-grid supply point were used.

The same set of Chinese power grid data that was used for the topological investigation in [13], was used for this study. However, only a limited set of electrical data from the real-world networks were available. They are, i. Installed capacities of the primary and the secondary/distribution substations and, ii. Conductor cross sections and cross sections related properties (e.g., per km impedance, thermal ratings) of the distribution lines.

The following sections of the paper describe the detailed approach of the investigation of electrical properties of real-world distribution networks using the above available two sets of data.

III. Definitions and Formulations of the Key Statistics

In order to extract the electrical properties of distribution networks, which are also associated with their topology, each real network is represented as a directed, weighted graph: $\mathbf{G} = (\mathbf{V}, \mathbf{E})$. **V** represents the set of nodes and **E** represents the set of edges in graph **G**. With reference to an electricity distribution network, **V** includes substations, distribution transformers, switches, busbars and consumer locations. **E** stands for physical connections between nodes through underground (UG) cables and overhead (OH) distribution line segments. Since all the networks used in this study have radial structures they can be denoted as rooted trees with the primary substation (PS) representing the root s of the corresponding network.

Node identifiers were specified according to the Breadth-first search (BFS) approach [20]. In this approach, node numbering starts at the tree root s $node_{id}$ equals to 1), and number the nodes in the next same depth level ($\acute{d}$) first ($node_{id} = 2, 3, 4 \ldots$), before moving to the subsequent depth level. Lengths (in km) of the distribution line segments are used as the weights of the edges in the graph. The depth level of a node u, in a tree is defined as the number of edges from the root node s, to the node u.

Definitions and formulations of the key electrical properties used in this study are described in the following section with reference to the 10 kV Chinese electricity distribution networks selected for the investigation. Table I provides a summary of the electrical properties investigated in this study.

A. Substation Capacity Related Properties

1) Primary Substations (PS)

Usually, a 10 kV distribution network is supplied by a primary substation which transforms voltage from 35 kV to 10 kV. Primary substations are often sited close to large industrial customers or at the load center. In the graph representations of electricity networks, the primary substation becomes the root node.

The installed capacities of these primary substations (PS_c) depend on the type of the areas where they are located. In rural areas, the primary substation capacity can be quite small with a single 35 kV/10 kV transformer and no more than two or three outgoing feeders. A feeder of an electricity distribution network is an exit route that carries electric power from the primary substation to the distribution substations. Primary substations in city center areas often have several large transformers and more than 10 outgoing feeders. The information of primary substations is specified in the following format (1).

$$PS = [node_{id}, PS_c(MVA), num_{of_{\text{feeders}}}]_{1\times 3} \tag{1}$$

$node_{id}$ is the identifier of the node where the primary substation is located, PS_c is the installed capacity of the primary substation and $num_{of_{\text{feeders}}}$ is the number of outgoing feeders from the primary substation.

2) Secondary Substations (SS)

The secondary substations, where power is transformed from 10 kV down to the 0.4 kV LV system, come in different types. In urban areas, secondary substations are primarily ground mounted and have higher installed capacities than in rural areas. In rural areas pole mounted substations are widely used.

In graph models of the distribution networks, each node representing a secondary substation is assigned with an installed capacity, SS_C. The distance (in km) from root s, to the secondary substations along the feeders ($dist_{s,SS}$), is obtained using the Djakarta's shortest path algorithm [21]. The list of secondary substations is represented in the matrix format as

TABLE I
Summary of the Electrical Properties

Category	Electrical properties
Substation capacity related properties	Installed capacity of the primary substation (MVA) Average installed capacity of a secondary substation (kVA) Variation of the installed capacities of the secondary substations with the distance to the source node along the feeders Load density (MVA/km^2)
Conductor cross section related properties	Average electrical distance (Ohms) between two nodes of the network (i.e. average resistance and reactance between two nodes in the network) Thermal ratings of the conductors (kVA or amperes)
Electrical performance of the network related properties	Total power loss to the total supplied power ratio (%) of the network Minimum and maximum recorded voltages of the network System load balancing index

shown in (2). N_{SS} is the total number of secondary substations in the network.

$$\text{SS} = [node\_id, dist_{s,SS}(km), SS_C(kVA)]_{N_{\text{SS}} \times 3} \tag{2}$$

3) Average Installed Capacity of Secondary Substations

The average installed capacity of secondary substations ($SS_{C,avg}$) in a network can be obtained from the above data using (3). A higher value of $SS_{C,avg}$ implies a higher electrical load density and a lower value of $SS_{C,avg}$ implies a lower load density in a selected area of the networks.

$$SS_{C,avg} = \frac{\sum_{i=1}^{N_{\text{SS}}} SS_{C,i}}{N_{\text{SS}}} \tag{3}$$

4) Distribution of the Capacities of Secondary Substations Along the Feeder Lengths

The distribution of consumer loads is a primary factor that determines the distribution of secondary substation capacities. The distribution of consumer loads can be different from one network type to the other. For example, in rural type distribution networks, usually the primary substations are located closer to the high-capacity loads while some distribution feeders stretch further to provide power to the far away low-capacity loads.

In order to capture the variation of secondary substation capacity with its distance to the root node, the following approach is used. The secondary substation capacities are plotted against the distance to the root node of each secondary substation. The distances are normalized (l_{norm}) by dividing the distances to each secondary substation from the root node, by the maximum feeder length $l_{\max}$ of the corresponding network as shown in (4). $l_{\max}$ of a network is the distance from root node to the furthest away secondary substation along a feeder. This normalization allows the comparison of the distribution of secondary substation capacities along the feeder length between different networks.

$$l_{\text{norm}} = \frac{dist_{s,SS}}{l_{\text{max}}} \tag{4}$$

5) Load Density (MVA/km2)

The load density LD (MVA/km^2) of a given area of the network is obtained by dividing the total installed capacity of secondary substations in the network by the total supply area (*Total area*) of the network and then multiplying this value by a demand factor k_d as shown in (5). A demand factor k_d, for this study is defined as a fraction of the installed capacity of a secondary substation in the distribution network, which is actually being consumed as the consumer load at a given instant of time. In the real-world networks, secondary substations do not operate in their maximum capacity under normal operating conditions. Therefore, it was assumed that, on average, secondary substations are operating at 60% of their capacities and hence, for the calculations, k_d is assumed to be equal to 0.6.

$$LD = \frac{\sum_{i=1}^{N_{\text{SS}}} SS_{C,i} \times k_d^i}{\text{Total area}} \tag{5}$$

According to the guide for planning and design of the Chinese distribution networks in reference [22], in the planning process of Chinese electrical power networks, the power supply areas are divided into different zones according to their load density σ, which is measured in MW per km^2. Load density is one of the major factors used widely by DNOs in many countries in their network planning and design guidelines for the selection of the network structure (E.g. radial, single/double ring), capacities of the main supply transformers, selection of the overhead lines (OH) or underground (UG) cables and for the selection of conductor cross sections.

B. Conductor Cross Section Related Properties

Usually, in radial feeders, the distribution line segments closer to the root node carry more power than the line segments further away from the source (Note: this explanation is valid when there are no distributed generators (DG) connected to the distribution network. With DGs connecting at various places, the line loadings in the distribution networks can be different from the above explanation). These characteristics of radial feeders enable the choice of multiple conductor cross sections for a single feeder. However, the use of a large number of different cross sections will result in an increased cost of the inventory [23]. To avoid high costs, specific recommendations are set by the network planners.

