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Handling Incomplete and Erroneous Grid Topology Information for Low Voltage Grid Observability Applications

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***Abstract*—Grid topology information plays an important role in grid observability applications such as fault detection and diagnosis. For these applications, data from customer connections should be processed jointly with measurements from the distribution grid by Distribution System Operator (DSO) systems and also correlated to the LV grid topology. In practical DSO systems, the LV grid topology data is frequently included in their databases and may come from different systems such as Geographical Information System (GIS) or other asset management systems, which store a relevant part of the grid topology in a type-specific format. However, in most cases, the grid topology information is not utilized for grid observability applications due to several challenges such as lack of standard data models, complexities in extracting topology information, incorrect/incomplete topology information, dependence on multiple databases etc. Thus, this paper presents challenges and complexities faced by electrical utilities in extracting/using grid topology information for observability applications. The challenges are demonstrated using topology models from two real medium-sized distribution grid operators, which are currently being used in two different European countries.**

***Keywords*—Low Voltage Grid Observability, Asset Management, Grid Topology Data, Smart Grid, GIS**

I. INTRODUCTION

The penetration of renewable energy sources into the power grids gives rise to several challenges, specifically regarding power quality. Conversely, photovoltaics (PV) and other grid-connected systems like storage provide opportunities including provision of new measurement points that to a large extent are already connected to Internet portals of the inverter vendors. In addition to being a source of grid-related measurements, the inverters can also provide actuation opportunities. Secondly, the massive deployment of Smart Meters (SM) provide opportunities for the Distribution System Operator (DSO) to obtain valuable information about the Low Voltage (LV) grid, which currently only target billing and advanced customer information services. Similarly, the information coming from an increasing number of grid-related data sources that are in principle accessible to the DSO is not yet utilized for grid operation and grid observability.

The information coming from SMs and other grid-related data sources has huge potential for increasing grid observability in terms of monitoring of voltage quality, calculation and processing of grid efficiency parameters, and detection and diagnosis of low-voltage grid faults. In order to achieve observability of LV grids, the data from the SMs, Inverters, and other measurement devices of the DSO needs to be correlated to the LV grid topology. However, fusing heterogeneous measurements data at DSO provides multiple challenges, such as [1]: (1) The interconnection of different systems with different criticality levels. (2) Measurements from devices with diverse identification schemes need to be related to a unique grid topology model. (3) Algorithmic challenges to deal with varying data quality as well as potentially inaccurate data. The varying data quality is due to the lack of standard data models that leads to complexities in extracting topology information. Moreover, due to the potential inaccuracies or incompleteness of topology information, algorithms should be designed such that they either depend on manually defined rules or extract information from multiple databases within a required amount of time. Therefore, both the algorithmic solutions as well as the connectivity and security from an ICT perspective need to be designed carefully.

1) Asset Management in Electricity Utilities: According to [2], in order to store information about grid components, electric utilities have a variety of software tools, where each tool has a particular business application. For instance:

- **Asset Management Systems**: These systems enable engineering record-keeping; the creation and tracking of maintenance schedules; supplier information, in some instances; and related project/work order information that records the history of the asset, from initial construction/assembly through retirement.

- **Geographic Information Systems (GIS)**: Principally, GIS (such as ArcMap [3]) is used to track the location of assets once they are installed and operational. GIS systems can also be used to track connectivity of electrical devices, i.e., to determine grid topology. Most DSOs use this as a software application and a technology enabler for asset information and various computations regarding assets.
- **Planning Systems**: Planning software solutions contain a mathematical model of the network, based on the asset configuration and the demand at each network "node". These planning systems use a model of the assets, which is generally built separately from the asset management or GIS systems at the utility.
- **System Control and Data Acquisition (SCADA)**: SCADA systems maintain sufficient asset information to enable dispatchers to operate the network. This information includes operational characteristics, connectivity to other devices, and telemetry information regarding the load on those devices. SCADA systems use real-time information telemetered from the electricity network within a second of actual occurrence in the field.
- **Distribution Management Systems (DMS)**: DMS adds a layer of modeling and computation onto the real-time depiction of the network to realize analysis and optimization. DMS depends more on the electrical parameters, while less on physical asset information.

