Cloud-based IEC 61850 communication simulation using a standardized network model

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***Abstract*— The Italian norm CEI 0-16 uses IEC 61850 for communicating with distributed energy resources connected to the medium voltage grid. This paper illustrates a CIM-based software tool for the evaluation of the communication network requirements, in terms of bandwidth, for the widespread implementation of such use case, by using real distribution networks as simulation scenarios. The simulation environment has been designed from the start with the possibility of distributing the simulation on multiple physical hosts, possibly running in cloud environment.**

***Keywords*— Semantic Model; ICT Standard; Interoperability, software development; model-driven**

I. Introduction

The Italian norm CEI 0-16 has chosen the IEC 61850 standard for the implementation of communications with distributed energy resources (DERs) connected to the medium voltage (MV) grid [1] and is currently defining the details of the data model (i.e. the logical nodes) and of the ICT architecture to be used. The interface should be used by DSOs and possibly also by aggregators, and the communication network used should provide performance levels suitable for all the prescribed services. An interesting point is thus the evaluation of the communication network requirements, in terms of bandwidth, for the widespread implementation of such use case, possibly by using real distribution networks as simulation scenarios [2]. The main contribution of this paper is the description of a novel simulation framework, developed as an evolution of the one described in [6], for performing such evaluations: more in detail, the novelties of this framework with respect to existing solutions are the following:

- The simulation is completely based on CIM (Common Information Model): everything is generated from an electrical network model based on a standard ontology. This is different with respect to existing approaches (e.g. [3], [4]), where many different models (e.g. CIM and IEC 61850) are combined together in order to obtain a very detailed ontological description of all the domains involved in the simulation (e.g. electrical, ICT, control etc.): in fact, these approaches are very powerful and general, however they are also very complicated since they require the joint use of many different data models. In this paper, on the contrary, only one master data model is used (the CIM): information which is not explicitly described in this data model (e.g. detailed DER control modes descriptions) is generated via the use of predefined rules and templates (see section III). Of course this approach is less flexible (the rules and templates are very much dependent on the specific use case being implemented), however it has the advantage of simplicity and also of relying on a single source of information, which is also much easier to handle and debug. In particular, the dataflow is always unidirectional, from CIM to other artifacts, which makes the configuration logic easier to understand and modify.
- The simulation runtime environment is based on Docker containers, orchestrated by Docker Swarm. This a a novel approach in the field of Smart Grid interoperability testing [5], which allows to simulate large-scale scenarios in an easy way by distributing it among many parallel hosts, possibly executing in a cloud-based environment.

More in detail, the simulation framework is implemented in a way that satisfies the following key requirements:

- be easily configurable in terms of scenario changes: not only different networks but also parameters like the kind of DERs that should be monitored (e.g. only generators above a given size)
- be easily configurable in terms of IEC 61850 services implemented: for example, measurements may be collected by direct polling or by using the reporting capabilities of the protocol. In turn, the reporting function has some important tunable parameters (see next paragraphs)
- be scalable: allow the simulation of a large number of devices.

The use of a standard IEC CIM network representation can enable the implementation of a wide set of use cases in a flexible environment. In particular, the simulation configuration can be derived automatically from the model, so that different scenarios can be easily tested and parametrized. Moreover, the application described in this paper, i.e. the testing of CEI 0-16 interface communication, could benefit from the availability of the whole distribution network of the city of Milan in CIM format (as already described in [6]). However, with respect to the application described in that paper, related to protection applications, the testing of DER communications requires a more complicated architecture:

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- The communication pattern is different: while protection logics basically require a peer-to-peer communication model, which can be easily mapped on the GOOSE (Generic Object Oriented Substation Events) protocol, the DSO-DER communication is inherently client-server, and would typically require the use of the MMS (Manufacturing Message Specification) protocol. This implies that the client should be also integrated in the simulation, which is the DSO SCADA system in charge of collecting data from field devices. The framework proposed in this paper is able to automatically configure an IEC 61850 SCADA module as well as the field devices, using the CIM network representation and an IEC 61850 template.
- The number of simulated devices is higher, not limited to a single distribution network feeder.
- The traffic analysis depends on how the IEC 61850 client-server communication is configured, in particular if a pure polling of devices is implemented or the reporting capabilities of the protocol are used. Moreover, the latter requires some form of electric network simulation, since measurement reports will be sent based on the observed changes of electrical quantities (e.g. significant variations in measured voltages and currents). For this reason, the same CIM network used for the configuration of IEC 61850 devices has also been used for the automatic configuration of a power flow simulation which has been directly integrated with the ICT simulation.