The distribution line segments in a network can be divided into a trunk and lateral branches (tie lines are ignored). The trunk refers to the backbone of a network and is the main route of power transfer from the primary substation down to the load centers. Usually, the trunk lines have larger cross sections and also a headroom is left for future expansions. Lateral branches are the distribution line segments that connect between trunk lines and the MV consumers and secondary substations.

The choice between OH lines or UG cables for a distribution line depends also on the type of area. UG cables are widely used in urban areas while OH lines are more common in rural areas. In addition, the choice of UG cables and OH lines are also heavily influenced by the cost of labor and material, and geographical constrains such are rivers, mountains, reserved areas, etc. [24].

1) Impedance of a Distribution Line

Depending on the conductor cross section (mm^2), the per km impedance (z) of a distribution line can be obtained using manufacturer manuals. Parameter r is the per km resistance and x is the per km reactance in (6). Shunt capacitance of distribution lines and short transmission lines is low, so it doesn't affect the performance of line parameters and other factors. Therefore, the shunt capacitance of the distribution lines is ignored [24].

$$z = r + jx \tag{6}$$

2) Electrical Distance Matrix

If the impedances of all the distribution lines are known, an electrical distance matrix (ED) for the network can be obtained as shown in (7),

$$ED_{ij} = \begin{cases} d(i,j) \times z(i,j), & \text{if } (i,j) \in E \text{ and } i < j \\ 0, & \text{otherwise} \end{cases} \tag{7}$$

where, $d(i,j)$ is the length of the distribution line connecting nodes i and j and $z(i,j)$ is the impedance of the distribution line connecting nodes i and j. The condition, $i < j$ of (7) ensures that only the upper triangle of the matrix ED is filled.

3) Average Electrical Distance between Two Nodes in a Network

Average electrical distance ed_{avg} between the nodes in the network is then obtained according to (8). N is the total number of nodes in the network and M is the total number of branches in the network.

$$ed_{\text{avg}} = \frac{\sum_{i=1}^{N}\sum_{j=1}^{N} ED(i,j)}{M} \tag{8}$$

4) Thermal Rating of the Conductors

Thermal rating/limit of the conductors is one major factor that limits the power flow through a distribution line. These thermal limits are intended to limit the temperature reached by the energized conductors and the resulting sag and loss of tensile strength. Thermal ratings (in terms of kVA or amperes) of the corresponding cross section and material type of the conductors can be found using cable manufacturers data manuals.

C. Electrical Performance Related Properties

In practice, electricity distribution networks are designed to meet many technical and economic standards to achieve the best performance in both normal and abnormal operating conditions. Power losses, voltage drop and feeder utilization are some of the most important indicators to describe the electrical performance of a distribution network.

1) Power Losses

Given the active (P_{ij}) and reactive (Q_{ij}) flows seen at the receiving end j of a distribution line segment e_{ij} (Fig. 2) with a conductor impedance $Z = (r + jx) \times l_{jx}$, the active power loss ($PLoss_{e_{ij}}$), reactive power loss ($QLoss_{e_{ij}}$) and apparent power loss ($SLoss_{e_{ij}}$) are obtained by (9), (10) and (11). l_{ij} is the length of the distribution line segment e_{ij}.

$$PLoss_{e_{ij}} = \frac{P_{ij}^2 + Q_{ij}^2}{V_j^2} \times r \times l_{ij} = \frac{S_{ij}^2}{V_j^2} \times R \tag{9}$$

$$QLoss_{e_{ij}} = \frac{P_{ij}^2 + Q_{ij}^2}{V_j^2} \times x \times l_{ij} = \frac{S_{ij}^2}{V_j^2} \times X \tag{10}$$

$$SLoss_{e_{ij}} = \sqrt{(PLoss_{eij}^2 + QLoss_{eij}^2)} \tag{11}$$

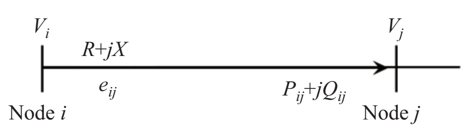


Fig. 2. Representation of a distribution line segment.

The total power loss ($SLoss_{\text{Total}}$) is the sum of the individual power loss in each line segment in the network. The ratio of total power loss to the total supplied power (*Power loss ratio*) is used as another performance evaluation parameter to compare different networks as shown in (12). $Ssupplied_{\text{Total}}$ is the total power supplied to the network.

$$\textit{Power loss ratio} = \frac{SLoss_{\text{Total}}}{Ssupplied_{\text{Total}}} \times 100\% \tag{12}$$

2) Voltage Drop

In a distribution network, a knowledge of voltage at different parts of the network can indicate the strong and weak parts of a network. Often a specific voltage drop (e.g. 6%) is permitted between the real voltage of a node and the rated voltage for that network. The voltage drop V_d in a distribution line segment e_{ij} can be calculated using (13):

$$V_d = \frac{P_{ij}}{V_j}(R + X \tan\varphi) \tag{13}$$

where, φ is the angle between voltage and current at node j. The total voltage drop $V_{d\text{Total}}$ is the sum of individual voltage drop across each line segment [24].

3) Load Balancing Index

Branch load balancing index, LB_{branch} and overall system load balancing index, LB_{sys} are used to determine the loading condition of the distribution network. Branch load balancing index is defined as a measure of how much a branch is loaded against the rated capacity of that branch. This is represented mathematically as shown in (14),

$$LB_{\text{branch}} = \frac{S_{\text{branch}}}{S_{\text{branch}}^{\max}} \tag{14}$$

where, S_{branch} is the complex power flowing through the branch and $S_{\text{branch}}^{\max}$ is the maximum rating or capacity of branch. Then, the system load balancing index LB_{sys} of the entire distribution network is obtained using (15),

$$LB_{\text{sys}} = \frac{1}{M}\sum_{\text{branch}=1}^{M} \frac{S_{\text{branch}}}{S_{\text{branch}}^{\max}} \tag{15}$$

where M is the total number of branches in the network [25].

IV. Power Grid Data for the Investigation of Electrical Properties

Suburban and urban network samples with radial structures were selected from the data of 10 kV Chinese electricity distribution networks. The networks were classified as suburban and urban according to the population density. Table II summarizes the basic information of the 10 kV network samples selected for this study.

Figure 3, shows an example of a real distribution feeder in a 10 kV electricity distribution network. The trunk line and the lateral branches are marked in red (thick) and blue (thin) lines. Installed capacities of the 10 kV/0.4 kV secondary substations are marked next to each secondary substation. The capacity of the 35 kV/10 kV primary substation is 20MVA. Conductor types used for the distribution lines are marked along the lines. Consider an example of conductor type LGJ-70/1.6 in Fig. 3, "LGJ" is the symbol of steel-cored aluminum strand, in which "L" the abbreviation of aluminum wire is, "G" is the abbreviation of steel core, and "J" is the abbreviation of stranded wire. The number "7"' refers to the cross section (mm^2) of the conductor [26]. In the network drawings, the number after the cross section (e.g. 1.6) refers to the length (km) of the distribution line segment with that conductor cross section.