These systems are usually independently implemented from each other and by different parts of an organization, therefore electric utilities struggle to manage these disparate systems to meet different business needs. For example, relevant engineers generally implement asset management and GIS systems while system operations organizations implement SCADA/DMS [2]. In general, the systems are developed by a variety of suppliers, thus they might be based on different programming languages, databases and human interface formats. Moreover, all these application software systems have been used for several years, consequently the individual systems are mature and even have a large user base. Electric utilities integrate some of these systems to create a stronger asset management framework, but virtually all of these interfaces are "project-ware" and not integrated products that are supported and upgraded by the respective software developers. Hence, several issues arise while working with such disparate systems, including redundant efforts, conflicting values, higher cost etc. Efforts are being made by the industry to develop "standard" data models, such as the Common Information Model (CIM) of EPRI/IEC (IEC 61970), and common integration standards for exchange of asset information, including the IEC 61968 and MultiSpeak® standards. Moreover, the development of standard integration architectures such as the Microsoft® Smart Energy Reference Architecture (SERA) have added to the tools for integrating asset systems [2].

Though these "standard" data models can be used for detailed description of grid assets, they currently have limited application in power system modeling mainly due to complexity. Secondly, the legacy software developed are mainly application-specific that consume data in proprietary formats, none of which uses, e.g. CIM [4]. Reference [4] investigated the use of CIM as one of the data ingestion sources developing an interoperable power grid data model to satisfy grid analytic requirements. Shukla et. al. [4] also present their work of abstraction and translation from CIM to a Bus-Branch model as a part of an overall system design and implementation for grid analytics and data interoperability. The challenge of making data accessible from different subsystems and then to enable data-intensive services on top of such heterogeneous data has been previously investigated in the context of electrical power grids in [5]–[8]. However, none of the aforementioned papers specifically addresses the challenges (and potential solutions) to deal with the incorrect/incomplete topology information in context of grid observability.

Consequently, this paper presents a list of challenges in terms of incorrectness/incompleteness in the topology information while making it usable for grid observability applications. The electrical power grid topology data used in this work is based on two real medium-sized distribution grid operators, which are currently being used in two different European countries. The remainder of this paper is organized as follows: Section II provides the architecture of the data fusion solution for grid observability and specifically describes the so-called grid topology subsystem and introduces the Grid Topology HeadEnd. Section III describes the two real-life topology models obtained from two different GIS systems that are currently being used by two different DSOs (one in Germany and other in Denmark). Subsequently, Section IV describes how grid topology HeadEnds process the topology information and lists the associated challenges in using the extracted topology information. Furthermore, handling the inaccuracies/inconsistencies in topology information with future directions are also described. Finally, Section V summarizes the paper and provides an outlook.

II. HETEROGENEOUS DATA PROCESSING FOR GRID OBSERVABILITY - ARCHITECTURE

This section introduces the overall architecture and the application context for the use of grid topology information. Figure 1 shows a classical middleware-based architecture [1] for data fusion that utilizes grid topology information in context of achieving grid observability. The main objective of data fusion solution is to use off-the-shelf computing hardware and existing communication technologies to leverage measurement functionality and, in a later stage, novel control coordination. As shown in Figure 1, the measurements from different subsystems (e.g. SMs and Inverter) are correlated with information from existing DSO subsystems, in order to enable and develop novel LV grid observability applications for voltage quality, grid operation efficiency, and LV grid out-age diagnosis. Subsequently, the achieved observability can be used by novel control coordination approaches, which may use the inverter actuation capabilities in conjunction with selected existing DSO actuation for voltage quality enhancement and loss minimization in the LV grid.

