Automated Verification of LV Network Topologies

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***Abstract*—The increasing penetration of low carbon technologies and electric vehicles is expected to place a considerable burden to Low Voltage (LV) power distribution networks. The previously passive management of LV networks will no longer be sustainable to cope with this growth. A more proactive approach is required to manage LV networks, usually achieved by using Power System State Estimation (PSSE) tools. The effective use of PSSE tools however, requires accurate reporting of each LV network's topology and configuration of assets (cables) that compose it. This paper presents a method for ongoing accuracy improvement of the LV networks topologies, by automating the process of approximating missing cable information and validating the network architectures. The method proposed was derived based on the assumptions that a specific network infrastructure was selected to meet a certain distributed customer loading requirement. The results obtained agrees with the assumptions, providing also a mechanism that scores the confidence level for the choices made to approximate any missing asset information.**

I. Introduction

Electricity is something the modern world often takes for granted. However, satisfying an ever-increasing need for reliable power needs to be balanced with environmental concerns, especially in terms of carbon emissions. This has resulted in a number of initiatives ensure a low-carbon power systems, such as embedded renewable generation (e.g. photo-voltaic (PV) panels, micro-wind) or electric-powered vehicles (EVs). Yet, a key downside of these new technologies is the burden they place on existing power network infrastructure [1], [2], especially if the management of this infrastructure does not progress in tandem with the changes. More specifically, we highlight a need to transform the previously industry-accepted passive management of the Low-Voltage (LV) networks to a more proactive approach, in order to better handle emerging phenomena such as the rise in the number of low carbon technologies (LCT) installed in domestic properties [3], [4] and the uptake of EVs [5].

A. PSSE for LV network and their difficulties

To ensure that LV networks operate effectively despite the increased burden [1], [2], a Power System State Estimation (PSSE) tool that monitors and adapts the LV network is required. For example, to ensure that any increase in uptake of EVs will not cause an increase in under-voltage violations downstream of the network; or the increase in LCT will not cause the increase in over-voltage violation instead.

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There is an abundance of PSSE tools developed and described in literature, and PSSE is a state-of-the-art and industry accepted tool, widely used to ensure the effective operations of the electricity networks for 33kV networks and above. However, this may not be the case for LV networks, for 11kV networks and less, with a number of literatures indicating the reasons why PSSE used in the transmission networks will not be effective for the LV networks [6], [7], [8].

The difficulties of PSSE for LV networks are not only because of the nature of the networks themselves (dynamic radial networks with asymmetry between the phase loading) but also, historically, the need to closely observe LV network operations was largely unnecessary. This is because most technical issues were planned *a priori* as part of the infrastructure design and planning phase, by providing a suitable 'minimum design' fit-for-purpose level of network capability based on customer demand. This would also include limited connectivity reconfiguration for security of supply in case of faults and maintenance of equipment. As a result, active observability of LV networks is historically low [6], [8].

If any network reconfiguration, including new connections, reinforcement or diversions is required, because of local area change of use, it was managed through good local operational awareness [6]. Due to expected increase in volume of existing customer energy use, driven by the LCT and EVs requirements, there is now a need to increase this network observability. This will be achieved through the roll-out of smart meters and increased levels of LV network monitoring. This availability of energy data will drive the use of PSSE for more automated awareness of the LV network.

The complexity of the PSSE is also higher for LV networks. There are large variabilities of LV cables types, which can impact on the PSSE analysis. The impedance ratio (R/X) for the transmission cables are typically low with $R/X < 1$, and this can be ignored by the PSSE. However, the impedance ratio R/X for LV networks are higher with $R/X >> 1$ or $R = X$ in some cases, and this can no longer be neglected in the analysis [7]. Incorrect ratings of the cables may also lead to incorrect constraint handling of the network, which in turn can increase the risk of network failures [9].

