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RESEARCH ARTICLE

Automatic Generation of Data Centre Digital Twins for Virtual Commissioning of Their Automation Systems

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ABSTRACT Data centres are becoming an increasingly important part of our society's infrastructure. The number of data centres is growing constantly, making growing the gross level of electrical energy consumption. At the same time, the rapid spread of sophisticated electrical devices as well as other automation systems in general produces an opportunity for making data centres an attractive player in the constantly designing energy market. But for this, new advanced technologies must be applied to solve the problems of complexity and heterogeneity in various types of data centre design. A new concept, which is based on the automated generation of a digital twin (DT) system, directly from its schematic representation is presented in this paper. A DT is a virtual version of an object or system, designed to aid decision-making and virtual commissioning through simulation, machine learning, and reasoning. In the scope of current work, the IEC 61850 standard is chosen as a starting point for a multi-step generation of the DT combining simulation model and decentralized control logic. As a result, the designed DT "clone" of an electrical system consists of the SIMULINK model of the electrical system plus the automatically generated control application (based on the IEC 61499 standard).

INDEX TERMS Digital twin, data centre, automation, IEC 61850, IEC 61499, MATLAB.

I. INTRODUCTION

Data centres are becoming an increasingly important part of our society's infrastructure. According to Masanet et al. [1], the demand for computing resources and data centre power has been steadily increasing around the world, accounting for about 1% of total electricity use. Growing consumption of electrical energy and its price enforce all IT (Information Technology) giants to rethink the concept of new data centres' power management process. Facebook's data centre, located in Luleå, Sweden, uses almost 70% less energy than the average data centre according to BBC News [2]. Using renewable resources in combination with efficient operation can reduce the amount of consumed power to even more impressive values. But at the same time, the wide propagation of data centres poses numerous challenges for both engineering and control of the latter: dynamic load characteristics become more erratic, requiring more sophisticated control, prediction, and virtual commissioning.

Firstly, Radovanovic et al. [3] found that within a day, the PDU (Power Distribution Unit) consumption level changes dramatically by more than 10% for more than half of the PDUs and intraday profiles are hard to accurately predict. That implies that more sophisticated algorithms and

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approaches should be used in order to meet the demand for sustainable development in future years.

Secondly, the problem of different electrical sources' use in data centres produces the demand for their unification under just one "umbrella" of a standard which makes the control process more determent, trivial, and less expensive. In relation to this problem, the authors of this paper want to demonstrate the abilities of the IEC 61850 [4] standard (its properties will be presented later in this text) to satisfy such demand. The IEC 61850 standard was initially developed for application in substation automation areas and is gaining popularity in many other areas [5], [6], [7], including data centres automation also.

Thirdly, modern data centres are equipped with the complex decentralized architecture of automation systems which requires an application of adequate software engineering architecture to it. The IEC 61499 [8] standard is addressing the challenges of distributed automation systems design and is gaining popularity among the leading vendors of automation (see *UniversalAutomation.org* [9]). IEC 61499 tools and controllers have been effectively employed in the different areas of automation systems, for example, electrical power management [10] and simulation of electrical systems [11].

As a commonly known trend for a solution to the problems which were aforementioned, the design of the system's digital twin (used here as "DT" for short) is used [12]. The DT is a new concept born in the field of Industry 4.0, combining static and dynamic models of automated systems. It is used for the online simulation of complex automated installations and their virtual commissioning [13]. In this study, the term *digital twin* refers to a multi-layer structure presented in Figure 1. Since the infrastructure of a modern data centre is itself a complex distributed automation system and must be tightly integrated with the evolving power system, the task of virtual commissioning and testing becomes very important. It is also a point that for a time being, the process of DT system design is still time-consuming, involving different specific knowledge. We hypothesize that this process can be substantially optimized by applying the automatic generation technique that would start from the available digital documentation of electrical systems.

The main idea of this paper is to design a uniform method for the automatic generation of a DT model of the data centre's electrical part directly from the specification file of the electrical system. The System Configuration Description file (or "SCD") of the IEC 61850 standard is taken as input data for further data transformations.

The contributions of this paper are as follows:

1) developing an automated method of creating DTs of automated data centre infrastructure for the purpose of its virtual commissioning, which includes:
   a) development of transformation rules for generating a simulation model based on the IEC 61850 specification of an electrical system of a data centre.

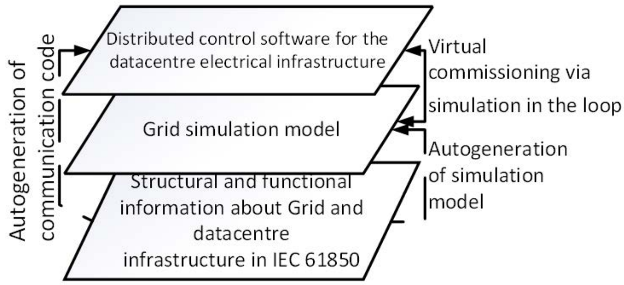


FIGURE 1. Digital Twin of data centre infrastructure integrated into the grid.

   b) enabling IEC 61499-based control application into the SIMULINK modeling as an important step in the virtual commissioning of the system under control.
   c) prototyping of a software tool that justifies the developed auto-generation method.
2) interoperability improving between IEC 61850 standard-compliant systems and data centres, by investigating and defining the common points between the aforementioned

The rest of this article is structured as follows: in Section II a review of related works is given. Section III describes the definition of a use case. Section IV briefly describes the details of the technologies used and depicts a flowchart of operation. Section V provides background information. Section VI presents the transformation templates integrated into the developed software tool, the developed transformation rules, and the generation workflow. Section VII is the result of the auto-generation discussed in the Section III case study. Finally, Section VIII presents the conclusion and further work.