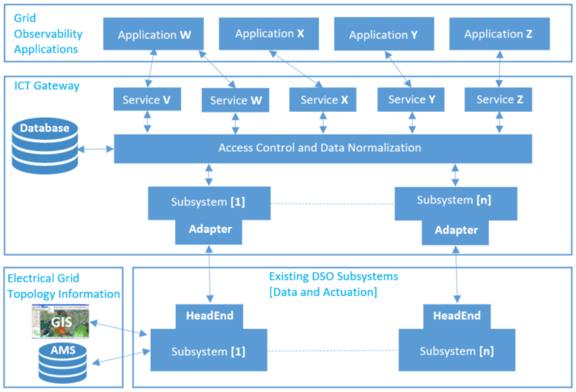

Fig. 1: System Architecture for data fusion, adapted from [1]

Information and Communication Technologies (ICT) Gateway is a middleware layer that provides a uniform application platform for domain-oriented applications by abstracting specific details about provider subsystem interface into a normalized/harmonized data model. This component is also responsible for taking care of issues related to reliability and security. On top of the ICT Gateway (ICG), grid observability applications are shown that use measurements and the grid topology information to calculate and visualize derived metrics such as grid losses, probability of faults, frequency of voltage variations, etc. These applications can be implemented independently of the used subsystems as they only interact with measurement and actuation subsystems via ICG. However, these applications may use an electrical model of the relevant parts of the distribution grid to, for instance, enable working with incomplete measurement scenarios, calculate missing measurands or detect/discard/replace erroneous measurements etc. (for details, see [1]).

In the architecture shown in Figure 1, recovery of missing data and/or validation of measured data rely on calculations using a grid model, which is an important aspect in data normalization. This requires the ICG to interact with a grid model that provides estimated values. This process is executed in parallel with other activities and as the ICG requires use of the grid model functionality. The process can be triggered by an application request for data or by the ICG itself as a part of a subscription based notification push to an application. For example, an application may have setup a subscription to specific information and before pushing information to this application, the ICG may perform a validation check or calculate missing information in similar fashion.

A representation of the grid topology is therefore required in order to enable processing of measurements and calculation of missing electrical variables from a grid model. This grid topology representation should be an annotated graph, in which edges represent cables or overhead lines, and nodes represent transformer, busbars in substation or junction boxes, sleeves or connected customers. Cables or overhead lines are annotated by relevant parameters, including in particular impedance. While, nodes may have multiple attributes including type and geo-location. Based on this information, the ICG then links measurement of voltages to nodes and measurement of currents to cables or overhead lines. The measurement data can also be used to validate the topology data.

In order to do obtain the annotated graph representation of the LV grid topology, ICG connects via topology Adapter to the Grid Topology HeadEnd (GT-HE). The design of GT-HE has been addressed in [9]. The GT-HE implements following functions:

- It initiates communication with the ICG over the corresponding adapter (i.e. the Topology Adapter) deployed on ICG by performing authentication and registration with the Adapter.
- Based on a pull/push manner provide updates of the current grid topology, i.e. list of nodes and connections in a specified topology, detailed information for a specified node or a connection.

In order to provide these data, the GT-HE needs to connect to relevant IT subsystems at the DSO. It is important to note that in some DSOs, the relevant information is distributed over different IT systems, e.g. cable and nodes are in the GIS system while information about connected customers such as Meter IDs and peak power are in the customer information database. Thus, as shown in Figure 1, GT-HE obtains the data from the relevant IT systems and extract the required annotated grid topology graph. In the following section, we present the scenario of two real medium-sized DSOs, one with around 50,000 customers that extracts its grid topology from GIS in a CIM-XML format, while the other with around 10,000 customers that extracts grid topology information from GIS in CSV format.

III. GRID TOPOLOGY INFORMATION - PRACTICAL EXAMPLES FROM MEDIUM SIZED DSOS

This section introduces the entities captured in grid topology subsystem that are extracted from two different GIS systems that reflect and describe the LV grid topologies. Moreover, the relation and function of power grid related entities but also the inconsistencies/inaccuracies in the representative grids are also described in this section.