B. Combined information for PSSE

To model the network operation, a good understanding of the LV network asset and connectivity configuration is required. Primadianto & Lu [10] show that to ensure accuracy in PSSE, data from several sources available for LV network management is needed. The data includes the consumers' consumption data, as well as the voltage and power flow, and also the network infrastructure obtained from Assets and Facility Management (AFM) systems, Geographic Information System (GIS) and Outage Management Systems (OMS). The asset and connectivity information consists of the types and lengths of cables used and how they are connected in the network. The asset information provides the impedance map of the network, and in turn the impedance ratio. This then gives an indication of how balanced the network is and how the energy (voltage, specifically) is distributed to the customers, specifically those farthest away from the substation.

Gathering asset information can also be a challenging and expensive task. One factor is the volume and significant age of most LV networks; with a high rate of change in assets replacement, maintenance and repair cycles. The accuracy of the asset information therefore relies on the operators for gathering the most recent information. Historical missing asset information and on site operators failing to follow rigorous data management processes for asset update or connectivity management are some of the most common issues identified.

This paper proposes a method to overcome this. It is part of a continual improvement program of the asset data management and is part of a bigger goal of providing analytical checks that can react to ongoing data management process failure and adapt to historical issues which are harder to fix with real data. In particular, we evaluate the use of a tree graph that translates GIS and AFM information, and which is suitable for the implementation of a tree-based search methodology to verify any missing asset information. The paper is divided into 5 sections; Section II evaluates existing methods of LV network analysis and verification. Section III describes how the LV network is modeled as a tree and how the trees generated are used to approximate the unknown cables (assets) information. Section IV discusses the results. Section V concludes.

II. LV NETWORK ANALYSIS

Despite the need for network topologies for LV network PSSE, a lot of the literature raises the common issue of a lack of available network information. This has prompted studies on how topologies can be approximated using smart meter data [7], [11], [12], [13]. There have also been attempts to perform LV network PSSE with inaccurate network information [14]. Reviews on previous work on PSSE for LV networks can be found in [15] and [10].

The uptake of these lab-based PSSE tools by Distribution Network Operators or DNOs, at present, is limited. This can be due to the large differences between the models of the networks used in the analysis and their actual LV network topologies, which may decrease the confidence level of the DNOs in implementing these lab-based solutions to monitor their own network operations. The first step, therefore, is to verify what they already know. The aim of this work is to verify the LV network topologies stored in the database, typically in the GIS. Most studies have concentrated on the PSSE algorithms. However, little was done to verify the LV network topologies using the available assets information, specifically to fill in the missing assets information.

III. METHODOLOGY

A good representation of the LV network is required before any analysis can be performed in approximating the missing unknown assets (cables) information.

A. LV network as a tree graph

The LV network is represented as a tree, with V nodes or *vertices*, and E links or *edges*. A node $v_i \in V$ indicates either the connection point that links one cable to another or the connection point that links a cable to an endpoint. An endpoint can either be a consumer of electricity on the LV network or an open point connection. A link $e_{i,j} \in E$ represents the cable segment between two connection points, nodes v_i and v_j. Each link $e_{i,j}$ is associated with $z_{i,j}$ that indicates the electrical impedance of the cable segment, its construction type and its cable length. Figure 1b illustrates the tree representation of the LV network shown in Figure 1a.