TABLE II
BASIC INFORMATION OF THE SELECTED SAMPLES OF 10KV SUBURBAN AND URBAN NETWORKS

Network type	Network ID	Area (km^2)	Population density ($/km^2$)	Total number of nodes	Total Number of branches	Number of outgoing feeders from the primary substation	Installed capacity of the primary substation (MVA)	Number of secondary substations in the network	Total installed capacity of secondary substations (kVA)	Maximum feeder length (km)
Suburban	1	66.2	482	254	253	7	8+5 = 13	92	16100	10.7
	2	142.0	328	399	398	5	2×10 = 20	129	20652	14.8
	3	64.5	405	285	284	4	2×10 = 20	109	20083	10.8
	4	80.9	449	173	172	4	2×10 = 20	65	13470	12.3
	5	108.5	256	204	203	5	2×8 = 16	81	17303	11.8
	6	78.5	369	196	195	4	2×10 = 20	76	15135	11.5
	7	84.1	473	321	320	6	2×10 = 20	117	24440	14.4
	8	88.0	508	351	350	7	2×10 = 20	109	28080	15.1
	9	32.2	422	169	168	6	5+6.3= 11.3	59	12580	6.8
	10	48.8	640	186	185	5	2×10 = 20	73	17650	7.1
Urban	11	9.8	1939	234	233	9	2×20 = 40	65	23850	3.8
	12	9.2	1935	237	236	7	2×50 = 100	98	50030	3.7
	13	10.0	1930	331	330	7	2×16 = 32	90	38200	3.5
	14	8.0	1750	205	204	7	50+63= 113	83	43900	5.2
	15	14.0	3200	328	327	8	2×50 = 100	125	72370	5.5
	16	16.0	3200	400	399	7	2×20 = 40	115	66380	4.8
	17	7.0	3600	227	226	6	31.5+20 =51.5	99	42250	4.0
	18	7.5	3600	217	216	6	2×50 = 100	96	42865	5.6
	19	8.0	3600	265	264	10	2×20 = 40	89	65080	5.1
	20	7.5	3600	153	152	7	2×16 = 32	50	27470	3.4

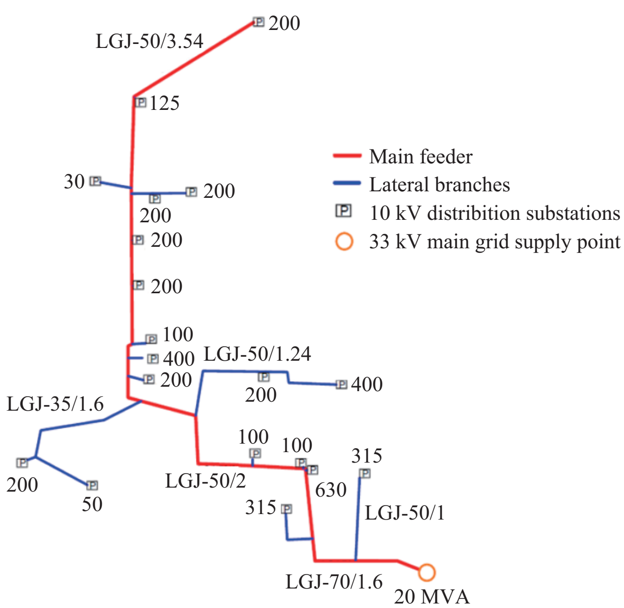


Fig. 3. A distribution feeder of a 10 kV electricity distribution network.

TABLE III
THE SELECTION OF CAPACITIES FOR PRIMARY AND SECONDARY SUBSTATIONS TRANSFORMERS IN 10KV NETWORKS

Substation type	Unit	Installed capacities
Primary substation (33 kV/10 kV)	MVA	5, 6.3, 8, 10, 16, 20, 31.5, 50, 63
Secondary substation (10 kV/0.4 kV)	kVA	20, 30, 50, 80, 100, 125, 160, 200, 250, 315, 400, 500, 625, 800, 1000

TABLE IV
PROPERTIES OF THE CONDUCTOR TYPES USED FOR 10KV DISTRIBUTION LINES [26]

Cable name	Cross section mm^2	Resistance per km (Ohms)	Reactance per km (Ohms)	Current rating at 90 degrees Celsius (A)
LGJ−35	35	0.82	0.38	180
LGJ−50	50	0.59	0.368	227
LGJ−70	70	0.42	0.358	287
LGJ−95	95	0.29	0.342	338
LGJ−120	120	0.23	0.335	390
LGJ−185	185	0.16	0.365	518
LGJ−240	240	0.12	0.358	610
LGJ−300	300	0.09	0.365	707

Table III summarizes the installed capacities of the secondary substations and primary substations of the selected set of suburban and urban network samples. It was noted that, at some primary and secondary substations, two or more transformers were installed to obtain a higher power supply capacity and to act as a backup unit due to the reliability constraints. Table IV summarizes the properties of widely used conductor types in the selected set of 10 kV distribution networks.

V. QUANTIFICATION OF THE ELECTRICAL PROPERTIES

In order to calculate electrical performance related network parameters, load flow simulations were conducted. However, the consumer load profiles, or load data were not available in the original data. To overcome this limitation, a few assumptions were made. A steady state power flow simulation for each network was conducted with the following assumptions.

i. A fraction (60%) of the installed capacities of secondary substations are used as the actual load connected to each load node.
ii. The power factor at each load node is considered as 0.9.
iii. Per unit voltage at the supply point is equal to 1.05 p.u.

Figure 4 visualizes the results of the evaluation of electrical properties of the above suburban and urban networks at the 10 kV level. Numerical values of the results are given in Table A in Appendix A.

In order to compare the statistical distribution of the electrical properties of urban and suburban networks, box-whisker

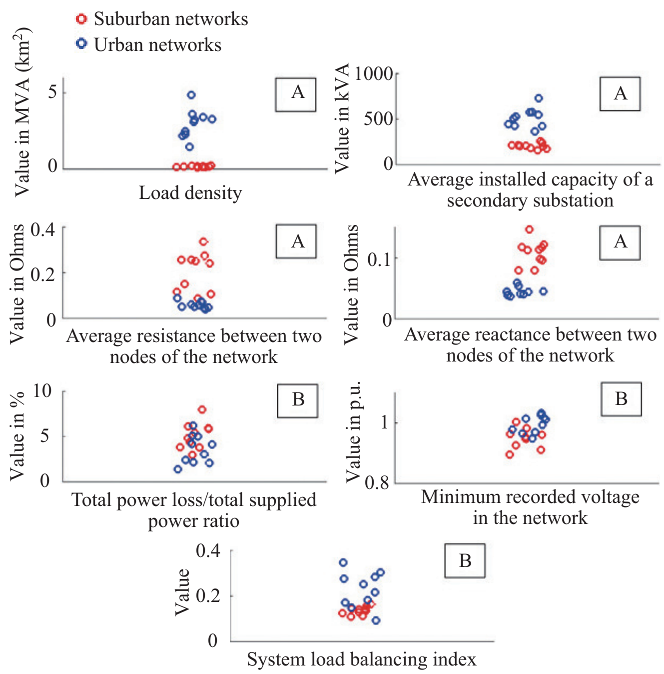


Fig. 4. Electrical properties of urban and suburban networks.

plots in Fig. 5 were generated. On each box, the central mark "|" indicates the median, and the front and rear edges of the box indicate the 25$^{\text{th}}$ and 75$^{\text{th}}$ percentiles, respectively. The whiskers extend to the most extreme data points not considered outliers, and the outliers are plotted individually using the "+" symbol.

From Fig. 4 and Fig. 5 it can be identified that some of the electrical properties are able to clearly characterize the two types of networks. These properties include load density, average installed capacities of secondary substations, average resistance and reactance between the nodes of the network (sub-graphs with letter A).