A. *CIM-XML based Grid Topology Information*

The first example of grid topology data was from a regional Danish DSO with close to 50000 customers. The information is exported from the GIS system called $ArcMap$ [3] into a single CIM-XML based file with a size around 500 MB, which is subsequently read and processed by the GT-HE. This topology information is based on a multi-secondary substations model that includes 22 power grid related entities (such as Substation, Power Transformer, AC Line Segments, Fuse, Breaker etc.), where each entity instance is identified via an ID called mRID. This mRID is used by each grid entity to refer to any specific other entity. The grid entities together with the approximate number of times each entity appears in the complete CIM-XML topology file are listed below in Table I. (Note: The table lists entities in the same sequence as they appear in the topology data and numbers are rounded to only point out order of magnitudes.)

TABLE I: Power grid related entities in CIM-XML file, see [10] for further elaboration of the table.

No.	Power Grid Entities	Number of Occurrence (Approx.)
1	Asset	36000
2	CoordinateSystem	1
3	Location	160000
4	PositionPoint	1000000
5	UsagePoint	40000
6	BaseVoltage	6
7	ConnectivityNode	200000
8	PSRType	4
9	Substation	23000
10	Terminal	460000
11	VoltageLevel	25000
12	ACLineSegmentExt	100000
13	BayExt	90000
14	Breaker	40
15	BusbarSection	25000
16	Disconnector	80000
17	EnergyConsumer	40000
18	Fuse	6000
19	LoadBreakerSwitch	6000
20	PowerTransformer	2000
21	PowerTransformerEndExt	4000
22	RatioTapChanger	2000

In this topology data, a $Substation$ can refer to any of the three entities in the grid i.e. $PrimarySubstation$, $SecondarySubstation$ and $CableBox$. The entity called $PSRType$ determines the subtype to which a $Substation$ refers. The top-level entity in a LV grid is a Substation with $PSRType$ $SecondarySubstation$ that is an entry point from the medium voltage (MV) grid to the LV grid. This entity is connected to the MV grid on one side and to the LV grid on the other side. The $BusbarSection$ entity plays the same role as junction box i.e. it has one cable as an input, but can have multiple cables as output via $ConnectivityNode$. An entity of type $ACLineSegment$ (cable) is responsible for making connections between all other entities via $ConnectivityNodes$ and $Terminals$. $ConnectivityNode$ represents points where terminals of AC conducting equipment are connected with zero impedance.

In order to model the details of a household connection and associate it with a metering device that acts as a data source, two entities are introduced i.e. $EnergyConsumer$ and $UsagePoint$. Here, $EnergyConsumer$ is a point in the network e.g. an end of house connection cable, while $UsagePoint$ is a logical or physical point in the network to which readings or events may be attributed. It is used at the place where a physical or virtual meter may be located. The $EnergyConsumer$ entity is connected to the $BusbarSection$ via $ACLineSegment$. To establish a relation between an $ACLineSegment$ (cable) and other entities, in particular when the entity is a household, the GT-HE has to be carefully designed and implemented (see [9]). For detailed description of each entity in Table I, see [10].

B. CSV File-Export from GIS based Grid Topology Information

The second example of grid topology data was from a regional German DSO with close to 10000 customers. The information is exported from the GIS system into six CSV files which are subsequently read and processed by the GT-HE. Table II lists the entities in the underlying GIS system.

TABLE II: GIS entities in Grid Topology Subsystem

No.	Power Grid Entities
1	Substation
2	Junction box
3	Sleeve
4	Household
5	Cable
6	Photovoltaic system

The following enumeration describes the subset of information from these files that is later utilized by the GT-HE:

- File with substation contains name of $SecondarySubstation$ and geo-coordinate.
- File with $Junctionboxes$ contains name of $junctionboxes$, geo-coordinate, serving $secondarysubstation$ name.
- File with $Sleeves$ containing two junction box names (for one or two of the cable ends out connected by the $sleeve$) and the geo-coordinate of the $sleeve$.
- File with $Household$ containing street address, junction box name that connects to that house connection box, serving $secondarysubstation$ name, geo-coordinate.
- File with $cable$ data contains names of $substation$ or $junctionboxes$ that are connected by the $cable$, cable type and cable length; $cables$ to house connection boxes are marked with a special remark containing the house number of the street address.
- File with distributed generation (in the chosen example all Photovoltaics) containing serving $substation$ and $junctionbox$ name, street address, geo-coordinate and peak power.