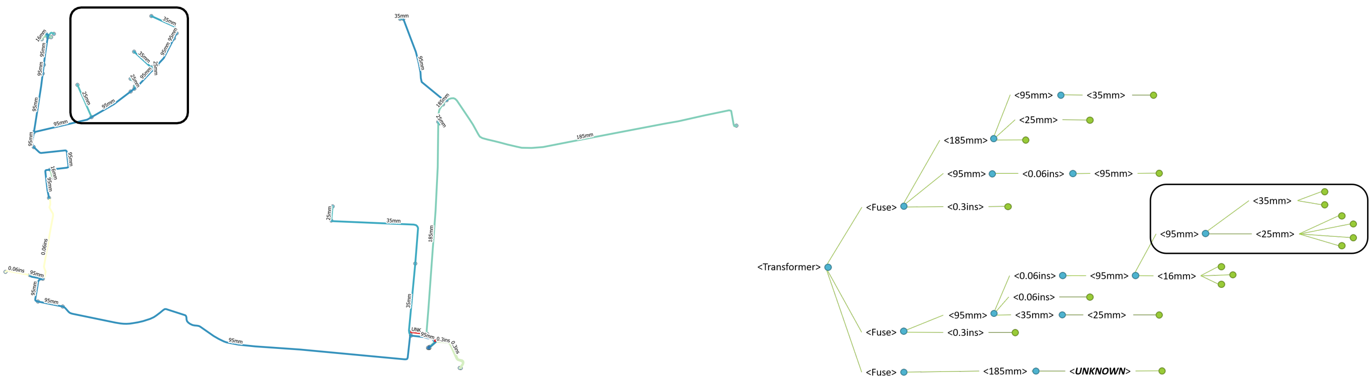
The LV network tree is a simplified representation of an LV network. Like the actual LV network, the tree shows how the mains cables are connected to one another. However, the connections to the services cables (cables at the end of the network) will differ between the tree and the actual network. The service cables that are of the same type, despite their actual connection locations and lengths, are classified as a single link, and they are attached at the end of the mains cable which they are all connected to. An example of this can be seen in the boxed areas in Figure 1. The four 25mm cables and the two 35mm cables are connected to a long 95mm mains cable, all at different connection points in the boxed area in Figure 1a, and are classified as one link for the tree in Figure 1b. These two cables are connected at the end of the 95mm cable in Figure 1b, with the filled blue circle indicating the common connection point and the green filled circles indicating the endpoints that they are connected to.

As shown in Figure 1, a substation can provide electricity to multiple circuits. If one traces the tree from the root node of a circuit (identified in Figure 1b as <Fuse>) to an endpoint (a filled green circle), the list of cables that creates the connection between the source (a closed fuse in a substation) to the endpoint is called an assets path.

B. Approximating the unknown cable asset

Two assumptions are made that guide the methodology to approximate missing cable information. First, if the unknown portion of a circuit (identified as *<UNKNOWN>* in Figure 1b) shares the same connection point with another cable, the unknown cable can be approximated with the other cable if it is of similar length and loading. This assumption hypothesizes that *a specific cable that is of specific length is selected for a specific type of distributed customer loading*.

If the unknown cable does not share its connection point with another cable (similar to the unknown cable shown in



(a) The LV network.

(b) Its equivalent network tree $G(V, E)$.

Fig. 1: The representation of an LV network as a network tree.

Figure 1b), or the available cable options have large dissimilarities in their lengths and loadings, the assets path with the unknown cable is then compared against other assets paths that have similar cable make-ups (except for the unknown segment) and that are also of similar combinations of lengths and loadings. This is based on the assumption that *a specific combination of cables and their lengths (assets path) is often selected for a specific type of distributed customer loading*.

To simplify the search, the assets path with the unknown is shortened so that the unknown cable is the last cable in the assets path. Assets paths that are selected for comparison will also be shortened so that they will have the same number of cables with the assets path that has the unknown cable. A score S_{a_m} is proposed to measure the similarity between the two assets paths.

