Towards Digital Transformation of Electrical Networks: from the Common Information Model - to the Heavyweight Ontology

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Abstract: Some prospects of digital development of electric networks in the context of their modeling and management based on lightweight and heavyweight ontologies are considered. The role of Common Information Model (CIM) in digital transformation during the transition from lightweight to heavyweight ontology is noted. The possibilities of heavyweight ontologies as rule systems for validating data models and domain models, as well as for planning and controlling operations in electrical networks are discussed.

1 INTRODUCTION

Power supply networks, covering all areas of the Earth's surface inhabited by humans, form geographically distributed systems of various scales, up to colossal in size and in terms of energy flows circulating in them. The coordinated functioning of the interconnected parts of these systems, ensuring their sustainable development is one of the tasks of the digital transformation of the electric power industry. Solving this problem requires continuous data exchange between subsystems on a growing scale. It should be based on integrated domain models, which are built as *ontologies* at the current level of digital modeling development.

Within the framework of the ontological approach, it is customary to distinguish between "lightweight ontology" and "heavyweight ontology" (Textor *et al.*, 2011). Lightweight ontology is a language for describing the concepts of a subject area, the vocabulary of which corresponds to a hierarchically ordered system of concepts. In heavyweight ontology, the behavior of domain objects and their management requirements are described by means of a system of rules (knowledge) (Yahya, 2021). A special part of the heavyweight ontology is the rules of validation of the ontology itself - both lightweight and heavyweight. They ensure the consistency of the ontology.

The article discusses some applications of heavyweight ontologies to ensure sustainable development and improve the management of power supply networks. The emphasis is on the content of ontologies - the languages of ontologies are not affected. Before presenting an ontology in a formal language, it is necessary to describe it in a meaningful way. For the ontologies of the electric power industry, this task is still far from a satisfactory solution.

2 ONTOLOGICAL APPROACH TO ELECTRIC GRID MANAGEMENT

2.1 On the Ontological Approach to Modeling

Ontology is a typical conceptual model for a variety of possible implementations of a domain (Gruber, 1995). It is expressed through general terms, without specifying objects and linking to specific situations. An individual object or situation may appear in an ontology if they are unique in the subject area.

Ontology can be represented by a conceptual graph, whose nodes represent concepts, edges represent relations between concepts. This graph can be called an ontology graph. If the set of ontology

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concepts is ordered hierarchically by levels of generalization, then this hierarchy will be a lightweight ontology of the modeled domain. It will be represented by an acyclic oriented graph.

The general purpose of modeling technical systems is to manage them. To describe the production technology and solve management problems, it is not enough to use only a lightweight ontology. Lightweight ontology is only part of the ontological model. In management tasks, this part is auxiliary, it supports the application of heavyweight ontology.

2.2 CIM in the Electric Power Industry: Between a Lightweight Ontology and a Heavyweight One

In the electric power industry, a lightweight ontology is implemented through the Common Information Model (CIM). CIM is constructed as a hierarchy of general concepts (classes), with their attributes. In addition, CIM contains associations - binary relationships between classes and between class objects. However, a heavyweight ontology should use not only binary relations, but also relationships of any arity. The implementation of the latter is possible on the basis of binary relations by constructing conceptual graphs of n-ary predicates.

The widespread introduction of CIM is one of the main trends of the current stage of development of the electric power industry. CIM makes it possible to unify data exchange for the management of power grids. However, the prospects for digital transformation in the electric power industry cannot be reduced only to this. Data unification serves to provide complete and high-quality information to technological applications. And heavyweight ontologies play a key role in improving these applications themselves.

2.3 Applications of Heavyweight Ontology to Model Validation

2.3.1 Structural and Semantic Validation of Domain Models

The transformation of the information space of the electric power industry to uniform CIM standards requires ensuring compliance with these standards of information from different energy companies. Ensuring the consistency and completeness of information is called its *validation*. Various methods of validation of digital models are implemented on the basis of appropriate rule systems. Each validation rule expresses a certain restriction on the content of information. The set of model validation rule systems forms an important part of the heavyweight ontology of the electric power industry.