II. RELATED WORK

As part of this work, a structured (systematic) review was carried out. A brief overview of related work has been implemented in the *IEEE Xplore* database. The reason for choosing this database was because the IEEE is the most famous standardization organization in the world. In addition, the authors found it very convenient and efficient to use the *IEEE Xplore* website search engine. The search pattern (1) was considered for research:

$$``WHAT''AND``LINKS''AND``TOWHAT'' \quad (1)$$

where the keyword *WHAT* was assigned the values "data centre", "electrical system", or "heterogeneous energy resource". The *LINKS* meant "simulation", "modeling" or "management". The keyword *TO WHAT* was assigned to the names of communication protocols and standards that are related to the control of heterogeneous electrical sources. As a result, template (2) was used, where *OR* is the inclusion criteria (increase in the number of similar works a search result) and *AND* is the exclusion criteria (implies restriction

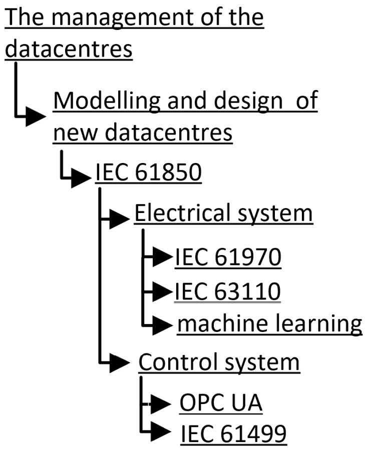


FIGURE 2. **The mind map that was chosen for the investigation frame.**

of the search results):

$$\begin{aligned}&(\text{``electrical system'' OR ``data center'' OR ``microgrid''})\\&\text{AND }(\text{``simulation'' OR ``modeling'' OR ``management''})\\&\text{AND }(\text{``IEC 61850'' OR ``IEC 61851'' OR ``IEC 61970''}\\&\text{OR ``IEC 61968'' OR ``IEC 63110''})\end{aligned} \quad (2)$$

As seen from the template (2) above, the issue of developing and modeling new data centres was taken into consideration where the matter of data centre control was thought to be of the utmost importance (for example, IEC 61499, or OPC UA [14]). The study's main finding is that IEC 61850 may be utilized as a link between several standards to make it easier to create a new data centre infrastructure. Thus, the research path that served as the foundation for the study is shown in Figure 2 in the form of a mental map.

Additionally, the following questions were taken into account during the review of the existing literature:

1) Who are the potential stakeholders of the research?
2) What is the diversity of standards that are already in use?
3) How IEC 61850 can contribute to increasing automation in the area of electrical systems management?

As a result, for the query (2), only conference and journal papers were included in the scope of interest. Also, only publications during the last 10 years were considered. Among of aforementioned 74 related works were identified, the most relevant of which are discussed in this section.

Firstly, the authors want to highlight the work of Higgins et al. [15] who proposed a development process combining the IEC 61850 model with an object-oriented and decentralized executable automation architecture to reduce design and re-engineering efforts, especially those associated with the software. The result of the above work is the automatic generation of an IEC 61499-compliant platform from an IEC 61850 "SCD" file for the electrical system under investigation. At the same time, they did not consider the need for automatic generation of the physical part of the electrical system itself, which is different from what will be presented in this paper.

These ideas were further developed by Andren et al. [5] who introduced the principles of data conversion from the IEC 61850 electrical system design to the IEC 61499 control system. They analyzed the data representation models of IEC 61850 and IEC 61499 and developed rules for converting from one standard to another. Also, they have presented a model-based engineering approach to the design and development of Smart Grid automation applications, practically implemented in a tool for automatically creating and deploying control applications based on IEC 61850 descriptions. Moreover, the distributed automation architecture of IEC 61499 was found very much compatible with the object-oriented approach of IEC 61850 paving the way to the automatic generation of executable artifacts from the static descriptions in IEC 61850, as it was investigated in works [16], [17]. Here the fact of relative interoperability between IEC 61850 and IEC 61499 data objects has been proven through the design of an algorithm that translates the "SCD" file of an electrical system into the IEC 61499 control project implementing automation functions over that electrical system. These works made a significant step toward to automatic generation of the DT parts.

OPC UA is a relatively young architecture, but at the same time a very promising type of communication protocol, gaining popularity in the automation area. The simplicity of the information model is one of the biggest advantages of that protocol [18]. Another benefit is that its information model can be populated and engaged with other communication protocols which were established previously. In this way, different information mapping techniques are already known today, among them manual (or direct) mapping (presented by Cavalieri and Regalbuto in [19]), and ontology formulation mapping (presented by Ingalalli et al. in [20]). The difference in both [19] and [20] against the current work is the lack of generation of the electric system model, which is considered a key feature of the current work.

IEC 61970 and IEC 61850 are widely used in power industry automation. But, because these two standards define data models and interfaces respectively, the resulting models are not uniform. Ling et al. [21] propose two aspects of the differences: the data model and the service model. IEC 61970 defines the capabilities of the information model and is widely used for enterprise integration.

In all related works presented above, the lack of a physical model can be observed, but it does not mean that this problem was not considered as well. In fact, there is a lot of research on modeling the behavior of data centers. In this way, Vesterlund et al. [22] present comprehensive modeling of the data centre. By analyzing a structure of an existing data centre, they defined the list of most important parameters (Table 1 in [22]). Then they are using mathematical equations to model the physical characteristics of the data centre. That makes the model fast and sufficiently precise (the calculation error is around 3.4 – 5.2%).

Furthermore, Berezovskaya et al. [23] followed the steps by refactoring the *monolithic* model into several *submodels*, and by simulating this model's behaviour, it is possible to significantly increase the power-savings factor of the real data centre (which, as the authors claim, can reach 68.6%).

Zhabelova et al. [24] addressed the complexity of smart energy systems automation by bridging the multi-agent approach to the decentralized logic design with advanced object-oriented engineering standard IEC 61850 is gaining popularity in the Smart-Grid domain. The standard was found suitable for application in the data centre's domain, despite it was initially designed for substation automation management. Confirming this finding, ABB in review [25], emphasized the practical benefits of applying IEC 61850 in the field of data centre power management.