C. Scoring the selected cable

Equation (1) is used to score the similarities between two assets paths, one with the unknown cable information and the other selected to approximate the missing cable information.

$$S_{a_m} = \left(\frac{\sum_{n=1}^{U_n-1} \frac{min(D_{a_n}, D_{u_n})}{max(D_{a_n}, D_{u_n})} + \frac{min(E_{a_{a_m}}, E_{u_u})}{max(E_{a_{a_m}}, E_{u_u})}}{U_n} \right) \times \left(\frac{\sum_{n=1}^{U_n-1} \frac{min(C_{a_n}, C_{u_n})}{max(C_{a_n}, C_{u_n})} + \frac{min(L_{a_{a_m}}, L_{u_u})}{max(L_{a_{a_m}}, L_{u_u})}}{U_n} \right) \quad (1)$$

U_n is defined as the number of cable types in the assets path P_u that has the unknown cable information u. P_{a_m} is the asset path that was selected to compare its cable type a_m (in P_{a_m}) with that of the unknown cable type u in P_u. As indicated in the previous section, all but the unknown cable type u in P_u and cable type a_m in P_{a_m} are the same. D_{a_n} is the maximum length for the (mains) cable n in P_{a_m}. D_{u_n} is the maximum length for the (mains) cable n in P_u.

If the unknown cable is located at the end of the circuit, $E_{a_{a_m}}$ is the median length for the similar (service) cable type a_m in P_{a_m} that is connected to a load. E_{u_u} is the median length for the grouping of the unknown cable type u, connected at the end of the assets path P_u.

If the unknown cable is located in the middle of the circuit, $E_{a_{a_m}}$, instead, is the median length for where the start of the (mains) cable a_m connects to other cables at the customer end. E_{u_u} is similar to $E_{a_{a_m}}$, but for the unknown cable u in P_u.

C_{a_n} is the number of cables connected to the (mains) cable n, towards the consumer end and in the assets path P_{a_m}. C_{u_n} is similar to C_{a_n}, but for the cable n in P_u. If the unknown cable is located at the end of the circuit, $L_{a_{a_m}}$ is the number of loads connected to cable type a_m in P_{a_m} and L_{u_u} is similar to $L_{a_{a_m}}$, but for the unknown cable type u in P_u. If the unknown cable is located in the middle of the circuit, $L_{a_{a_m}}$ and L_{u_u} instead are the number of cables connected to cable type a_m in P_{a_m} and u in P_u.

If the two cable types n share the same connection point (the filled blue circle in Figure 1b):

$$\sum_{n=1}^{U_n-1} \frac{min(D_{a_n}, D_{u_n})}{max(D_{a_n}, D_{u_n})} = 1 \quad (2)$$

$$\sum_{n=1}^{U_n-1} \frac{min(C_{a_n}, C_{u_n})}{max(C_{a_n}, C_{u_n})} = 1 \quad (3)$$

If there are multiple choices available to approximate the missing cable information, the score S_{a_m} will guide the selection, with $m \in M$, and M is the number of assets path(s) P_{a_m} selected for comparison. The unknown cable u in assets path P_u is approximated with cable a_x in P_{a_x} because P_{a_x} has the highest score S_{a_x} (4).

$$S_{a_x} = max(\{S_{a_1}, S_{a_2}, ..., S_{a_M}\}) \quad (4)$$

The cable type a_x (in P_{a_x}) is selected with the assumption that the assets path with the unknown (P_u) is most similar to the assets path P_{a_x}, which the selected cable type a_x is a part of. The closer the score S_{a_x} to 1, the higher the similarities between the two assets paths P_{a_x} and P_u, and cable type a_x can best approximate the unknown cable type u. This agrees with the two assumptions outlined above.

D. Hierarchical search and matching multiple assets paths

The search space available to perform this comparison analysis can be huge. One can search among all LV networks in one particular country or the search space can be as small as a single settlement. As a proof of concept, our initial analysis was limited to a specific postcode area, which constitutes a suburban and rural area. This initial area of interest is relatively small. However, the objective is then to evaluate the proposed methodology to approximate the missing assets information in a county-sized search area.

The search space will increase more than ten-fold. Therefore, to cope with the large search space, the search to approximate the missing cables information is performed in a hierarchical manner, beginning with (i) the local search, (ii) the clustered search and finally, if needs be, (iii) global search.