IV. PROCESSING AND FORWARDING OF DATA BY GT-HE

Once GT-HE completes authentication and registration with the Adapter, exchange of data and control messages between the two entities can take place. Topology Adapter initiates and can send messages to GT-HE to request: (a) Information about all topologies maintained by HE, e.g., topology name, number of nodes and cables; (b) List with all elements in selected topology; (c) Detailed information about an element; (d) All sub elements of a selected element. Based on the request from Adapter, GT-HE can push updates to the adapter, e.g.:

(a) updated elements in existing topology, (b) new topology imported/maintained in HE. Although the communication follows a request/response paradigm, data can either be pushed on each detected change, i.e., a topology update, in the subsystem or ICT Gateway can request the entities on-demand. Following subsections describe how GT-HE for two described topologies process their relevant topologies.

A. CIM-XML based Grid Topology Information

In order to process data contained in the CIM-XML file and establish relations between entities in the grid topology, the GT-HE is designed and implemented such that is passes through the following steps: (for details of design and implementation see [9]):

1) Extract and parse $substation$ data, later referenced by subsequent entities;
2) Parse entities that refer the already extracted/parsed $Substation$ as their equipment container, such as $BusbarSection$, $PowerTransformer$ (in case of a $SecondarySubstation$) etc.
3) Proceed parsing towards the last entity in the topology tree i.e. $EnergyConsumers$ by tracking the subsequent entities (such as $Terminals$, $ConnectivityNodes$, $Disconnectors$ etc.) and relating those to the already processed $Substation$ as well as the $BusbarSection$.

The outcome from GT-HE comprises of different tables that reflect different node types and of a table with the list of all cables where for each cable a starting entity and an ending entity are defined.

Challenges in Processing CIM data at GT-HE: Several modelling and mapping issues (in terms of incompleteness, inaccuracies and even parsing data) were identified and addressed while deriving network information from CIM-XML data. The challenges and algorithms for parsing/extracting CIM based topology data have been addressed in [9], therefore this paper only presents challenges in terms of incompleteness and inaccuracies in topology data as follows:

- The topology data uses composite design pattern throughout, thus entities cannot be directly interlinked i.e. there is no explicit mapping between a $Substation$ and an $EnergyConsumer$ etc. An $ACLineSegment$ only refers to the entity/node (referred as $EquipmentContainer$) to which it is directly connected.
- There is no such terminology as $Sleeve$ in the available data. Consequently, a subset of sleeves has been manually processed by following rules that have been manually defined in the implementation.
- There is no information about consumption by households. Note that the consumption itself is not a part of topology but it is required as a parameter in the topology for observability applications.
- A $UsagePoint$ can refer to three different entities i.e. Meter, Consumer or a Generator (i.e. Wind Power Plant or Photo Voltaic Power plant). This information is obtained from a separate database and linked to the topology model via mRID or Meter IDs.
- The length and type of the cable between $EnergyConsumer$ and $UsagePoint$ (i.e. between a customer connection box and meter) is not present in the grid topology data.
- Vertical distance is not included in the cable length i.e. cable lengths within substations and junction boxes are only measured to the center of its geometric shape.
- Once retrieved from the given data, the grid topology requires an automatic validation process, which not only account for the required information in the topological structure but also the isolated nodes in the grid.
- Cable reactances are frequently not specified by the cable vendors. Mapping from cable type to cable reactance needs to be seen as only approximate.

B. CSV file based Grid Topology Information

In order to process data contained in the CSV files and establish relations between entities in the grid topology, the GT-HE processing follows these steps:

1) Extract and parse substation data, later referenced by other entities;
2) Parse junction boxes and associate them to the already processed substations;
3) Parse households and associate them to the already processed substations and junction boxes;
4) Parse generators data and associate it to the already processed entities (substations, junction boxes, households).