The discrete ranges of variation of these properties in suburban and urban networks are summarized in Table V. In suburban networks, load densities and the average installed capacities of SSs are considerably lower than that of the urban networks. In the real situation, these observations from the results are reasonable, as the urban areas are highly populated, and a higher number of commercial and industrial consumers are located in the urban areas than in the suburban areas. However, this study has managed to quantify these characteristics of suburban and urban networks in terms of load densities and average capacities of SSs and clear differences between the ranges of variations of the values have been identified.

According to the results, average resistance and reactance of the edges connecting two nodes of the urban networks are lower than that of the suburban networks. This observation from the results is explained by two factors of the real-world networks; (i) as studied in [13] regarding the average edge length between two nodes in the suburban and urban networks, urban networks have shorter average edge lengths between two nodes of the network than in the sub urban networks (ii) conductors used in the urban networks for distribution lines have larger cross sections and hence lower resistances and reactances.

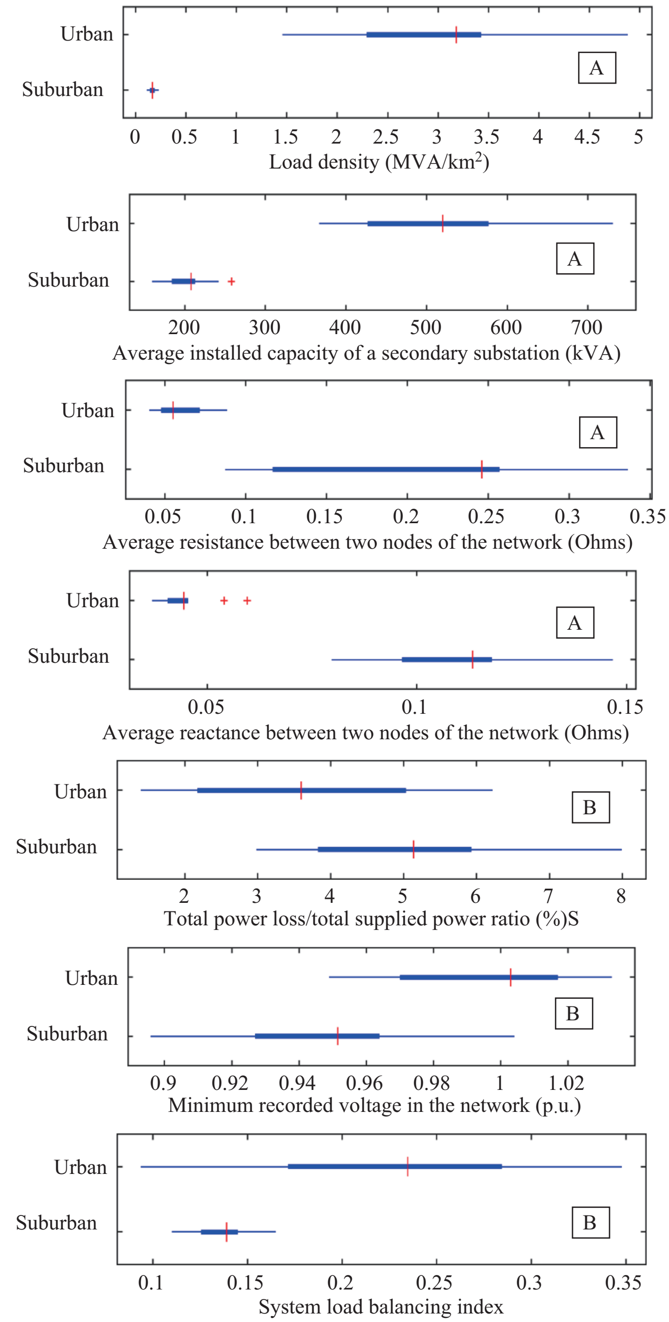


Fig. 5. Electrical properties of urban and suburban networks.

The electrical properties categorized with letter "B" in Fig. 4 and Fig. 5, have overlapping ranges of variations, but with noticeable trends. From the box-whisker plots, it can be observed that the load balancing index and the minimum recorded voltages of urban networks tend to be higher than the suburban network, while the total power loss to total supplied power ratio in suburban networks tend to be higher than that of the urban networks. These noticeable trends can be caused by the following reason. In suburban networks, distribution lines usually carry electric power along long distances than in urban networks, resulting in higher power losses, and higher voltage drops in suburban networks than those of the urban networks. As there are overlapping ranges of variations of electrical properties categorized with letter "B" in Fig. 4 and Fig. 5, these properties cannot clearly characterize the two types of networks. Maximum voltage was always recorded at the primary substation of the network as 1.05 p.u. and hence it was not used as an observation for this study.

TABLE V
THE RANGES OF VARIATIONS OF THE ELECTRICAL PROPERTIES OF SUBURBAN AND URBAN DISTRIBUTION NETWORKS

Electrical property	The range of variation	
	Suburban networks	Urban networks
Load density (MVA/km^2)	0.116–0.234	1.460–4.881
Average installed capacity of secondary substations (kVA)	160–258	367–731
Average resistance between two nodes of the network (Ohms)	0.087–0.336	0.041–0.089
Average reactance between two nodes of the network (Ohms)	0.080–0.147	0.037–0.060

VI. VALIDATION OF THE NETWORK CLASSIFICATION USING ELECTRICAL PROPERTIES

A clustering exercise following the same clustering approach described in the topological investigation in [13] was carried out with the results in Table VI for electrical properties of the networks.

First, all "seven" electrical properties described in Table VI were chosen as the cluster variables. The k-means algorithm was used to group the 20 networks into two clusters. The grouping was done by using all "seven" variables, exactly following the suburban and urban classification done by the population density parameter of the networks. Hence, this step was used to validate the urban, and suburban classifications of the networks by using the electrical properties.

The results shown in Fig. 6 are graphical representations of the case where, different subsets with "three" parameters were chosen as the cluster variables. In the first two cases (Fig. 6(a) and 6(b)), the selected sets of cluster variables were accurately able to group the network samples into two cluster as defined by the population density of the networks. However, the third set of cluster variables shown in Fig. 6(c) did not cluster the network samples into the right groups. Similar to that of the topological investigation [13], this observation explains the importance of careful selection of network properties when characterizing different network types.

VII. IDENTIFICATION OF THE KEY ELECTRICAL PROPERTIES FOR CHARACTERIZING ELECTRICITY DISTRIBUTION NETWORKS

From the results, it is evident that the electrical properties derived from the data of installed capacities of the secondary substations and the conductor cross sections used for distribution lines are able to characterize the different types of networks.

The distribution of the installed capacities of the secondary substations is an indirect representation of how the consumers are distributed in a network, which is not possible to be derived from the planning and design guidelines. Therefore, realistic allocation of the installed capacities of the substations on a network is important in achieving realistic representations for different types of electricity distribution networks.

The allocation of the conductor cross sections of a suburban type real world distribution network is shown in Fig. 7. Similar to the network in Fig. 7, as with all the real-world network samples selected for this study, the trunk lines are assigned with larger cross sections while the laterals are assigned with slightly smaller conductor cross sections. Also, a maximum of 3–4 different types of conductor cross sections were observed in each network used for this study, which also is consistent with the normal practices of network planning and design [22].

In the network modelling point of view, further investigation of the distribution of the installed capacities of the secondary substations has clear benefits. If the topologies of synthetic distribution networks can be generated using some tool to resemble real-world networks, the next challenge is to assign realistic electrical properties to those topologies.

Detailed findings from a real-world network investigation about the distribution of substation capacities can enable ways (e.g., using PDFs) of assigning substation capacities to the nodes of synthetic network topologies. Once the capacities of the secondary substations are assigned the selection of conductor cross sections and other electrical equipment can be done following the traditional approach for planning and design of distribution networks.