II. USE CASE AND REQUIREMENTS

The basic communication scenario used to demonstrate IEC 61850 traffic simulation is shown in Fig. 1. In this figure a SCADA module, located in an HV/MV substation, collects data from DERs connected to the underlying distribution network, in terms of active and reactive power as well as voltage levels at their connection point. Of course the SCADA can also collect local substation measurements, in particular the active and reactive power related to each feeder. However, this use case can have several variants with different requirements on the telecommunication infrastructure: the type of monitored

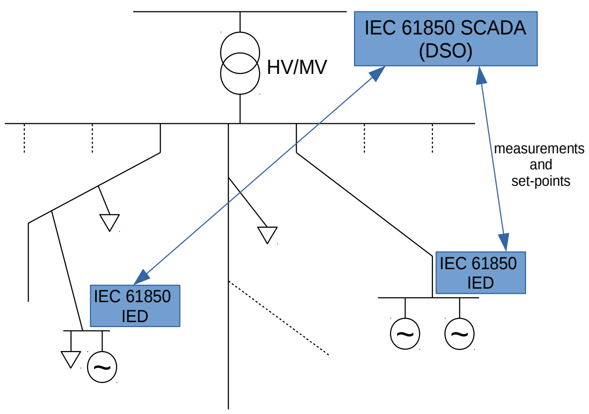

Fig. 1. Basic CEI 0-16 scenario

devices depends on the application's needs and on the actual implementation strategy.

In the most demanding scenario, full observability of the network is obtained by monitoring active and reactive power of all loads and generators connected, and voltages at all the busbars: this clearly requires a very robust and capillary communication network. A second, less demanding, scenario requires the monitoring of the generators only, and of the transits at the start of each feeder: it is then possible to calculate the aggregated load value by difference. A third possibility is to monitor only some of the generators, and then apply a state estimation algorithm, possibly based also on additional information like meteorological data, in order to obtain a reconstruction of the full network's status. Another variable to consider is the temporal resolution of the measuring loop, since this has an impact on the precision of the state estimation process.

Given all these possible variations, a simulation environment for testing the impact that each design variable has on the telecommunication network is an important tool for choosing the best implementation strategy.

III. CIM-BASED CONFIGURATOR

As already pointed out, all of the simulation's configurations has been generated starting from a standard CIM file representing the distribution network of the city of Milan. In detail, the generated data includes:

- IEC 61850 ICD files for each device, compliant with the CEI 0-16 data model. These files are also used to automatically configure the SCADA module.
- A network representation compatible with an off the shelf power flow calculation tool
- A mapping file for connecting the simulated IEDs to the measurements generated by the power flow calculation tool

This data is configurable in terms of the parameters illustrated in the previous paragraph:

- Measurements collection cycle time: this is actually configurable in the IEC 61850 Report Control Blocks period. Of course, it is also possible to use a more efficient 'spontaneous' generation of reports based on the variation of measurements, and in this case the deadband interval can be configured. In a similar way, the SCADA's polling time can be configured.
- The types of devices connected to the given distribution grid for which communication should be implemented: for example, only for the generators above a given size (e.g. 1 MW). If no limitation is given, then a configuration is generated for each busbar which has at least a load or a generator connected to it.

In this way, one obtains a very flexible simulation environment for testing all of the possible deployment scenarios of this use case, applied to a real-world distribution network.

As already pointed out in the introduction, one fundamental architectural choice for the simulation environment is the use of the CIM electrical network description as the only source on information: since the IEC 61850 specific information is not modeled explicitly, it is generated via the use of predefined rules and templates. More in detail, a file containing the general structure of a DER unit according to the CEI 0-16 norm is used as a "blueprint" for instantiating the actual ICD files: in this way, the CIM-based configurator doesn't need to know anything about the low level details of the IEC 61850 data model (e.g. the precise description of the generator's control modes), since these are encoded in the template. The configurator will only need to know the names of the logical nodes to instantiate whenever it finds some specified pattern in the input data model, described by simple rules: for example, one rule inserted into the configurator might be:

- if the input CIM model contains an object of type BusbarSection, and an object of type GeneratingUnit is associated to that BusbarSection, and the nominal power of this GeneratingUnit is above a given size, and no other device is connected to the same BusbarSection, then instantiate an IEC 61850 IED with the following logical nodes: DRCC, DRCT. DOPM, MMXU.