In the simplest cases, validation detects if the parameter value goes beyond the allowed set. For example:

- non-existent (in the specified namespace) name of the class, attribute, association;
- impossible value of a physical parameter;
- dispatcher name of the device that is not in the dictionary;
- non-existent brand of the product;
- non-existent name of the owner of the assets, etc.

Semantic validation also controls combinations of object attribute values. Deeper validation controls semantic consistency between technological models, i.e. their structure. Let's consider an example illustrating the danger of a discrepancy in the methods of constructing technological models.

According to (IEC 61970-301, n.d.), objects of the CIM class of power equipment *ConductingEquipment* (bus sections, power lines, power transformers, switching operations, etc.) are connected to each other by means of objects of the *ConnectivityNode* class. In this case, an object of the *Terminal* class must be placed between the node of the power device and the connecting node. Suppose there is a *BS* bus section described in the model as an object of the *BusbarSection* class, which is a subclass of the *ConductingEquipment* class. Suppose that it is required to build a model of attachments of power transmission lines and transformers to this bus section in accordance with CIM standards. The CIM language allows you to build such a model in two ways. In the first variant, all attachments to the *BS* object are connected to it by means of a single node - an object of the *ConnectivityNode* class. This node connects to *BS* via a single *Terminal* class object. In the second variant, each attachments is connected to the *BS* bus via its *ConnectivityNode* class node, separately from other attachments. An object of the *Terminal* class is inserted between each of these *ConnectivityNode* objects and the *BS* bus section. In this case, as many objects of the *Terminal* class will be connected to the *BS* object and through them as many objects of the *ConnectivityNode* class as there are attachments to the BS bus section.

Suppose there are two companies developing software for managing power grids, and one company uses the first method of CIM-description of bus attachments, the other company uses the second method. Both developers follow CIM standards, however, applications created by one developer will

incorrectly process information received from applications created by another developer. This will mean the collapse of data unification by means of CIM.

Other examples of this kind can be given. They lead to the conclusion: it is necessary to standardize and control not only data models, but also structural and semantic models of the subject area. In relation to the above example, deeper standardization will mean choosing and adopting as a standard only one of the possible ways to model bus attachments in the CIM standard. When validating specific digital models, their fragments should be automatically checked for compliance with standard configurations.

The considered tasks relate to the field of model validation, which can be called *structural and semantic*. One of its types is also the control of associations. It consists in checking the validity of references of some objects to others in accordance with the definitions of associations between the CIM classes of these objects. This is the control of pairwise attachments of objects, but in general it is insufficient for structural validation of models. As the example above shows, more complex shapes composed of objects of different classes should be controlled. This control is mainly reduced to analyzing the topology of graphs whose vertices represent objects of classes, edges are associations between objects (Golovinskii et al., 2019). Methods for analyzing the topology of such graphs are described in (Golovinskii, 2001; Golovinskii, 2005; Golovinskii et al., 2019) as calculations in a special graph algebra.

2.3.2 Technological Validation of Models

Structural and semantic validation of digital models serves to coordinate data models between participants of information exchange. But the standardization of data formats and structures in the exchange of data between the components of the information environment does not yet fully ensure the information compatibility of the components. Technological knowledge and models of production processes also require coordination between components.. At the same time, the need to unify the rules of domain modeling faces the problem of technology variability. The development and complication of technological processes in power systems changes and complicates the content of technological models. This necessitates the creation of a mechanism for interfacing data transmission with components of the information environment that is more flexible than the one currently implemented on the basis of CIM.

The idea of such a mechanism is to build an ontological model of the entire information environment using CIM, covering not only information, but also software and hardware components and their complexes (Textor *et al.*, 2011). CIM classes created for the electric power industry must be consistent with the available automated technologies, with the application software used in them. This coordination will be called *technological validation* of CIM models.