Challenges in Processing topology data at GT-HE: The main issues appeared and faced during the processing are as follows, where three challenges are analog to the CIM based topology data example:

- The GIS system stops at the house connection box. The private cable from the connection box to the customer meter is not included in the GIS data. The type of the cable depends on the size of the building, the length of that cable is typically in the range between 1m and 20m.
- Cable Lengths: vertical distance not included in the cable length; cable lengths within substations and junction boxes are only measured to the center of its geometric shape. Consequence: cables are typically 1-2 meters longer than specified for each above-ground cable end. Substation cables may be 3-5 meters longer than specified in the GIS data.
- For grid modeling and grid observability, the cable type and cable length needs to be mapped to its resistance and reactance. Cable reactances are frequently not specified by the cable vendors and mostly have to be estimated.
- Cables cannot be mapped to the streetlight entities due to incomplete information/details on how the streetlight feeders are connected.
- Due to the lack of exact reference to a cable, a similar problem appears in sleeve entities where it is not trivial

to find out on which cable a particular sleeve is installed. Consequently, a subset of sleeves has been manually processed following rules that have been manually defined in the implementation.

In addition to the inaccuracies above that are common to both examples, the following challenges were also observed for both DSO:

- House connection boxes are not identified by a unique name but by their street address. This street address is only partially contained in the corresponding entry of the file on cables. Missing information can in most cases be resolved through the junction box id of the cable origin.
- Fuses are not part of the GIS data. Instead, the GT-HE uses DSO-specified rules to determine placement of fuses. It is estimated that the application of these rules leads to a correct placement and size of a fuse in 95% of the cases.
- Disconnectors in the disconnector status file could not be associated to a specific cable based on the data - only to a junction box. This leads to potential ambiguities when a junction box has more than two outgoing cables. The geo-coordinate of the disconnector then needs to be used to determine the likely cable by mapping to the cable direction.
- In order to find out the type of customer (i.e. peak consumption, and whether it contains an inverter of what peak power), street names were needed to make the association of a cable to a specific household. Different spellings of street names were observed in the data that needed to be resolved by approximate string mapping.

For both the examples discussed, once the input file(s) are parsed and relations between the entities have been established on the GT-HEs, the outcomes can be communicated to the ICT Gateway.

From these examples, it is clear that extracting topology data directly from the GIS systems possess several deficiencies and inaccuracies to be accurately used for grid calculations or observability applications. This paper discussed the topology information from only two DSOs, while looking into more may give rise to a different list of challenges in terms of inaccuracies and incompleteness. These challenges can be temporarily addressed by either manually defined rules in implementation or depending on multiple databases to extract correct information. Nevertheless, we cannot recreate the missing data. Therefore, one of the solutions is to get feedback from the process and help DSOs to update topology models and increase data quality. However, this feedback may not be useful in all situations. For instance, the status of a fuse/disconnector can easily be changed (from normally open to normally close and vice versa) and a missing cable resistance or reactance can be added based on the feedback from another data sources. While, for a cable length, it is not possible to measure the exact length after being installed under-ground. Consequently, there is a need to have a subsequent data model that quantifies but also keeps track of these uncertainties.

V. OUTLOOK AND FUTURE WORK

This paper presents challenges faced by electrical utilities in extracting/using grid topology information for observability applications. These challenges in terms of inaccuracies and incompleteness in the data are demonstrated using topology models from two real medium-sized distribution grid operators, which are currently being used in two different European countries. The challenges range from lack of standard data models to complexities in extracting topology information and incorrectness/incompleteness of topology information to dependence on multiple databases. The inaccuracies/deficiencies in the data can be addressed by either manually defined rules in implementation or depending on multiple databases to extract correct information. However, in the long run a feedback from the process to help DSOs in updating topology models and increase data quality as well as subsequent data model are required that quantify and keep track of the uncertainties in topology data. Future work should demonstrate approaches that work with quantification of uncertainties in the grid topology information. The design and implementation of a data model but also validation of how successful is the data model are also under consideration. Furthermore, approaches to employ database technology for persistence, indexing and efficient retrieval of topology information will also be considered subsequently.

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