The field of artificial intelligence (AI) [26] also finds application in data centre modeling. Zohdi has developed a framework [27] for determining the optimal cooling strategies to achieve a given temperature in a system using a minimum amount of energy. In this work, the author uses a thermo-fluid model based on the Navier-Stokes equations [28] and the first law of thermodynamics. This model is then combined with a genome-based machine learning algorithm to develop a digital twin of the system under study. As the author states, the main advantage of this approach is that the developed model can run in real-time or faster than the real physical system, which makes it suitable both as a design tool and as an adaptive controller.

In summary, the conducted short survey shows clear signs of the growing use of the IEC 61850 standard for engineering the infrastructure automation of the data centre. However, it was also noted isolation of the *electric system simulation* branch from the design of the *control branch* of that electric system means that these two directions are investigated separately from each other. The development of software applications for automating such hybrid systems and their virtual commissioning requires a lot of effort and time. To bridge this vacuum and begin the process of resolving these issues, the authors propose a novel approach, which is considered to be the first step toward the transformation of the IEC 61850-related "SCD" file into the DT model.

III. USE CASE DEFINITION

Let us consider a basic building block of the data centre infrastructure – the emergency power system of data centers and take it as an example for further investigations. Its structural scheme is shown in Figure 3 and the corresponding electric circuit is shown in Figure 4. Here, the AC/DC converter "D1" means that it has 2 transformation modes (one is from alternating to direct current (or AC/DC), and another one is DC/AC). When the utility source (not depicted in Figure 4) is connected and functioning, power flow will be as depicted in Figure 5 (left part). The green line here depicts electrical power that goes from an external power source to an improvised consumer (depicted as "LOAD"). The yellow line depicts electrical power that will only pass through if the charging process of the battery "BT1" is established. If the fault status of the utility source is registered by the voltage sensor "VT1", power flow will be as depicted in Figure 5 (right part). The red line here depicts that no power goes between the main utility and the load.

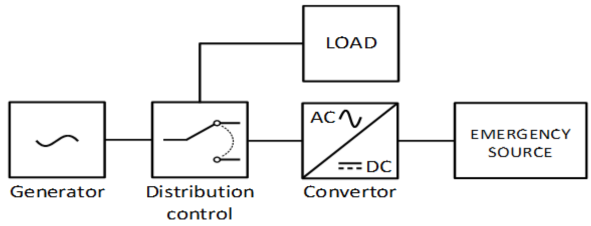


FIGURE 3. Emergency power supply structural scheme of a data centre.

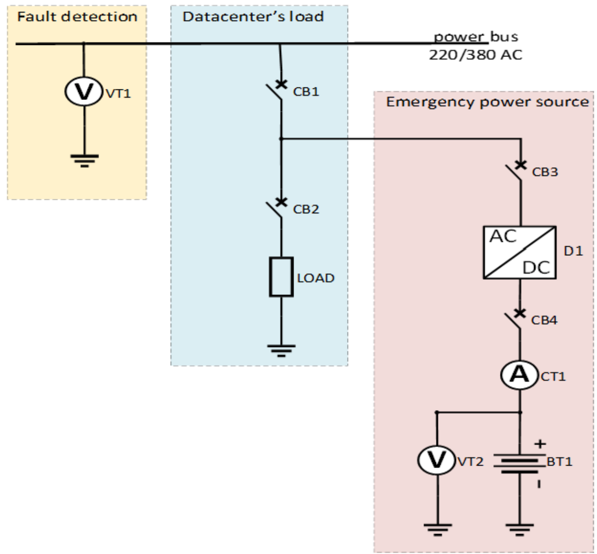


FIGURE 4. Typical diagram of emergency power supply circuit of data centre diagram.

From the paragraph above it can be concluded that *voltage* and *current* characteristics were chosen as the main in the scope of this research. This was not done by accident. To provide evidence as to why the proposed use case was chosen, the authors would like to refer to the work of Meisner et al. [29]. In this paper, the authors note that data center power consumption is perhaps one of the most important factors to consider during the data center design phase. Carefully selected server power technology can reduce average power consumption by up to 74%, or billions of dollars globally. Therefore, data center validation in terms of power supply is an urgent task.

Summing up this part, the focus of this use case is to automatically generate the DT model of the data center's uninterrupted power system. As a result, generated system should have the same behavior that it has in its real representation (fault detection feature, control over different current breakers, charging/discharging capabilities of the battery source, etc.).

The authors want to emphasize once again that the novelty of this work lies in the creation of a heterogeneous system (physical model + control system) over the electrical system,

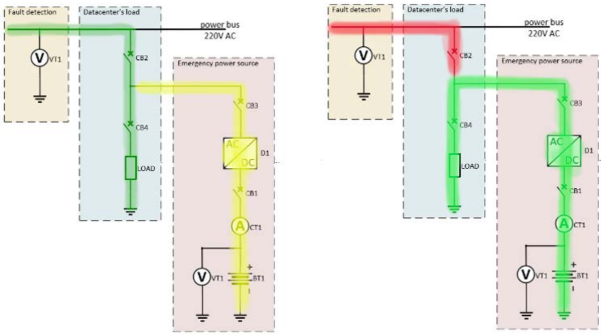


FIGURE 5. **Data centres's electrical power flow under different conditions, where (a) is the "grid-connected" mode (from left) and (b) is the "isolated" mode (from right).**

which is considered a digital twin model in the current context. This means that the presented scheme (Figure 4) is taken only to demonstrate the possibilities of the declared idea. To focus more on the proposed transformation method rather than the specific details of the system under study, the scenario has been greatly simplified.

IV. PROPOSED ENGINEERING FRAMEWORK

The proposed engineering base is designed to automate the development and verification of the logic of distributed automation of the data centre power supply system, facilitated by an automatically generated simulation model. The result of this study is displayed in the form of an *Auto generation tool*, shown in Figure 6, which uses the "SCD" file as input and generates a simulation model of the designed electrical system as well as a new IEC 61499 application to control the simulated model. As a result, these two files constitute a DT system, useful for obtaining physical characteristics (current, voltage, state of charge (SOC), etc.) as well as for virtual commissioning of its distributed automation, including a variety of control signals.