The traditional approach for planning and design of distribution networks involves forecasting of electricity demand, locating and sizing substations, designing the layout of the power distribution network and finally the selection of electrical equipment (e.g. selection of conductor cross sections for OH lines, UG cables) [24]

VIII. NETWORK DEPTH DEPENDENT ELECTRICAL PROPERTIES

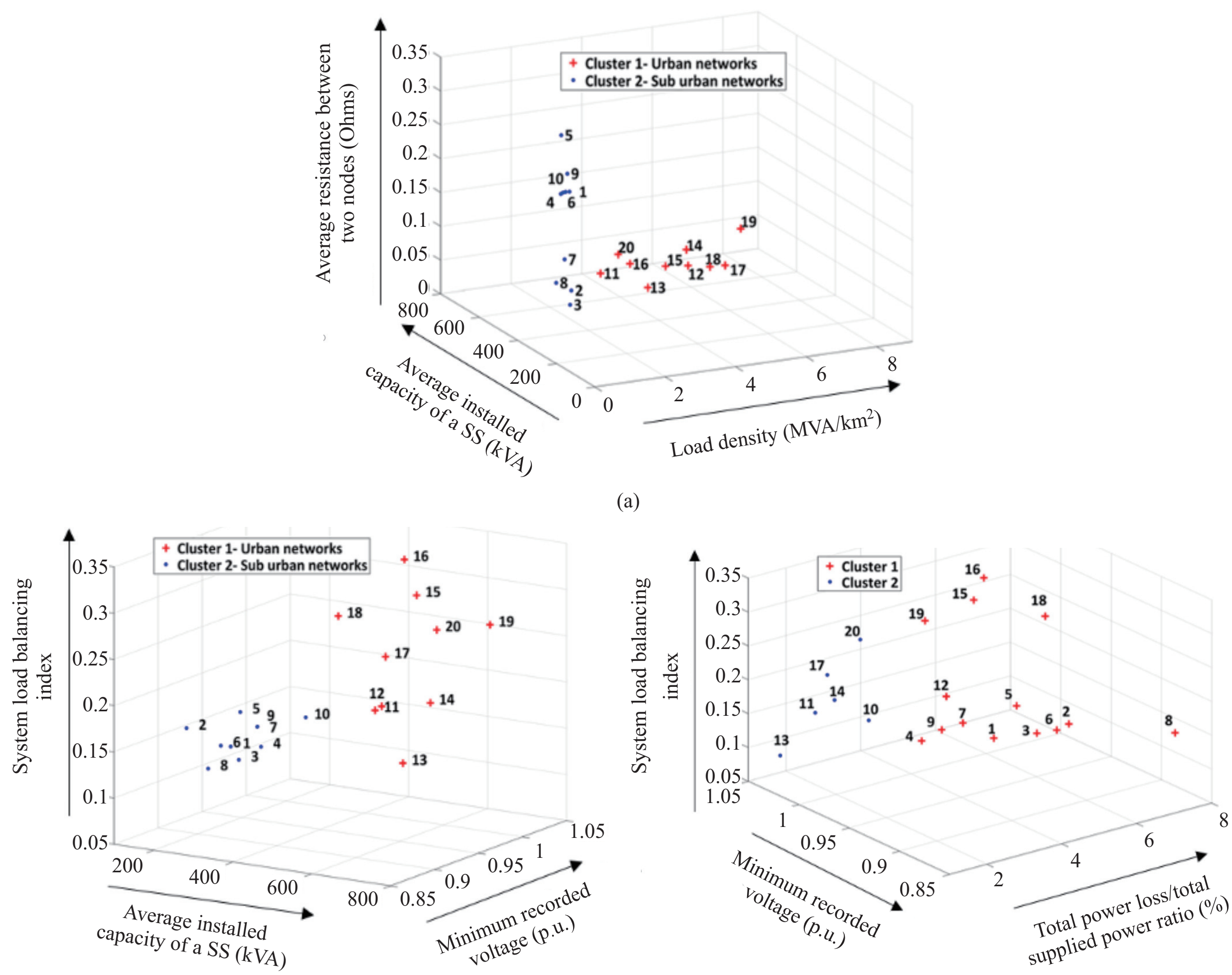
In this section the depth dependent electrical properties are investigated. The depth in this study is the normalized distance, l_{norm} from the root node to the other nodes in the network, as shown in (4). The aim is to capture the realistic distribution of secondary substation capacities of suburban and urban networks.

Figure 8(a) and 8(b) show the distribution of the installed capacities of secondary substations in suburban and urban networks with the normalized distance from root node to each secondary substation. The information in Fig. 8(a) corresponds to all the suburban networks used in the study and similarly Fig. 8(b) corresponds to all the urban networks.

The range of variation in secondary substation capacities in urban networks is much larger compared to that of the suburban networks. Distribution of installed capacities of

TABLE VI
ELECTRICAL PROPERTIES OF THE 10kV SUB-URBAN AND URBAN NETWORKS

Network ID	Load density (MVA/km^2)	Average installed capacity of a secondary substation (kVA)	Average electrical distance between two connected nodes		Total power loss/total supplied power ratio (%)	Minimum recorded voltage (p.u.)	System load balancing index
			R (Ohms)	X (Ohms)			
1	0.146	175	0.2566	0.1129	4.84	0.949	0.1257
2	0.145	160	0.1167	0.0798	5.85	0.912	0.1568
3	0.187	184	0.0874	0.0798	6.13	0.954	0.11
4	0.166	207	0.2571	0.1179	3.83	0.983	0.1134
5	0.159	213	0.3364	0.1467	5.43	0.948	0.1651
6	0.116	199	0.2515	0.1176	5.93	0.927	0.136
7	0.174	209	0.1504	0.0986	4.42	0.964	0.144
8	0.191	258	0.1071	0.0965	7.99	0.896	0.1294
9	0.234	213	0.2757	0.122	3.8	0.962	0.1448
10	0.217	242	0.2409	0.1138	2.98	1.004	0.142
11	1.46	367	0.0886	0.0449	2.17	1.027	0.1496
12	3.263	511	0.0511	0.0446	4.14	0.970	0.1834
13	2.292	424	0.0456	0.037	1.4	1.033	0.0938
14	3.293	529	0.0715	0.0596	2.42	1.017	0.1716
15	3.102	579	0.0405	0.0391	5.11	0.979	0.3047
16	2.489	577	0.0519	0.0407	5.03	0.966	0.3479
17	3.621	427	0.0613	0.0412	2.09	1.012	0.2169
18	3.429	447	0.0584	0.0444	6.22	0.949	0.2844
19	4.881	731	0.0479	0.0455	4.21	0.994	0.2771
20	2.198	549	0.0742	0.0541	3.05	1.015	0.2526



(a)

(b)

(c)

Fig. 6. Cluster assignments based on different selections of electrical properties as cluster variables.

secondary substations reflects the distribution of consumers. In the suburban networks, consumers are not as densely and evenly populated as in urban networks. Usually, the networks are designed in such a way that the main supply points are