1) Scoring the multiple matches: The initial search will compare and select the cable type that best approximates the unknown cable from those that share the same connection point (filled blue circle in Figure 1b). However, there may be a better option in another assets path in that same circuit or in another circuit.

If the two search mechanisms approximate the same cable type a_m, the score for that cable will increase based on the number of matches that it found (5).

$$S_{a_m} = S_{a_{m_1}} \times \prod_{r=2}^{R} (1 + S_{a_{m_r}}) \tag{5}$$

R is the number of matches for cable type a_m, and at each match occurrence r, a score of $S_{a_{m_r}}$ is calculated. The cable type a_x selected to approximate the unknown cable type u will be evaluated after each search level based on the scores calculated using (5) and are compared using (4).

The brings us to our third assumption which indicates that *the more often a particular combination of cables (assets path) are found, the higher is the likelihood that the combination of cables is effective for a particular distributed customer loading requirement*.

2) Local search: The local search is performed first to approximate the unknown cable u in the circuit. Local search compares the assets path with the unknown cable P_u with all other assets paths in its own circuit and in the circuits that shares the same transformer as P_u. This is based on our fourth assumption which states that *the circuits that share the same source are of balanced distributed customer loading, and therefore will have the common combination of cables used at specific lengths (assets paths)*, which the unknown cable u can be approximated from. For the network in Figure 1, the circuit with the unknown cable information can be compared against itself and two other circuits that share its transformer.

3) Clustered search: Local search is beneficial for circuits that share their transformer with others, as it has its 'nearest neighbours' to compare against. However, a large proportion of the circuits do not fall within this category.

If the local search is unable to find a suitable approximation, the search space is to be widened to include more circuits geographically closer to the circuit with the unknown, for example in the same postcode area or in the same county. The danger of this is that, with the increase in the search space, there will be an increase in the computation time. The search space is therefore best curtailed, so that only those circuits in the selected area of interest that are of similar characteristics are selected for comparison.

The second hierarchy for search is to cluster the circuits from the selected area of interest based on their lengths and their distributed customer loadings, and to perform the assets paths comparison only if the circuits fall into the same category. In our analysis, the k-medoid algorithm is used to cluster the circuits.

4) Global search: If there is no cable type found to approximate the unknown cable u using both local and clustered information, the comparison is then performed on all other circuits not included in the first two options. We refer to this as global search. Because of our initial small area of interest, global search is required. As we increase the geographical area of interest, for example, from one postcode area to an entire county, global search may not be necessary.

IV. RESULTS

Table I shows the results of approximating the missing cables (assets) information using the method presented in the previous section. The table is split into two parts: (i) the unknown cable type u located at the end of the circuits (these cables are often the missing service cables information) and (ii) the unknown cable u located in the middle of the circuit (the missing mains cables information). In these two parts, they are further split into two (as illustrated in Figure 2):

1) full assets path, where the comparison requires all the cables in the two assets paths P_u and P_{a_x} to match except for the one unknown cable type u in P_u and the cable type a_x in P_{a_x} selected to approximate u. Therefore, a strict match is required before a score can be calculated.
2) partial assets path, which uses only the cable previously connected to the unknown cable u (at the source end) and another cable prior to that cable. With this, a less strict match is required before the score is calculated.

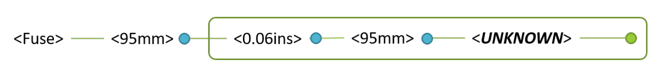


Fig. 2: Full assets path vs. partial assets path (boxed area).

The reason for these two options can be seen in the table, with low percentage of the missing cables approximated using the full assets path, and a much higher percentage approximated when the partial assets path was used. One reason for this is that the strict match of all but the unknown cable u is needed when using the full assets path.