Of course the above example is one of the simplest possible rules, but much more elaborated patterns are possible, for example by taking into account the different types of generators, weather they are inverter-based or not, weather there are also loads connected to the same busbar and the presence of schedules or regulating controls associated to the generators or to the loads. However the main point here is that, even if the rules can include quite complex pattern matching rules on the input CIM file, they don't need to know much about the generated IEC 61850 data model: only the names of the logical nodes are necessary, since all the (possibly complex) information content of these nodes is already hardwired into the template. This is possible since the structure of the needed logical nodes is precisely defined in the CEI 0-16 norm, and thus there is no need to dynamically instantiate them by directly manipulating the IEC 61850 data model. This, in turn, provides a great simplification of the configurator's code, since it only needs to understand a single data model: the CIM.

IV. Cloud-based Simulation

As already pointed out in the introduction, scalability of the simulation environment is a key requirement: for this reason, it has been designed from the start with the possibility of distributing the simulation of IEDs on multiple physical hosts, possibly running in cloud environment. In particular, each IED file generated by the CIM file processing will be automatically executed by a Docker container running an IEC 61850 module (Fig. 2.): moreover, this container will read its simulated state (i.e. the power and voltage measurements assigned to it by the configurator) from a network connected real-time database (described in detail in Section VI). This real-time database, in turn, is populated by the values generated, starting from the same CIM network used for IED configuration, by a power flow calculation tool instance running on any node of the network (not necessarily the same node that runs the database or the docker instances).

Docker containers are lightweight isolated execution environments, which can communicate over a virtual overlay network: this allows to obtain a very scalable simulation

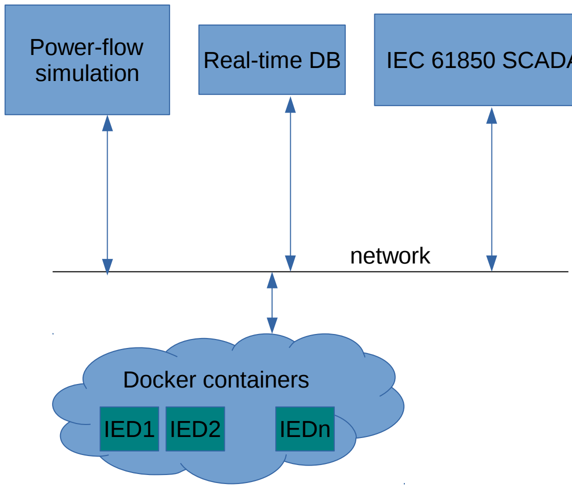

Fig. 2. CEI 0-16 simulation architecture

environment. In particular, the scalability of the solution is "horizontal", meaning that the individual containers can be flexibly allocated to physical hosts as needed, even dynamically (i.e. new physical hosts can be added or removed while the simulation is running), which means that even very large scale simulations are possible without modifying the proposed architecture.

V. Simulation Results

As already described, two main data exchange patterns can be used in order to implement the simulation scenario: polling and spontaneous reporting. In the first case the presence of an electrical simulator is not really crucial, since the ICT network traffic associated to DER monitoring is not influenced by the actual measurements. In the reporting case, on the other hand, the generation of reports from the DER units is directly connected to changes observed in the measured values, so that a realistic evaluation of the ICT traffic must be supported by a proper electric simulation.

Of course, the second scenario is much more convenient, in terms of bandwidth, than the first: as an example, a polling simulation scenario with 200 IEDs, related to a single HV/MV substation of the city of Milan, is shown in Fig. 3. (where the Y axis shows the traffic measured in bytes per second). The polling period is set to 20 seconds. The periodic traffic

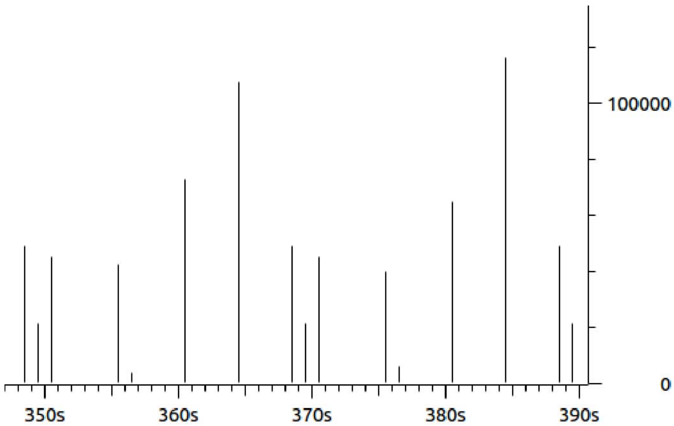

Fig. 3. Polling simulation with 200 IEDs

generated by this scenario can be avoided by using the reporting capabilities of IEC 61850, an example of such pattern is shown in Fig. 4..