The procedure begins with design documentation in the form of an "SCD" diagram (depicted as an *IEC 61850 compliant environment* in Figure 6), which includes components related to electrical equipment and conforming to the IEC 61850 standard. Thus, during the virtual commissioning phase, the developed automation logic can be tested against a simulation model. Specific implementations of the requirements can be added to the backbone automation logic. This procedure can be repeated several times, with virtual commissioning taking place at each stage.

As a result, the qualitative methodology of the proposed approach was developed in two stages, namely:

1) *Data collection*. The procedure begins with the design of documentation and is divided into two stages.
   a) *Participant observation*. Includes the main electrical equipment of the data centre and its IEC 61850 compliance (see Figure 4).
   b) *Recursiveness*. The design under study can be changed at the stage of data collection (correction of the original "SCD" file is not prohibited).

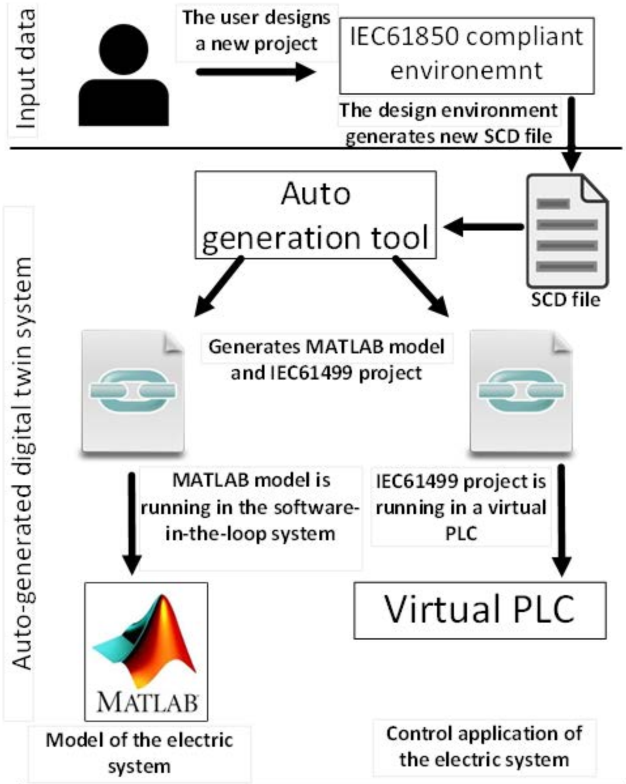


FIGURE 6. **Engineering flow in the proposed framework.**

2) *Data analysis*. Pattern recognition of the developed "SCD" file. This step is represented by three sub-steps, namely:
   a) *Coding*. This step is already implemented in the IEC 61850 standard since all the abstractions under investigation are associated with specific words/labels (more details on this will be presented in Section V, part A).
   b) *Thematic analysis of the pattern*. Converting encoded words to structured data (data fitting) and generating a template (to be explained in Section VI).
   c) *Content analysis*. Pattern stack generation. Analysis of the received template stack, creation of the corresponding model, and its verification against the original "SCD" file (to be explained in SectVII).

V. BACKGROUND

A. IEC 61850

As it was briefly represented in Section I, IEC 61850 is an international standard covering various aspects of smart power distribution systems, including communication protocols for various equipment in a substation, protection, control/measurement equipment, and intelligent electronic devices (IEDs). Main characteristics of IEC 61850:

1) *Data modeling*. Primary objects, as well as protection and control capabilities, are represented as standard

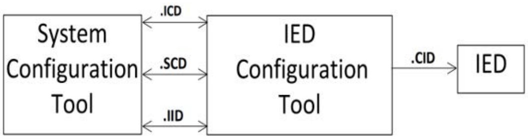


FIGURE 7. Different types of configuration files and their usage.

logical nodes (LNs) that can be grouped into different logical devices.

2) *Fast transmission of events*. Generic Substation Events (GSE) are designed for fast event data transmission in peer-to-peer mode.
3) *Transfer of sample data*. Sampled Value Control Blocks are used in circuits to handle Sampled Value Transmission (SVCB).
4) *Data store*. Substation Configuration Language (SCL) is a specification for storing all configured data in a standardized format
5) *Directory of logical objects*. All IEC 61850 devices use the same object and function namespaces, allowing objects to be integrated into the data centre power system.

The advantage of the IEC 61850 standard is that it has a well-defined catalog of names for entities. This means that by knowing the name of an IEC 61850 element, one can accurately determine its type, functions, parameters, and properties. This feature makes IEC 61850 especially attractive for the automatic creation of DT systems.

According to the workflow implied by IEC 61850, two types of configuration tools are required, *System Configuration Tool* and *IED Configuration Tool*, as shown in Figure 7. The structure of the electrical system and the required functions are described in the system configuration files (‘‘SSD’’ and ‘‘SCD’’) when the exact IED models that perform these functions are included in the IED configuration files (‘‘IID’’, ‘‘ICD’’, ‘‘SCD’’ and ‘‘CID’’). System configuration tools (as exemplified by ‘‘Helinks’’ [30] in this article) include graphical editors for compiling systems from objects and storing descriptions in the form of ‘‘SSD’’ and ‘‘SCD’’ configuration files.

IEC 61850-6 defines five types of files to work with SCL files: ‘‘SSD’’, ‘‘ICD’’, ‘‘SCD’’, ‘‘CID’’ and ‘‘IID’’. Here is a definition of some of them:

SSD - System Specification Description: This file describes the topology of an automated electrical system as well as the required functions but does not include the exact models of the IEDs that perform these functions.

SCD - Substation Configuration Description: A file containing the entire system configuration, including the information model of the selected physical equipment, network settings, data flows, etc. An ‘‘SCD’’ file consists of a ‘‘.ssd’’ file and several ‘‘.icd’’ files.