The number of times a specific assets path was selected during both local and clustered searches is also higher when the partial assets paths were used. This is indicated by the higher number of asset scores $S_{a_x} > 1$ when utilising the

TABLE I: Percentage of unknown assets approximated

	The unknown cable at the end of the circuit		The unknown cable in the middle of the circuit	
	Full assets path	Partial assets path	Full assets path	Partial assets path
Local search	4.97%	9.37%	22.29%	29.78%
Clustered search	5.16%	20.57%	14.47%	29.37%
Global search	6.20%	33.22%	7.90%	22.63%
Percentage of dissimilar approximated assets	1.77%		4.19%	

partial assets paths (Figure 4), in comparison to those using the full assets paths (Figure 3). However, based on the figures, the majority of the assets paths are only seen once during the search because the peaks of the distributions are $S_{a_x} < 1$.

If discounting all the asset scores $S_{a_x} > 1$, despite the low numbers of unknown cables approximated using the full assets path, Figure 3 shows that the scores S_{a_x} for the cables selected are higher in comparison to those selected using the partial assets path. This is because of the strict match requirements of the full assets path. The distribution of scores when using the full assets path and local search have their peaks closer to 1, in comparison to the results of the clustered search and/or when partial asset path was used. The results is in agreement with our assumptions:

1) *a specific cable that is of specific length is selected for a specific type of distributed customer loading*.
2) *a specific combinations of cables and their lengths (assets path) is often selected for a specific type of distributed customer loading*.

As the search space is widened from local search to clustered search, The attributes of the assets paths in the clustered circuits, specifically their lengths may too differ in accordance to their circuits requirements. The differences in lengths will reduce their scores, as shown in Figure 3. These distributions of scores validate our following assumption, which states *the circuits that do share the same transformer are of balanced distributed customer loading, and therefore will have the common combinations of cables used at specific lengths (assets paths)*.

The score can therefore measure the confidence in the selected cable a_x to approximate the missing cable information u; as the higher the score S_{a_x}, the higher the likelihood of similarities between the two assets paths P_u and P_{a_x}, and the higher the confidence that the cable with the missing information u in P_u is that of the selected cable a_x in P_{a_x}.

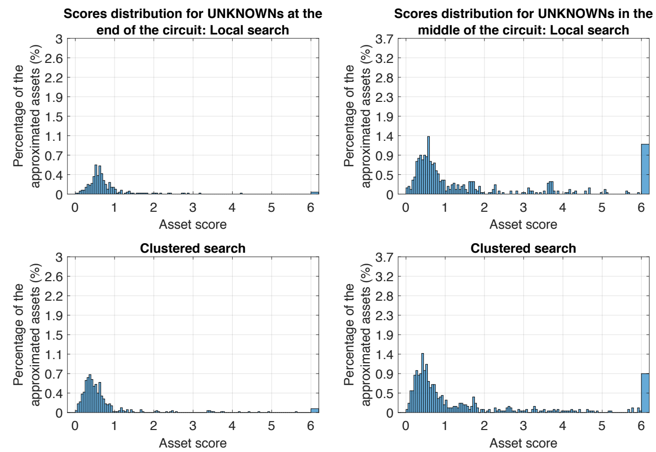


Fig. 3: The scores distributions when using the full assets path.

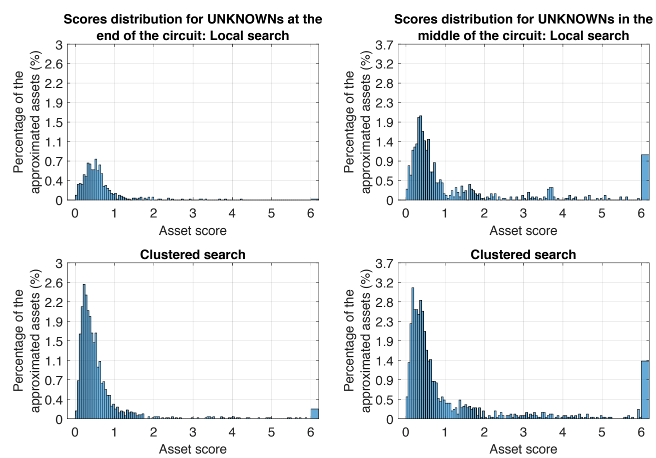


Fig. 4: The scores distributions using the partial assets path.