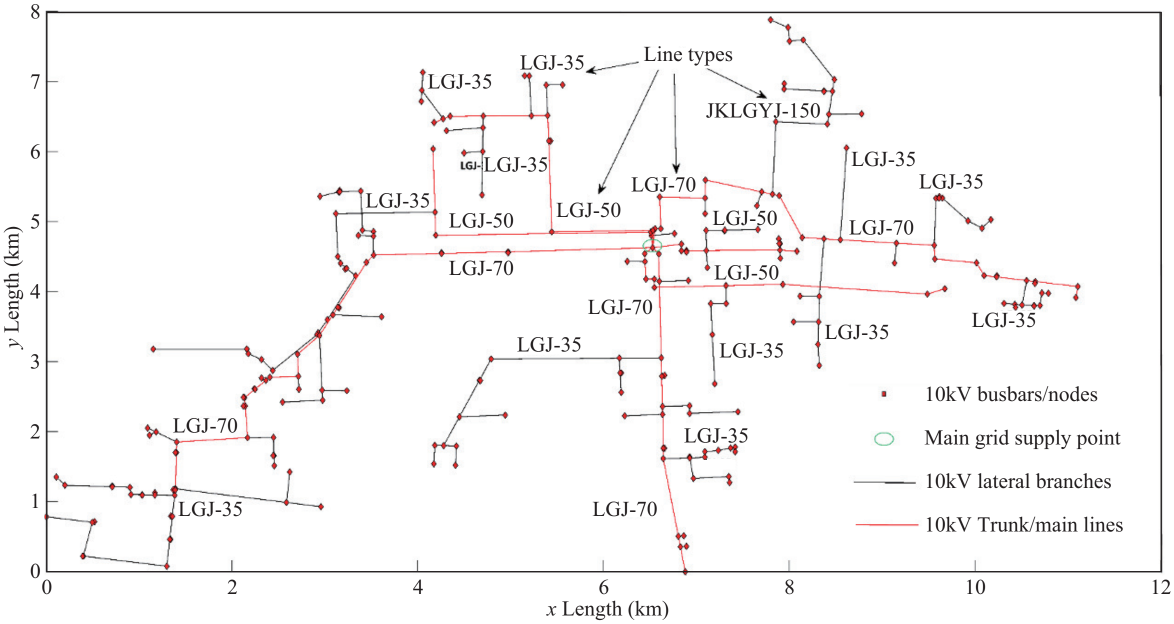


Fig. 7. Network layout and the selection of conductor cross sections of the suburban type network no.1.

located closer to the load centers. Therefore, in the suburban networks, the number of secondary substations with higher installed capacities are closer to the root node. Whereas in urban networks, high capacity secondary substations are spread almost evenly throughout the lengths of the networks.

A. Definition of "Depth Levels" for the Analysis of Electrical Properties

In order to better understand the distribution of the secondary substation capacities, the networks are divided into 3 levels according to the normalized lengths, l_{norm} from the source node as shown in Fig. 9. For example, secondary substations within the normalized distance 0 and 1/3 belong to the $level_1$ of the network as shown in (16). The number of levels can be varied and a sensitivity study with different numbers of levels can be conducted to identify the best number of levels to capture the depth dependent properties of different types of networks. However, this part of the study is not covered in this paper.

$$level = \begin{cases} level_1, & 0 < l_{\text{norm}} \leqslant 1/3 \\ level_2, & 1/3 < l_{\text{norm}} \leqslant 2/3 \\ level_3, & 2/3 < l_{\text{norm}} \leqslant 1 \end{cases} \tag{16}$$

B. Probability Distributions of the Depth Dependent Electrical Properties

Applying the Kernel distribution fitting methodology described in [27] and [28], the PDFs of the installed capacities of secondary substations at different levels of the two network types are calculated. Unlike a histogram, which discretizes the data values into separate bins, the Kernel distribution sums the weight functions for each data value to produce a smooth, continuous probability curve. The Kernel density probability distributions for the installed capacities of secondary substations in each level are formulated using (17) and (18).

$$f_h(y) = \frac{1}{nh}\sum_{i=1}^{n} K\left(\frac{y-y_i}{h}\right) \tag{17}$$

$$K(y) = \frac{1}{\sqrt{2\pi}} e^{-\frac{y^2}{2}} \tag{18}$$

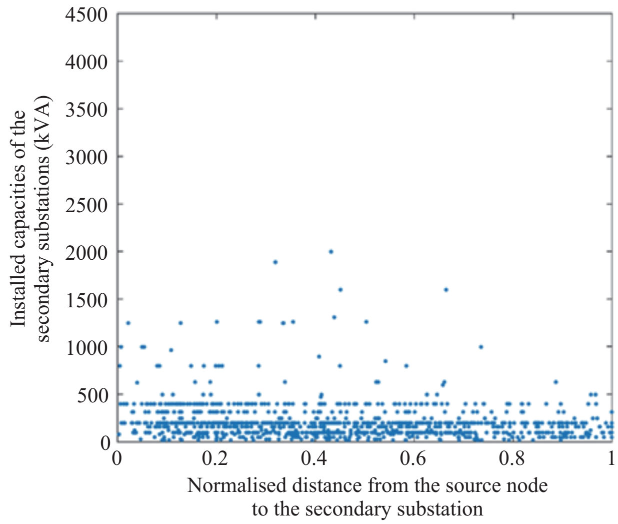
Variable y in (17) and (18) refers to the installed capacity of a secondary substation at a given level of the network. y_i refers to the capacity of a secondary substation i and n refers to the total number of secondary substations in that level. The Kernel distribution is defined by a kernel smoothing function $K(y)$ and a bandwidth value h that controls the smoothness of the resulting density curve. In this model, the "normal" Kernel smoothing function described in (18) was used. The bandwidth value h is considered to be the optimal for estimating densities for the normal distribution [29].

Basic statistics, such as mean and standard deviation of the probability distributions, can be used to describe the shape of the PDFs derived from the above Kernel density estimation. In probability and statistics, the mean value, $\overline{y}$ (i.e. is the same as the expected value of y, $E(y)$) is referred to as the central tendency of a random variable, y characterized by a probability distribution, $f_h(y)$ as shown in (19). Standard deviation, std is a measure that is used to quantify the amount of variation of a set of data values from the mean, as shown in (20). Here the operator $E(\cdot)$ denotes taking the expected value of a random variable.

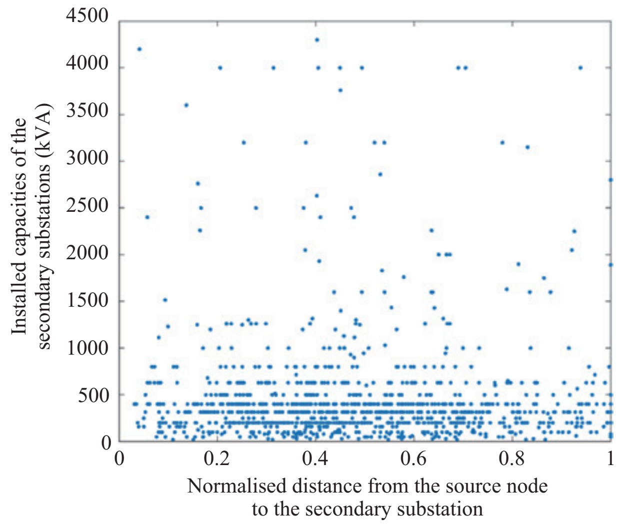
$$\overline{y} = E(y) = \int_{-\infty}^{\infty} y f_h(y) \tag{19}$$

$$std = \sqrt{E((y-\overline{y})^2)} \tag{20}$$

Figure 10 shows the resulting PDFs of the Kernel density estimation for secondary substation capacities of suburban and



(a)



(b)

Fig. 8. Distribution of the installed capacities of secondary substations with the normalized distances from the source nodes in, (a) Suburban networks (b) Urban networks.