While CIM developers create new classes, it is not always easy for practical engineers to establish the relationship of the latter with actually functioning industrial technologies. Engineers are more familiar with the style of thinking in categories of tasks, whereas CIM represents an approach focused on the hierarchy of concepts. From the point of view of the object-oriented approach (OOA), tasks are secondary to concepts and objects.

Nevertheless, OOA also allows you to model task systems. An example of how this feature is used in programming is Windows Management Instrumentation (WMI) technology. It is designed for centralized control and management of various parts of the computer infrastructure in the Windows environment. It is a unified and extensible system of access interfaces to any devices and applications that operate under Windows. WMI is based on CIM: all operating environment data is represented in WMI as class objects, with their properties and methods.

Something similar can be organized for the technological validation of digital models of the information environment of the electric power industry. Let's start by describing the components of the application software using CIM classes. We will consider it as the primary level of technological validation of semantic models of electric power equipment. This validation level will be implemented by matching these models with the components of the applied software. Software modules from different developers performing the same functions will be described as objects of the same class. For example, dispatch control systems use different steady-state calculation modules. We will describe all of them as objects of the same class. Let's call this class, say, *Flow*. In another class, we will combine programs for calculating short-circuit currents. Let's call this class of modules, for example, *ShortCircuit*. We will do the same with all other application programs. The set of attributes in the description of the software module will be its "passport".

By means of associations, we describe the attachments of classes of software modules with classes of equipment. They will determine the

framework for the composition of input and output information for software modules. According to them, the compliance of the introduced new classes with existing technologies will be monitored. This control can be automatic. However, for the same set of equipment, different calculation modules can use different calculation schemes. Therefore, in the general case, associations between software modules and equipmnt need to be determined not directly, but through intermediate objects of calculation scheme classes.

Having built classes of software modules and their calculation schemes, as well as their necessary associations, we will be able to know for each class of equipment which software modules are associated with information about this equipment – use it at the input or form it at the output.

Next, we will build higher levels in the hierarchy of components of technological control systems. For example, a Distribution Management System (DMS) solves a certain set of tasks. Different DMS instances solve the same application tasks, but different software modules can be used for the same task in different DMS. Let's define the DMS class as a container class whose objects contain sets of program modules of classes *Flow*, *ShortCircuit*, etc. We will create similar classes for the Energy Management System (EMS), Outage Management System (OMS) and other dispatching control subsystems. In combination with the classes of software modules described above, we will be able for each class of power equipment to know in which subsystems of technological control (process control systems) information about objects of this class of equipment is used.

We will build similar technological models for other automated systems operated in the industry. This will allow you to automatically identify, for example, redundant classes of equipment. When a software module becomes obsolete and is decommissioned, the CIM data from the hardware description model that was used by this module may be superfluous. It is necessary to check whether their use by other software modules continues. Without special automated support tools, such verification is difficult. The proposed method of CIM modeling the composition of the applied software used will allow it to be automated.

2.4 Ontology of technological management of electric networks

The general principle of the rules of heavyweight ontology can already be found in the ancient Roman theorist and teacher of eloquence Marcus Fabius Quintilianus. He owns the saying: Every law either gives, or takes away, or punishes, or commands, or forbids, or permits. More often, this thesis is quoted abbreviated: Every law either commands, or forbids. In such a brief form, Quintilian's formulation clearly indicates two types of rules to which the heavyweight ontology of operational (real-time) control of electrical networks is reduced. These are *rules-prescriptions* of operations and *rules for operation interlocks*.

2.4.1 Operation Interlocks

Numerous switching operations are made in the power grid to bring the equipment into repair, to put it into operation after repair, to restore power supply to consumers after an accident and for other purposes. At the same time, at any moment, including during switching operations, each power device that is energized must be reliably protected by relay protections. Therefore, switching operations on power devices in a working circuit are always accompanied by switching operations on secondary devices – main and backup protections, measuring transformers, automatic switching of the reserve, etc. As a result, switching procedures often become very complicated. These complications increase the probability of personnel errors during operations, which can cause damage to equipment and loss of life. To reduce such risks, a system of various interlocking of the wrong operations is used.