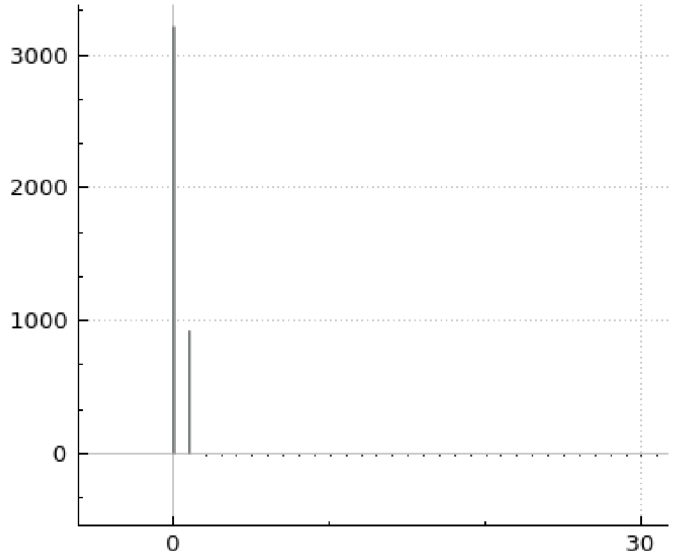

Fig. 4. Reporting simulation example

In this case the communication only occurs in presence of significant variations in measured values (the deadband is configurable in a standard way in the IEC 61850 template), in the case of Fig. 4. the events close to 0 seconds are related to switches operations. The important point here is that both simulations were generated from the same CIM network, and also the switching events used for simulating the reporting scenario where executed by operating on the CIM network, automatically interfaced to a power flow calculation tool by the simulation configurator. The generation of events also allows to better highlight the role of the real-time database component in the overall simulation architecture, as described in the following paragraph.

VI. THE ROLE OF THE REAL-TIME DATABASE

The main point of the real-time database component is having an effective and yet simple way of connecting various simulation components (in particular, the simulated IEDs and the electrical simulator), by preserving the common CIM reference to data objects (in order to guarantee interoperability) but without adding unnecessary complication to the interface. The choice was then to adopt the simplest storage model, which is the key-value, i.e. the repository can be thought of as a big set of tuples in which each entry is identified by a unique key, with an associated value. In this paper's scenario, the key value can be the leaf name of an IEC 61850 data attribute, while the value is clearly the value of the data attribute. Since the IEC 61850 names are automatically generated from CIM, the link to the original data model is guaranteed.

Key-value stores are a particular sub-category of noSQL databases, which have attracted a lot of interest in recent times, especially in relation to cloud-based applications; in these context 'keys' and 'values' are usually just strings, with no inherent structure, there are no datatypes to which a value can be bound. Notable exmples of such databases are Redis, Memcached, Apache Cassandra. The reason for the success of these tools is that their extremely simple data model allows for very efficient, scalable and fault-tolerant implementations. The drawback is that expressiveness is limited with respect to a traditional relational database, moreover no ACID (Atomicity, Consistency, Isolation, Durability) guarantees are usually in place. A real-time repository for the collection of live data from field (in this case, a simulated field) is suited for this storage model, given the driving requirements illustrated before; with respect to ACID, a relaxation of this model is in general acceptable, given the inherent volatility of the stored information (so that, for example, durability should not be a critical point): a particularly interesting solution experimented by the authors is Redis, which supports an important property for this paper's use case: publish/subscribe mechanisms.

The plain key-value structure can seem too simplistic at first, since the IEC 61850 data model is based on a tree-like data representation (see Fig. 5. for example). However, this rich structure need not be fully represented in the simulation's runtime, since only the leaf components of the model must be contained in the repository (i.e. the non-leaf objects don't have any associated value). The main operations implemented by the repository must thus be the following:

- *get(key)*: returns the value stored under key
- *set(key, value)*: creates a tuple (key, value), if key already exists its value is updated

Of course, it can be argued that it must also be possible to retrieve all the leaf values associated with a given Data Objet, for example, and this might be cumbersome to implement in a plain key-value store, where the upper Data Object level is not represented; this apparent problem is however easily solved by simply retrieving all the keys starting with a given value, i.e. by appliying simple regular expression to key values; the tree-like