The authors find the biggest advantage of the IEC 61850 standard is that it has a strongly defined catalog of names for logical objects. It means that by knowing the name of the IEC 61850 element it is possible to establish accurately its type, functions, parameters, and properties. This feature makes IEC 61850 attractive for an automatic generation of DT systems. In Table 1 some of the IEC 61850 LNs are presented.

TABLE 1. List of IEC 61850 objects.

IEC 61850 Type	LN Class	Description
VTR	TVTR	Voltage transformer
CTR	TCTR	Current transformer
CON	ZCON	Power converters (including AC/DC)
CBR	XCBR	A circuit breaker with the function of current protection
	CSWI	Control over a circuit breaker
	CILO	Controlled switchgear operation
CAB	ZCAB	Power cable
BAR	ZBAT	DC battery source

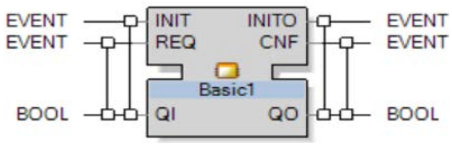


FIGURE 8. IEC 61499 FB example view.

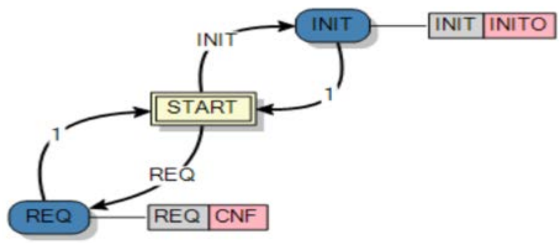


FIGURE 9. Example of Execution control chart view in IEC 61499.

B. IEC 61499

IEC 61499 is an international standard defining the distributed architecture for industrial process measurement and control systems. It is best suited for modeling and implementation of distributed automation systems, which fits well with the current smart energy automation, including large data centres. IEC 61499 permits an application-centric design, in which one or more applications are built for the entire system and then deployed to the available devices, defined by networks of interconnected function blocks. A device model provides a software abstraction for control devices composing systems. The system model includes applications, mapped to instances of device types connected with communication segments. The mapping model describes the application’s distribution across the devices.

The main design artifacts of IEC 61499 are Function Blocks or FB for short (as an example, see Figure 8), which have event and data interfaces. Input events are used to activate the execution of FBs that leads to an evaluation of the internal state machine called Execution Control Chart (ECC) (as an example, see Figure 9).

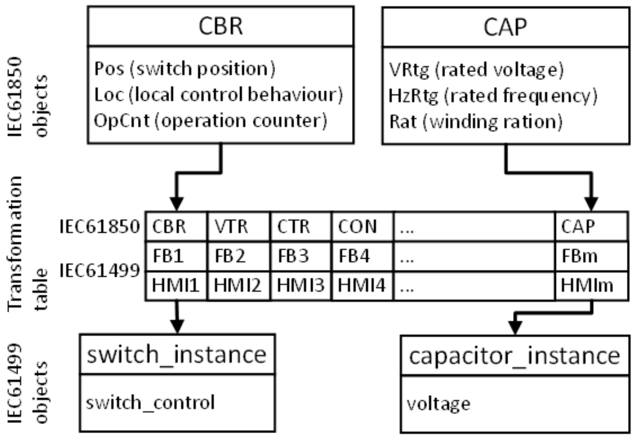


FIGURE 10. Transformation process from IEC 61850 to IEC 61499.

The Human-Machine Interface (HMI) is also an IEC 61499 standard-related tool, which is used for the generation of human-triggered events for the designed system of FB. With the help of an HMI, engineers can initiate the triggering process of input/output data of FBs.

VI. MODELING NOMENCLATURE, GENERATION FLOW, AND TRANSFORMATION STEPS DESCRIPTION

According to the structure of the proposed technical framework (Figure 7), the DT model of the datacentre power supply system consists of two parts:

1) SIMULINK-model of electrical equipment.
2) Control application over the simulated model (IEC 61499 based)

The model was tested with help of the software-in-the-loop (SiL) simulator. The automatically generated IEC 61499 control application was tested in a virtual PLC. The option of virtual simulation of IEC 61499 applications is supported by almost all IEC 61499 design environments, such as NxtStudio (from NxtCONTROL group) and EcoStruxure Automation Expert (from Schneider Electric).

A. GENERATION FLOW (IEC 61850 - IEC 61499)

As mentioned in Section V, an attractive benefit of the IEC 61850 standard is the catalog of logical objects associated with electrical objects. As well as electrical components' interconnection (as it is shown in Figure 4), a data centre power supply system can be also represented as several IEC 61850 objects (or LNs) connected to each other according to the electrical system diagram. At the same time, because the IEC 61499 standard is vendor independent and not biased to specific hardware topology, in theory, it is possible to design any IEC 61499 FB and assign it to IEC 61850 object. Therefore, in terms of an object-oriented approach that authors are going to represent in this work, where each IEC 61499 object can be represented as a *class*, inputs/outputs of FB are the *class variables*, and the input/output events are *functions* of classes. Based on this information, the authors developed a *translation table* that acts as a *bridge* between IEC 61850 LN and IEC 61499 FB.

```
1  // array_of_iec61850_objects - stack of all
2  // founded IEC61850 logical nodes
3  // it is already pre initialized at this step
4
5  accum_array = null
6  foreach object_1 in array_of_iec61850_objects begin
7    accum_array.add(object_1)
8    foreach object_2 in array_of_iec61850_objects begin
9      if object_1 != object_2 begin
10       if object_1.connection == object_2.connection begin
11         accum_array.add(object_2)
12       endif
13     endif
14   end
15   clear_similar_connection(accum_array)
16   create_simulink_connections_from_array(accum_array)
17   accum_array.clear()
18 end
```

FIGURE 11. Pseudo-code of the analysis of IEC 61850 components stack.