The most dangerous operations are those that can cause an accident directly during their execution – short circuit, explosion, fire, etc. Less dangerous are operations that do not lead to an immediate accident, but bring it closer, reducing the safety margin of the circuit, its reliability. Such operations should be blocked too.

The requirements for interlocks are presented in general form in the regulatory and technical documentation on the design and operation of electrical networks - for example, in (PJSC Rosseti, 2020). Each type of interlocking is described by the corresponding generic rule. These rules represent the second part of Quintilian's thesis: "the law forbids". They indicate not individual devices, but only device types and relationships between them.. An example of such a rule: "«It is not allowed to turn on the disconnector when the adjacent breaker is closed”.". The device on which the intended operation should be performed can be called the main one in the rule. The other devices in the rule are defined as being in a certain relationship to the main device.

To verify the admissibility of the intended operation, each generic interlocking rule applicable to it must be concretized. According to the concretized main device, the other devices mentioned in the rule should be concretized as well. The permission for the operation or its lock depends on the state of these devices. The interlocking rule describes those combinations of their state parameters that forbid the execution of the operation.

If necessary, the simulation model also calculates the values of the device state parameters that should occur immediately after the operation. Certain combinations of values are also checked for them, and if the combination turns out to be forbidden, the operation is locked.

Historically, the simplest concretized interlocks were performed by hardware, for example, interlocking disconnectors with adjacent grounding devices and breakers. These interlocking schemes are mechanical, electromechanical, electromagnetic and key-transfer. Logically complex locks cannot be implemented by such means. They were described in the instructions for the operational personnel of energy enterprises, to which their application was assigned.

The described ontological representation of interlocks opens the way for digital substations to fully automate any interlocks. The main difficulty here lies in constructing logically complete definitions of the relationship between the main device in the interlocking rule and the other devices mentioned in it. The interlocking rules concretizing is based on these definitions (see (Golovinskii, 2016; Golovinskii et al., 2019)).

The implementation of a system of interlocking rules is facilitated by the fact that one such rule usually does not depend on the others. Thanks to this, the interlocking system can be built up gradually by adding locks one by one in any order. On the other hand, the general interlocking rules restrain each operation independently from the other operations, regardless of the control task being solved. As a result, they may allow needless operations that do not lead to the purpose of switching, unless these operations are not dangerous for people and equipment. To overcome this disadvantage, another kind of interlocking rules can be used - prohibitions of «needless», «aimless» operations. They filter operations in accordance with a given strategy for solving the control task.

2.4.2 Scenarios for Switching Operations

The interlocking rules regulate the switching technology indirectly. They indicate what should not be done, but they do not say what should be done to achieve the goal of a particular management task. The optimal solution to the switching problem is difficult to find, based only on the interlocking rules.

Since the switching operations on power switching devices must be accompanied by switching operations in secondary circuits and numerous verification operations, complex switching procedures arise, which can contain up to one and a half hundred operations or more. The regulatory and technical documentation for the electric power industry provides generic sequences of operations for all major types of switching tasks (Rosstandart, 2014). These generic sequences can be called *switching scenarios*. Some energy companies also independently develop their switching scenarios taking into account local conditions.

The switching scenario consists of two parts: a description of the initial situation and a list of commands. The first part specifies the type of the main device of the switching procedure (power line, transformer, bus section, switch, protection device, etc.), the type of work (output of the main device for repair, commissioning after repair, switching to other power sources, etc.) and the position of the switching devices. The second part lists the operations that need to be performed in the specified order on devices that have one or another relation to the main device.

The system of switching scenarios is an important part of the heavyweight ontology of electric grid management. The general structure of any scenario can be described by a rule of the form

$$T \rightarrow C_1, C_2, \ldots, C_n ,$$

where T is the first part of the scenario that formulates the switching problem, C_1, C_2, ..., C_n is a list of descriptions of operations for solving this problem. The devices on which operations are performed are not fully specified in the descriptions of operations. For each device, only its type and relation to the main device are specified.