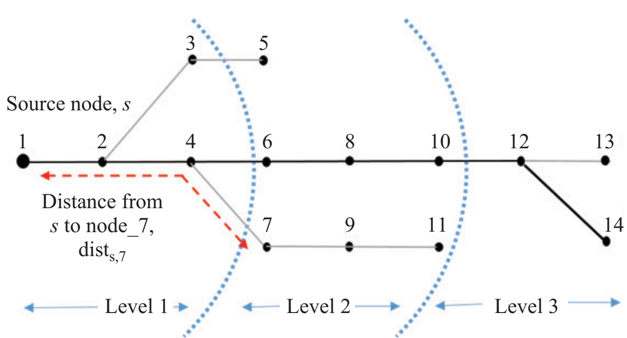


Fig. 9. Representation of levels of a network for the analysis of electrical properties.

urban type networks. Substation capacities are positive values. Therefore, only the positive values of the x-axis are shown in the figure. "Standard deviation" is shown only on one side of the "mean" due to the same reason.

From Fig. 10 it can be observed that the mean values of the PDFs of suburban networks are gradually decreasing when moving down from level 1 to level 3. This means, that in suburban networks, the higher capacity secondary substations are installed closer to the primary substation and the capacities of the secondary substations, which are further away from the PS and tend to have smaller values. Also, in suburban networks, the standard deviation of the PDFs has the highest deviation from the mean at the first two levels of the network. This explains that in the first two levels of the suburban networks, the secondary substation capacities vary within a large range of values from high capacities to low capacities. However, the standard deviation of the PDFs at the far ends of the networks is much smaller, showing that the installed capacities of SSs at the far ends of the networks vary between a small range of values.

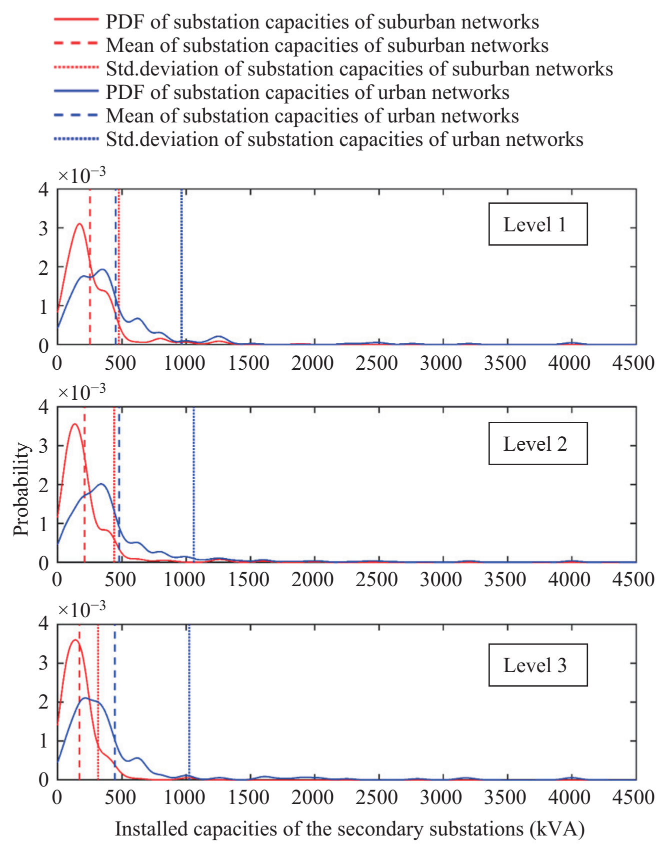


Fig. 10. Level dependent distribution of the installed capacities of secondary substations in suburban networks.

In the urban networks, the mean and standard deviations when going down from level 1 to level 3, do not change significantly. According to the results in Fig. 10, the mean installed capacity and standard deviation of the secondary substations at all 3 levels of an urban network is around 500 kVA. These observations of the changes in mean and standard deviation explains that, in general, the capacities of secondary substations in the urban networks are distributed almost evenly throughout all the depth levels of the networks.

It is evident that standard deviations and means of the PDFs in urban networks are much higher than that of the suburban networks for all the depth levels in the networks. Therefore, the results show a clear difference of the SS capacity distribution among suburban and urban networks.

IX. Conclusions and Future Work

Investigating electrical properties of real-world electricity distribution networks has great benefits of providing random-realistic test network models for various simulation studies. In this present study, an in-depth investigation of the electrical properties on real-world MV electrical power networks is presented. A list of electrical properties of distribution networks are defined and formulated.

A set of available data from real-world networks regarding the installed capacities of distribution substations and the conductor cross sections of the distribution lines were used for the study. The selected set of networks were grouped into two categories as suburban and urban networks according to the population densities of the actual areas where they are located. Later this grouping of the networks was validated through a clustering approach which used the electrical properties of the two network types. A novel approach to obtain depth dependent electrical properties was developed. Kernel density PDFs for the secondary substation capacities with the distance from the source nodes of the two types of networks were investigated.

The main outcomes of the study are as follows:

1) Substation capacities and the conductor cross sections are able to characterize the electrical features of suburban and urban networks;

2) Results from the clustering approach showed the importance of feature selection when characterizing different types of distribution networks;

3) The depth dependent approach was able to better capture the differences of the distribution of secondary substation capacities along the feeder lengths of the two types of networks.

Though, the networks analyzed in this paper might not reflect the characteristics of urban and suburban networks in some other areas in China, the idea is that the proposed methodology is replicable to apply to various sets of real-world networks if there is a need to characterize the networks based on their electrical properties.

Similar investigations will be conducted in the future for MV rural networks and for LV networks of different types (urban, suburban, and rural). These results together with topological characteristics identified in [13] will be used to build a network generation tool which can produce statistically similar, random-realistic networks at MV level.

References

[1] C. H. Tie and C. K. Gan, “Impact of grid-connected residential PV systems on the Malaysia low voltage distribution network,” in *Proceedings of 2013 IEEE 7th International Power Engineering and Optimization Conference (PEOCO)*, 2013, pp. 670–675.

[2] S. Abeysinghe, S. Nistor, J. Wu, and M. Sooriyabandara, “Impact of electrolysis on the connection of distributed generation,” *Energy Procedia*, vol. 75, pp. 1159–1164, Aug. 2015.

[3] F. J. Ruiz-Rodriguez, J. C. Hern?ndez, and F. Jurado, “Probabilistic load flow for radial distribution networks with photovoltaic generators,” *IET Renewable Power Generation*, vol. 6, no. 2, pp. 110–121, Mar. 2012.

[4] K. Clement-Nyns, E. Haesen, and J. Driesen, “The impact of charging plug-in hybrid electric vehicles on a residential distribution grid,” *IEEE Transactions on Power Systems*, vol. 25, no. 1, pp. 371–380, Feb. 2010.

[5] P. Mancarella, C. K. Gan, and G. Strbac, “Evaluation of the impact of electric heat pumps and distributed CHP on LV networks,” in *Proceedings of 2011 IEEE Trondheim PowerTech*, 2011, pp. 1–7.

[6] C. K. Gan, D. Pudjianto, P. Djapic, and G. Strbac, “Strategic assessment of alternative design options for multivoltage-level distribution networks,” *IEEE Transactions on Power Systems*, vol. 29, no. 3, pp. 1261–1269, May 2014.

[7] J. D. Watson, N. R. Watson, D. Santos-Martin, A. R. Wood, S. Lemon, and A. J. V. Miller, “Impact of solar photovoltaics on the low-voltage distribution network in New Zealand,” *IET Generation, Transmission & Distribution*, vol. 10, no. 1, pp. 1–9, Jan. 2016.