Due to the strictly defined names of LNs in IEC 61850, they can be uniquely identified. For brevity, Figure 10 shows the conversion of only some of the IEC 61850 LNs.

B. GENERATION FLOW (IEC 61850 - MATLAB)

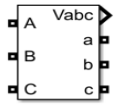
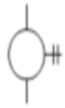
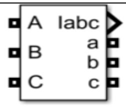
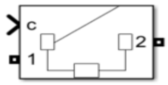
Another part of DT generation is related to the creation of the MATLAB/SIMULINK model. For each IEC 61850 object, the corresponding MATLAB/SIMULINK object is taken from the existing SIMULINK library (rightmost column shown in Table 2). The content of Table 2 is presented in the *Auto generation tool* (represented in Figure 6) as a transformation table (in the same way as implemented for the transformation to IEC 61499 FBs).

C. TRANSFORMATION STEPS (IEC 61850 - MATLAB)

The conversion procedure for MATLAB/SIMULINK Model generation consists of the following steps:

1) Read the "SCD" file and create an array of IEC 61850 objects (see Table 1) with the given properties.
2) Transform the array of IEC 61850 objects (obtained from the previous step) into SIMULINK objects (according to Table 2).
3) Create a new (blank) MATLAB model.
4) Place transformed SIMULINK objects from step 2 in the newly created model from step 3. MATLAB script is used for that.
5) Create connections between SIMULINK objects in the new model according to the "SCD" file. This process is based on working with a stack (or array) of IEC 61850 objects obtained in step 1. The array is analyzed according to the FIFO (First In - First Out) principle. The IEC 61850 stack analysis pseudo-code is shown in Figure 11. Here, the *accum_array* object, initialized in line 5, is a list of all objects that have similar connections. The algorithm compares the elements in the IEC 61850 array one by one (lines 6-14) and populates *accum_array* with new IEC 61850 objects (line 11).

TABLE 2. Transformation mapping table IEC 61850 - MATLAB/SIMULINK.

IEC 61850 object			SIMULINK object
Scheme designation	*IEC 61850 designation*	*Graphical view*	
VT1, VT2	VTR		 Three-Phase V Measurement
CT1	CTR		 Three-Phase I Measurement
CB1-CB4	CBR		 Breaker
LOAD	PSH		 Series RLC Branch

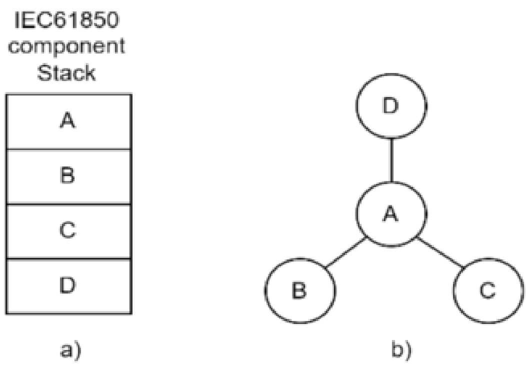


FIGURE 12. 'accum_array' stack (a) with a schematic representation of connections between objects (b).

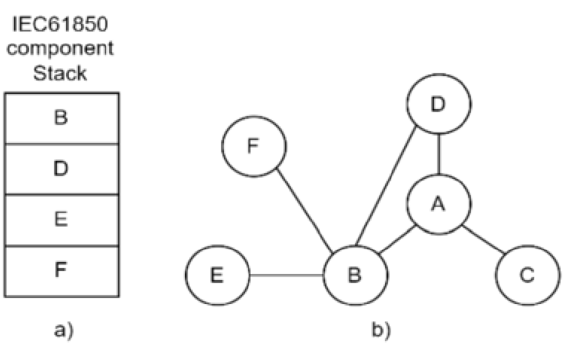


FIGURE 13. 'accum_array' stack (a) with a schematic representation of connections between objects (b) during the next iteration of the algorithm.

At the end of each "round" of analysis, any similar IEC 61850 connections found must be cleared to prevent an infinite loop (line 15).

The resulting *accum_array* (Figure 12, a) is the source for building SIMULINK connections (line 15 in Figure 11),

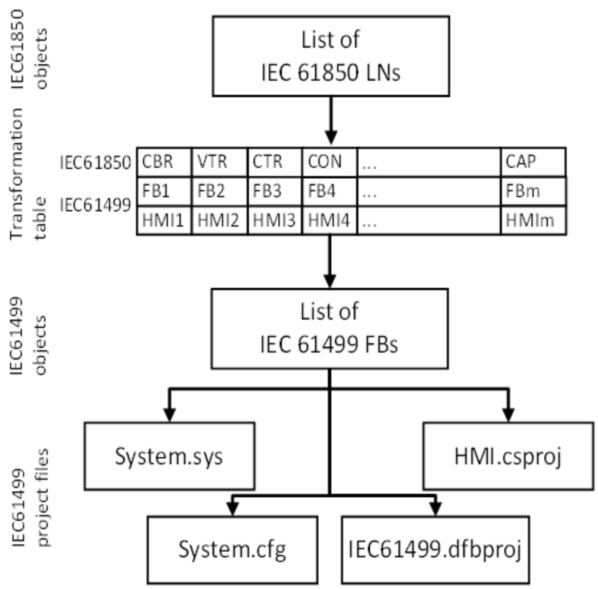


FIGURE 14. Generation flow of the IEC 61499 project files from the IEC 61850 stack.

where the connection structure is represented as a "star" with one central object and several rays around it (Figure 12, b). The first object in the list is always the center. Because each IEC 61850 object (or LN) can have $N >= 0$ connections, the same object can appear multiple times in the resulting *accum_array* stack. Let's imagine that the result of the next iteration of the IEC 61850 stack analysis is shown in Figure 13 (a). It means that the resulting wiring diagram for the SIMULINK objects is shown in Figure 13 (b).