A. Hierarchical search criteria

Table I indicates that dissimilarities of the selected approximated cables can occur. This is because if one was to use the partial assets path, the number of occurrence R in (5) that a specific partial assets path was selected can be higher in comparison to when the full assets path was used. As a result, the score S_{a_x} will be higher when using the partial asset path because of the higher frequency of match R; this is despite the possibility that the other cables in the assets path are not matching. This is the drawback of using the partial assets path.

Figure 5 shows the distributions of the scores differences between the two dissimilar cable types selected using the full assets path and the partial assets path. Although difficult to see from the figure, those selected have distributions that are positively skewed (local information and for the unknowns located at the end of the circuits, skewness = 1.6383, and for those in the middle of the circuits, skewness = 0.3693; when using clustered information and the unknowns located at the end of the circuits, skewness = 2.7068, and the other, skewness = 2.3371). This indicates that the cables selected using the full assets path are of higher scores in comparison to those selected using the partial assets path. This is in agreement with the assumptions presented in Section III. It is therefore

TABLE II: The differences between the two-hierarchical approach and when using only the partial assets path

	The unknown cable at the end of the circuit	The unknown cable in the middle of the circuit
Percentage of unknown assets approximated using partial assets path only	63.16%	81.79%
Percentage of unknown assets approximated using the two-hierarchical approach	64.78%	82.20%
Percentage of dissimilar assets approximated	12.35%	12.69%

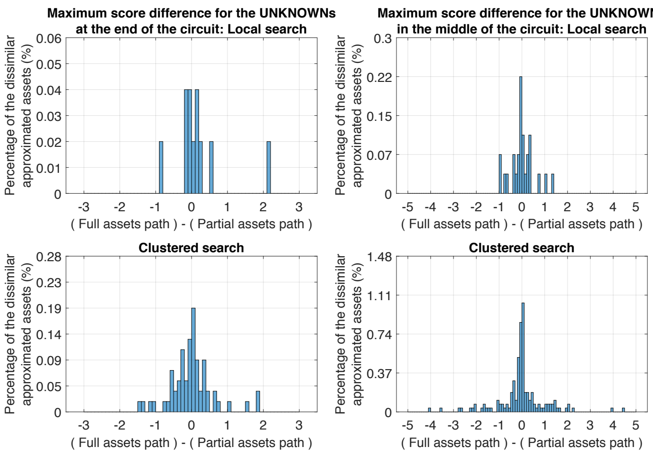


Fig. 5: The differences between the two scores' distributions.

better to approximate the unknown cables first using the full assets path. The remainder will then be approximated using the partial assets path (the two-hierarchical levels of analysis). Table II lists the summary of results when comparing the searches using only the partial assets path and that of the proposed two-hierarchical levels of analysis.

V. Conclusion

The way in which LV networks operate is beginning to change. The growth of sustainable LCT and the potential increase in EVs use is likely to increase the burden on the LV networks. The previous passive management of the LV networks will no longer be sustainable, requiring the need of PSSE for LV networks. In order for PSSE to operate effectively for LV network management, the accurate reporting of LV network topologies and infrastructure will also become necessary. The paper proposed a method to improve the accuracy of the reporting of LV network topologies, describing an approach that automates the process of approximating missing cable information and validating the network architecture.

The method proposed was derived based on the assumptions that a specific network infrastructure was selected to meet a certain distributed customer loading requirement. The results obtained are in agreement with the assumptions made, providing for a mechanism to also score the confidence level for the choices made to approximate the missing asset information.

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