[8] N. R. Watson, J. D. Watson, R. M. Watson, K. Sharma, and A. Miller, “Impact of electric vehicle chargers on a low voltage distribution system,” in *Proceedings of EEA Conference & Exhibition*, Wellington, 2015, pp. 1–28.

[9] Z. F. Wang, A. Scaglione, and R. J. Thomas, “Generating statistically correct random topologies for testing smart grid communication and control networks,” *IEEE transactions on Smart Grid*, vol. 1, no. 1, pp. 28–39, Jun. 2010.

[10] G. A. Pagani and M. Aiello,”The power grid as a complex network: a survey,” *Physica A: Statistical Mechanics and its Applications*, vol. 392, no. 11, pp. 2688–2700, Jun. 2013.

[11] F. Barakou, D. Koukoula, N. Hatziargyriou, and A. Dimeas, “Fractal geometry for distribution grid topologies,” in *Proceedings of 2015 IEEE Eindhoven PowerTech*, 2015.

[12] J. L. Hu, L. Sankar, and D. J. Mir, “Cluster-and-connect: an algorithmic approach to generating synthetic electric power network graphs,” in *Proceedings of 2015 53rd Annual Allerton Conference on Communication, Control, and Computing (Allerton)*, 2015.

[13] S. Abeysinghe, J. Wu, M. Sooriyabandara, M. Abeysekera, T. Xu, and C. Wang, “Topological properties of medium voltage electricity distribution networks,” *Applied Energy*, vol. 210, pp. 1101–1112, Jan. 2018.

[14] G. A. Pagani and M. Aiello, “Towards decentralization: a topological investigation of the medium and low voltage grids,” *IEEE Transactions on Smart Grid*, vol. 2, no. 3, pp. 538–547, Sep. 2011.

[15] P. Hines, S. Blumsack, E. Cotilla Sanchez, and C. Barrows, “The topological and electrical structure of power grids,” in *Proceedings of the 43rd Hawaii International Conference on System Sciences*, 2010, pp. 1–10.

[16] J. Grainger and W. D. Stevenson Jr, *Power System Analysis*, New York: McGraw-Hill, 1994.

[17] M. Ponnavaikko and K. S. P. Rao, “Optimal distribution system planning,” *IEEE Power Engineering Review*, vol. PER-1, no. 6, pp. 60, Jun. 1981.

[18] H. N. Tram and D. L. Wall, “Optimal conductor selection in planning radial distribution systems,” *IEEE Transactions on Power Systems*, vol. 3, no. 1, pp. 200–206, Feb. 1988.

[19] Table 6-demographic yearbook 2013, 2013.

[20] [20] []B. Awerbuch and R. Gallager, “A new distributed algorithm to find breadth first search trees,” *IEEE Transactions on Information Theory*, vol. 33, no. 3, pp. 315–322, May 1987.

[21] J. C. Chen, “Dijkstra’s shortest path algorithm,” *Journal of Formalized Mathematics*, vol. 15, pp. 144–157, Mar. 2003

[22] *The Guide for Planning and Design of Distribution Network*, DL/T 5729–2016, 2016.

[23] M. Ponnavaikko and K. S. P. Rao, “An approach to optimal distribution system planning through conductor gradation,” *IEEE Transactions on Power Apparatus and Systems*, vol. PAS-101, no. 6, pp. 1735–1742, Jun. 1982.

[24] E. Lakervi and E. J. Holmes, *Electricity Distribution Network Design*, 2nd ed., London: IET, 1995.

[25] M. A. Kashem, V. Ganapathy, and G. B. Jasmon, “Network reconfiguration for load balancing in distribution networks,” *IEE Proceedings-Generation, Transmission and Distribution*, vol. 146, no. 6, pp. 563–567, Nov. 1999.

[26] Zhejiang Chint Electric Cables Co. Ltd, Wire and Cable series. http://en.chintelectric.com/wwwroot/images/upload/private/12/1%20Products

[27] A. Z. Zambom and R. Dias. (2012, Dec.). A review of kernel density estimation with applications to econometrics. [Online]. Available: https://arxiv. org/abs/1212.2812

[28] MathWorks. Statistics and machine learning toolbox, Documentation 2018.

[29] B. A. Turlach, “Bandwidth selection in kernel density estimation: a review,” in *In CORE and Institut de Statistique*. 19933.

Sathsara Abeysinghe (M'18) received the B.Sc. degree in Electrical and Electronics Engineering from the University of Peradeniya, Sri Lanka in 2014, and the Ph.D. degree in Electrical Engineering from Cardiff University, U.K. in 2018. Since 2018 she is working as a post-doctoral research associate at the Centre for Integrated Renewable Energy Generation and Supply at Cardiff University. She was a visiting scholar at Tianjin University in China and conducted statistical analysis on a large amount of electricity distribution network data. She also spent a secondment at Toshiba TRL in Bristol, and during that time she employed machine learning techniques in her research. Her current research activities focus on statistical assessment of energy distribution networks, analyzing the grid impact of low carbon technologies and the flexibility provision from decentralized resources.

Muditha Abeysekera (M'18) is a Lecturer at Cardiff University, UK. He received the B.Sc. degree in Mechanical Engineering from University of Peradeniya, Sri Lanka (2010), the M.Sc. degree in Sustainable Energy Engineering from Royal Institute of Technology, Sweden (KTH- Kungliga Tekniska Högskolan-2012) and Universitat Politecnica de Catalunya (UPC) – Barcelona, Spain, and his Ph.D. degree in Electrical Engineering from Cardiff University, U.K. (2017). From 2017-2019 he was a post-doctoral research associate at the Centre for Integrated Renewable Energy Generation and Supply at Cardiff University. His research interests are on the design and optimization of multi-energy system infrastructure, the study of the whole system impact of local energy systems and the decarbonization of the heat sector in the UK.

Jianzhong Wu (M'04) is a Professor of Multi-Vector Energy Systems and Head of School of Engineering, Cardiff University, U.K. He received his B.Sc. (1999), M.Sc. (2002) and Ph.D. (2004) degrees in Electrical Engineering from Tianjin University,

He joined Cardiff University in June 2008 (Lecturer 2008; Senior Lecturer 2013; Reader 2014; Professor 2015). From 2006 to 2008, he was a Research Fellow in the University of Manchester. Professor Wu researches on Smart Grid and energy infrastructure (modeling, analysis and optimization of integrated smart energy supply networks). He has contributed to more than 50 EU, EPSRC and industry funded projects as a Principal Investigator or a Co-investigator.

Mahesh Sooriyabandara (SM'07) is currently the Managing Director of Toshiba - Bristol Research and Innovation Laboratory, U.K., and also an Honorary Visiting Professor with the School of Engineering, Cardiff University, U.K.

He received his B.Sc. degree in Electronic and Electrical Engineering from the University of Peradeniya, Sri Lanka, and his Ph.D. degree in Engineering from the University of Aberdeen, U.K. In 2012, he received the Toshiba Research Europe's Distinguished Researcher Award and Toshiba Corporate R&D Prize for his contribution to smart grid communications. In 2013, he received Toshiba Corporation's Corporate Technology Prize in recognition of research that led to one of the largest smart meter wireless mesh networks in the world. He has more than 90 peer-reviewed publications, several book chapters, and holds more than 20 patent applications. He is involved in standardization activities within IETF, IEEE, and ETSI, and is a Fellow of IET.