One problem with converting IEC 61850 objects to MATLAB/SIMULINK objects is the lack of obvious identification of IEC 61850 object connections that MATLAB/SIMULINK objects have. As a result, the following

FIGURE 15. **The interface of the designed generation tool.**

TABLE 3. **List of transformation rules.**

N	Description
1	The maximum number of connection sides for *ALL* IEC 61850 and MATLAB/SIMULINK objects is 2 *(LEFT and RIGHT)*
2	*ONE* connection line in IEC 61850 results is *EQUAL TO* 1, 2, or 3 MATLAB/SIMULINK connection lines (depends on the MATLAB object type)
3	The contact numbering of SIMULINK and IEC 61850 objects as this: *LEFT-TOP* contact is the *FIRST*, the *RIGHT-BUTTOM* is the *LAST*
4	*ONLY TWO* objects are connected by a connection link
5	*IF 3 OR MORE* IEC 6150 objects are linked, the "primary" object, which is directly connected to all other objects (so-called "star" topology), will be *THE FIRST* item having that common communication line
6	The number of MATLAB/SIMULINK connections wires between two objects *IS EQUAL TO THE MINIMUM NUMBER OF PORTS* of 2 interconnected objects

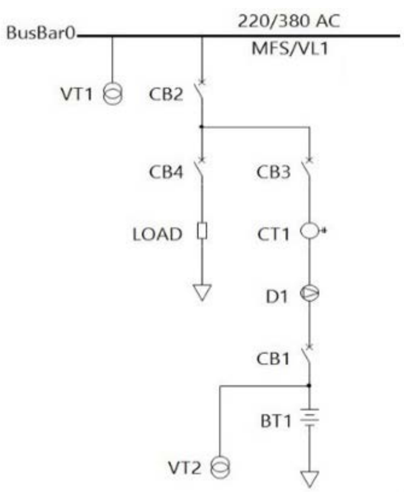


FIGURE 16. **IEC 61850 design of the electrical system (represented in the *Helinks* environment).**

rules were created to convert an IEC 61850 object to a MATLAB/SIMULINK object (see Table 3).

When the analysis of IEC 61850 objects is over, then the resulting schematic representation is saved in form of a MATLAB script (line 16 in Figure 11).

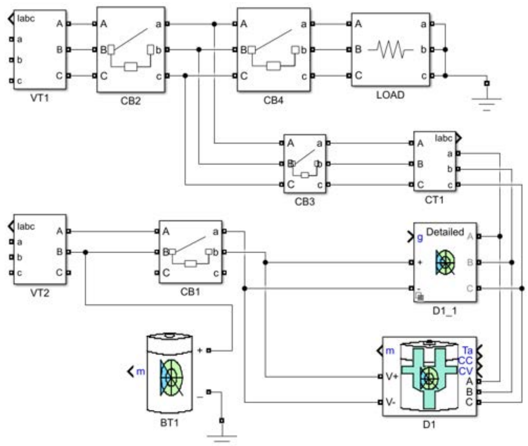


FIGURE 17. **Auto-generated SIMULINK model view.**

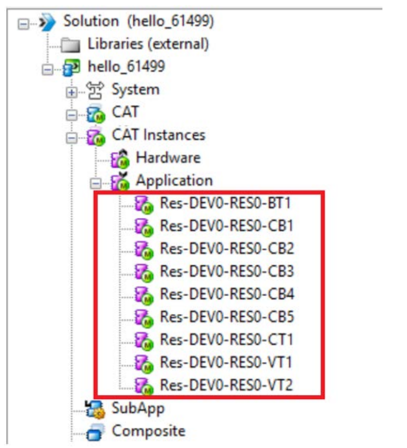


FIGURE 18. **IEC 61499 auto-generated project tree view.**

D. TRANSFORMATION STEPS (IEC 61850 - IEC 61499)

The auto-generation approach of transformation to IEC 61499 FBs is simpler than in the case of the SIMULINK model because the automation control applications have a different abstraction level. It means that it is not necessary (or even adverse) to have predefined connections between blocks of the system (as it is in the case of the SIMULINK model). Since IEC 61499 project files also have an XML (Extensible Markup Language) structure (like IEC 61850), the transformation process is reduced to generating a new IEC 61499

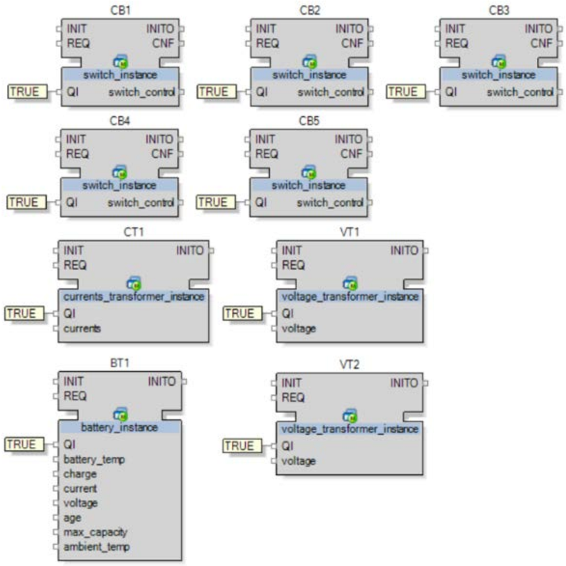


FIGURE 19. Auto-generated system of FBs.

draft and deploying the XML structures (of new FBs descriptions) in it. The schematic representation of that idea is presented in Figure 14.

TABLE 4. Comparison of existing solutions with the designed one.

existing solutions	Supported extensions				
	IEC 61850	IEC 61499	IEC 61970	OPC UA	MATLAB
This work	V	V	-	-	V
[15]–[17]	V	V	-	-	-
[19], [20]	V	-	-	V	-
[21]	V	-	V	-	-

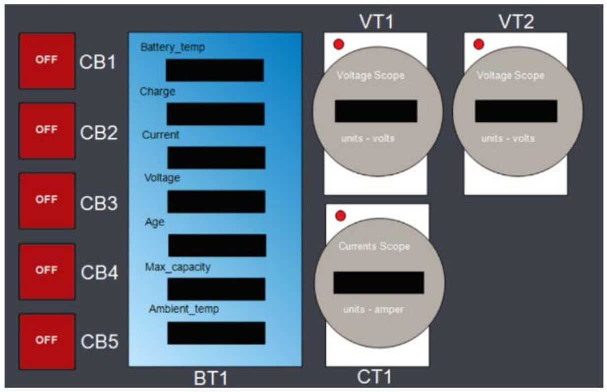


FIGURE 20. Auto-generated HMI.