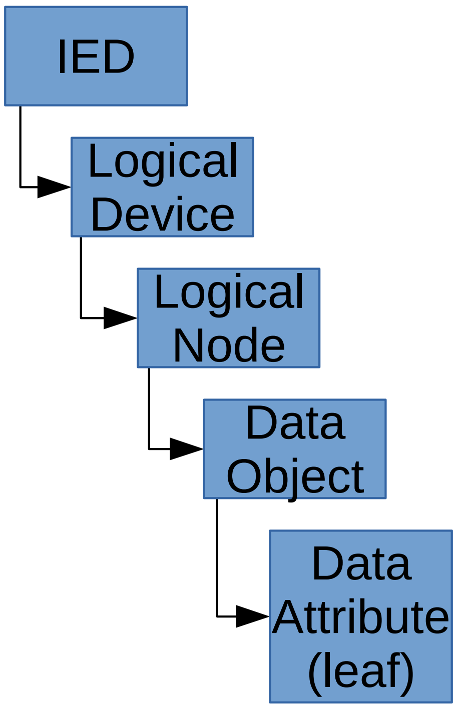

Fig. 5. EC 61850 data model example

structure of an IEC 61850 data model allows for this implementation, which applies to all the upper-level data structures, like Logical Nodes or Logical Devices. Referring to Fig. 5., the retrieval of all the values associated with a Data Object can be translated by the implementation into a sequence of ordinary get(key) commands. Other options might also be employed in case of very large data sets, where the computational cost of performing a lot of get(key) commands might be too high, if the data store allows the representation of sets, i.e. unordered collections of keys (this is a feature offered by Redis): in this case all the keys related to a certain Logical Device, for example, can be inserted into a set which can be queried more efficiently than a search over the whole dataset.

Another thing to note in this storage-centric setup of the simulation framework is the fact that a publish-subscribe mechanism is useful for communication between the various database clients: for example, in the reporting scenario it is used to inform the electrical simulator about changes in the network state (e.g. breaker opening). An example of such messaging pattern is shown in Fig. 6., where the user publishes a message in the real-time database in order to notify a change (e.g. a switch position): the message must refer to a valid CIM identifier for the given object, as described in the network description used to configure the simulation. The real'time database will then trigger the power flow simulation, which will produce updated simulation values. The IEDs which see a change in their measurements (IED2 in figure) will then generate IEC 61850 reports to the SCADA.

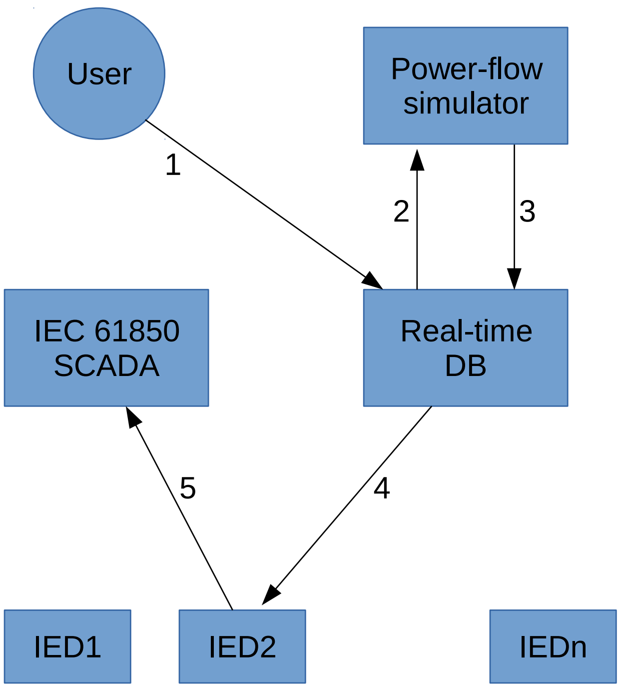

Fig. 6. Use of Redis publish-subscribe capabilities

In conclusion, the shared database concept allows the simple implementation for the simulation's state and for the exchange of events which might affect its execution. All the modules which are interfaced to the database are decoupled and can be changed or removed without impacting the other modules, resulting in a robust architecture. As a last point, the database is well suited for a cloud-based setup, so that it fits well into the use case described in this paper.

VII. Conclusions and Further Steps

In conclusion, the main contributions of this paper are the development of a CIM-based simulation configurator for CEI 0-16 monitoring scenarios, implemented in an easily configurable model-driven way and a cloud-ready simulation execution environment which allows the simulation of a great number of communication nodes.

A further improvement of the simulation framework would be the use of a WAN (Wide Area Network) emulator for the communication between the SCADA and the IEDs: such emulator can be a dedicated hardware device as well as a software module running on each Docker container, for example the Netem tool [7].

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