Drawing up a plan for solving a given switching task to which the scenario relates consists in concretizing the latter. To do this, a concrete main device of the scenario is set, and all other devices on which operations should be performed are determined by it. This concretizing is still performed manually, although the task of automating it was set back in the 1970s. Automation should reduce the complexity and

timing of making switching plans, which is especially critical in emergency situations. However, this task has not yet received a satisfactory practical solution. The main obstacle was the lack of elaboration, insufficient formalization of the heavyweight ontology of switching control. It is especially important in each generic switching task to formalize the relationship of the devices involved in the operations to the main device of the task. But this formalization was not carried out at the proper level.

2.4.3 Ontology of Automatics

In addition to switching scenarios, another type of ontological rules-prescriptions in the operational and technological management of power grids is formed by rules describing the operation of automatic devices - measurement, protection, signaling, etc. Initially, these devices were created on the basis of relay and switching circuits, then on the basis of microcontrollers. The mathematical model of such a device is a finite state machine. This is a logic circuit with memory that perceives input signals, changes the contents of its memory (the state of the automaton) under their impacts and generates output signals. The response of this device to the input signals depends on its state. Thus, a finite automaton A is defined by a pair of functions

$$s' = \varphi(i,s) \quad \text{and} \quad o = \psi(i,s)\,, \qquad (1)$$

where i is the input signal, s is the state of the automaton A before the signal i arrives, $\varphi(i,s)$ is the state-transition function of the automaton, $\psi(i,s)$ is the output function of the automaton, s' is the new state of the automaton A after it is triggered by the input signal i, o is the output signal.

The input signals arrive at the input of the automaton A at discrete time points. The sets of states and output signals of automaton A are also discrete. Therefore, formulas (1) can be written as a pair of generic rules

$$\varphi(i,s) \to s' \quad \text{and} \quad \psi(i,s) \to o\,.$$

To simulate a real automatic device, it is necessary to concretize the state-transition function φ and the output function ψ. Concretizψing the pair (i,s) specifies the device triggering event.

Thus, the operation of the automation of the electrical network is modeled in a heavyweight ontology by a system of rules. These rules-prescriptions, as well as switching scenarios, are covered by the first part of Quintilian's thesis: "the law commands".

2.5 On the Calculation of Parts of Ontologies

To apply ontologies, it is necessary not only to present knowledge in a formalized form, but also to manage it: to search for it, analyze it, and transform it. Examples of such operations are:

- folding (contraction) of the model into a more general model;
- deploying the model into a more detailed model;
- coupling of heterogeneous models;
- logical inference on rule systems; etc.

To solve various problems of this kind, a uniform approach is possible, based on the representation of ontologies by conceptual graphs and graph calculation operations by means of special algebra. This algebra and its applications are described in (Golovinskii, 2001; Golovinskii, 2005; Golovinskii, 2016; Golovinskii et al., 2019).

3 CONCLUSIONS

The content of the current stage of digital transformation of the electric power industry is the unification of data exchange in the Common Information Model (CIM) standard. From the point of view of the overall goals of digital transformation, this unification is an intermediate task. It improves the quality of modeling and management of electric power systems, which should ensure:

- increased reliability of their operation;
- improvement the quality of electricity supply to consumers;
- reduction of environmental loads on the biosphere;
- reduction of the role of fossil fuels in the energy balance.

The ontological approach plays a key role in shaping conceptual framework for the digital transformation of the electric power industry. The ontology of the electric power industry, like of any subject area, is divided into lightweight and heavyweight. The lightweight ontology describes the composition and structure of the production assets of the electric power industry. Heavyweight ontology accumulates knowledge about the functioning of electric power systems and their management. The implementation of a lightweight ontology is provided by CIM. The widespread introduction of heavyweight ontology is an urgent and promising task.

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