VII. TOOL DESCRIPTION AND RESULTS

A. DESIGN OF THE PROGRAMMING TOOL

To implement generation based on the principles presented in this paper, a software tool was developed. The interface of the tool is shown in Figure 15. It has two tabs for previewing the generated results (from left to right): the XML structure of the loaded IEC 61850 "SCD" file, and the generated MATLAB script of the electric charging station model. To generate a new IEC 61499 project the user needs to go to *File - Generate IEC 61499 project*.

B. TESTING AND RESULTS

The electrical scheme of an emergency power system of the data centre (see Figure 4) was taken as an example for a demonstration of the results. The same scheme was recreated in the IEC 61850 compliant design environment *Helinks* (see Figure 16). The authors would like again to highlight that the proposed electrical system under investigation is taken for demonstration purposes only. It is very simplified and cannot be applied directly to some real-life hardware. The electric schema of the system shown in Figure 3 has been created in *Helinks* environment and the "SCD" file needed for the initial transformation process has been generated.

Once the IEC 6180 project has been developed and the project's "SCD" file has been generated, it's time to load this file into the developed application and generate a new MATLAB model corresponding to this IEC 61499 project with the control application inside. The result of auto-generation is presented in Figures 17 - 20. Auto-generated MATLAB/SIMULINK model is represented in Figure 17. From Figure 17 it is possible to assume that with help of transformation tables (Figures 10 and 14) and rules (see Table 3) the electrical scheme of the identical topology was successfully generated. Connections between components are routed correctly, and all components' names are transferred properly.

A view of the auto-generated IEC 61499 project structure is presented in Figure 18. Here it can be seen that the designed IEC 61499 project already includes an application with several precompiled instances. Names of these instances are replicated names of blocks defined during the IEC 61850 electrical scheme design (see Figure 16). It is worth noting that for demonstration purposes, only 4 IEC 61850 LNs has been added to the transformation table of the designed application (see Figure 14), and therefore only 4 different types of IEC 61499 instances have been auto-generated (they are presented in Figure 18).

The automatically generated IEC 61499 structure of FBs is presented in Figure 19. Though this system of FBs is considered as not complete and cannot be directly used, a big part of the manual work for FBs design and their internal configuration has been done automatically, which already saves enough time. The HMI view is shown in Figure 20. It has the same number of objects as in Figure 18 (instances) and Figure 19 (FBs).

The demonstration of automatically generated results now is finished. At this point, insignificant (from the time-cost point of view) and hardly specific information is needed from a designer to finalize both the MATLAB/SIMULINK model and the automatically generated IEC 61499 project.

Before summing up, the proposed approach is compared with existing solutions (Table 4) to highlight the value of ongoing work. As can be seen from Table 4, only the current research results confirm the possibility of converting the IEC 61850 electrical system model into a MATLAB model. This fact distinguishes the present study from other works.

VIII. CONCLUSION AND FUTURE WORK

In this paper, an approach was presented to convert the IEC 61850 system configuration project file of the data centre power supply system into the MATLAB/SIMULINK physical model and IEC 61499 control application. Specific transformation rules have been designed and integrated into the code.

Enterprises engaged in the maintenance and construction of electrical systems with a focus on reliability, reconfigurable computing, and automation can be considered potential stakeholders, as well as engineers and enterprises that are already working with the IEC 61850 standard.

The advantages of the presented work are as follows:

1) *It is compatible with IEC 61850 standard output files*. The developed approach is compatible with the IEC 61850 "SCD" file. This allows the output files of an IEC 61850 compliant tool (the *Helinks* environment in the case of this study) to be used as input files for another application (developed in this work).
2) *Reusing design files*. Reuse of already created IEC 61850 "SCD" files helps reduce the development time for new engineering solutions.
3) *The auto-generated IEC 61499 solution is vendor independent* and can be used for any device that supports IEC 61499.

The limitations include:

1) *The number of supported IEC 61850 objects is limited*. At this stage, only a subset of IEC 61850 existing objects is supported (as has been discussed in Section VII B).
2) *Not all IEC 61850 objects can be uniquely mapped to SIMULINK objects*. Most SIMULINK components have what is known as polarity (when an object has input and output pads), but this information is not specified in IEC 61850, so there is a risk of automatically generating a SIMULINK model that cannot be modeled at all, or the results will be incorrect. To minimize the risk of creating a new model incorrectly, the operator still needs to visually check the SIMULINK model itself and manually correct the model in case of inconsistencies.
3) *IEC 61850 component library limitation*. Although the IEC 61850 library has all the most important components for designing a simple mode charging station, it is still not enough in size even for a medium complex project. Currently, IEC 61850 has 91 LNs divided into 13 logical groups. Thus, the development of the IEC 61850 component library is vital to the further development of the approach presented in this article.

Auto-generation of the hardware-loop model of the electrical system for real-time simulators (such as OPAL-RT) is considered one of the possible directions for the development of this work. The proposed development will facilitate the process of commissioning the final design of IEC 61499 according to the developed electrical model topology before it is finally deployed in a real control system.

DISCLAIMER

The content and views expressed in this material are those of the authors and do not necessarily reflect the views or opinions of the ERA-Net SES initiative. Any reference given does not necessarily imply the endorsement by ERA-Net SES.

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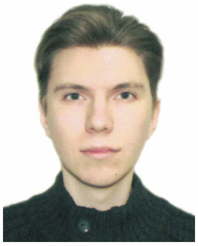

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