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EDITED BY
Wei Xi,
China Southern Power Grid, China

REVIEWED BY
Jinsong Bao,
Donghua University, China
Rufeng Zhang,
Northeast Electric Power University, China

*CORRESPONDENCE
Fengzhang Luo,
luofengzhang@tju.edu.cn

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Ontology modeling method applied in simulation modeling of distribution network time series operation

Fengzhang Luo[1]*, Shaoting Feng[1], Yang Yang[2], Zhiqi Ao[2], Xueling Li[2] and Yanxin Chai[2]

[1]Key Laboratory of Smart Grid of Ministry of Education, Tianjin University, Tianjin, China, [2]Digital Grid Research Institute of China Southern Power Grid, Guangzhou, Guangdong, China

Aiming at the difficulties in the realization of timing simulation in the digital twin environment, this article proposes an ontology modeling method applied to the simulation modeling of distribution network timing series operation. First, the two-layer ontology modeling architecture is introduced, and the power system domain structure ontology and the business-based application ontology are constructed. Second, based on the dynamic ontology modeling method, combined with the operational simulation business requirements, the sequential operation simulation ontology model is dynamically constructed. Finally, the effects of the modeling method in terms of simulation expression and modeling efficiency are shown through practical application example, and the modeling methods are compared and analyzed. The results provide a reference for the technical realization of power grid modeling in digital twin environments.

KEYWORDS

ontology modeling, time-series operation simulation, distribution network planning, digital twin, electric power grid modeling

1 Introduction

The "Fourth Industrial Revolution" represented by digital technology is accelerating, leading to great changes in global production modes and organizational methods (Pu et al., 2021). At the same time, the large-scale access to new energy and power electronic equipment in the future will lead to an explosion of power grid data, which will be driving the digital transformation of the power grid around the world. As a bridge connecting the physical real world and digital virtual space (Grieves, 2005; Tuegel et al., 2011), the digital twin technology enhances the self-perception, decision-making, and evolution capabilities of a power grid through modeling, simulation, and manipulation in virtual space, which can effectively support the data-driven digital twin research and various digital operations (Snijders et al., 2020; Zhang et al., 2020). The real-time calculation and analysis capabilities of digital twins can strengthen our understanding of the current and planned states of the power grid and improve the decision-making of operation and planning (Nguyen et al., 2021). It can be said that the construction of the power digital twin is an effective way to realize digital power grid and promote the construction of smart power grid (He et al., 2020; Wang et al., 2021).

The electric power digital twin needs to realize the real-time mapping of the action, behavior, and state of the real system, which depends on the support of the ability to collect, integrate, and share massive data and information accumulated by different systems. However, most of the data management systems are independent of each other, the degree of data reuse between systems is low, and the business systems are still centered on each other. As a result, the application system development always starts from scratch and directly analyzes and processes the original data. Obviously, this kind of application system construction mode is slow and inefficient, and it cannot meet the fast and real-time requirements of the digital twin. In order to realize the rapid response to the application system requirements under the digital twin environment, it is necessary to integrate the general capabilities of each system and improve the efficiency of business implementation.

Most of the existing modeling techniques are static-level modeling, and the static-level description modeling cannot be connected with the dynamic application logic and lack real-time interaction with the environment. Therefore, in addition to the static model, a dynamic simulation model at the mechanism level should be constructed to realize the presentation and interaction of high-fidelity digital twins. As a knowledge modeling method, ontology modeling has a strong semantic expression ability that can effectively realize the standardization and normalization of terminologies and improve the sharing of data, which is the basis for realizing data normalization. At the same time, the ontology model can contain both parts of the mechanism level and parts of the application level, which also makes it possible to integrate the domain knowledge representation and software application logic (Pradeep et al., 2021). Existing modeling techniques usually start modeling and software programming after a specific application requirement is proposed, and the same application requirement between different systems also needs to be re-modeled again and again. The problem of repetitive modeling can be solved by using ontology modeling technology. For the same application requirement, only one ontology model needs to be constructed, and different systems can be expanded on the basis of the constructed ontology model and configured using a separate configuration tool (Pradeep et al., 2021). In other words, ontology modeling can realize application-oriented modeling.

After the concept of ontology was put forward, it has been widely applied in the computer field (Musavi and Hashemi, 2019; Morales and Melgar, 2017). The advantages of ontology modeling mentioned previously make it possible to apply the modeling ontology method in the electric power digital twins' construction in recent years (Hippolyte et al., 2016; Massel and Massel, 2021). Massel and Massel (2021) proposed the ontology approach for constructing power digital twins. Fragments of the ontology system used in the development of a digital twin of a solar power plant are given in Massel and Vorozhtsova (2020) and Massel and Massel (2020). Ravikumar et al. (2018) presented process ontology along with a systematic methodology for building process models of end-to-end process operations of power utility. Hippolyte et al. (2016) implemented a general intelligent energy framework through a multi-agent system and semantic web ontology. Teixeira et al. (2020) introduced Tools Control Center's application ontology, which can support the interoperability among the different considered systems. In China, ontology-based information modeling has been applied in the common information model (CIM) (Xie et al., 2008; Xie et al., 2007), especially in data management (Huang and Diao, 2008; Zhang et al., 2011; Huang and Zhou, 2014), safety monitoring (Yu et al., 2020), energy management (Liang et al., 2009; Hippolyte et al., 2016), and other aspects. These research studies have shown the advantages of ontology in realizing data standardization and interoperability. However, most of these research studies are based on static ontology models, which cannot be applied to describe the dynamic evolution process of the real power grid. The dynamic mechanism model contained in the ontology model can be fully utilized to describe the dynamic operation process of the power grid. Coupled with the interoperability of ontology, it is possible to integrate applications at syntactic and semantic levels between different systems. In other words, new applications can be developed faster according to specification requirements, allowing solutions to be configured according to specific requirements.

Aiming at the difficulty of lack of information sharing among systems, low efficiency of system development, and high time cost, this article proposes an ontology modeling method applied in simulation modeling of the time series operation of the distribution network. First, the two-layer ontology modeling architecture is introduced, and the power system domain structure ontology and the business-based application ontology are constructed. Second, based on the dynamic ontology modeling method, combined with the operational simulation business requirements, the sequential operation simulation ontology model is dynamically constructed. Finally, an example is given to demonstrate the effectiveness of the ontology modeling method in terms of simulation expression and modeling efficiency, and the modeling methods are compared and analyzed. The results provide a reference for the realization of the power grid modeling technology under digital twin environment.

The remaining part of this article is organized as follows: The basic concepts and related theoretical models and structure of ontology are introduced in Section 2. The two-layer ontology modeling method is introduced, and the time-series operation simulation ontology model is dynamically constructed in Section 3. Case studies are provided in Section 4. Section 5 gives the conclusions of this article.

2 Basis of the ontology modeling method

2.1 Ontology concept

The concept of ontology was originally proposed in the field of philosophy to study the essence of existence and the theoretical definition of objective objects. Later, with the development of artificial intelligence, ontology was gradually applied in the computer field, and experts have been studying its definition all the time. The current definition with a high degree of acceptance is proposed by the German scholar Studer et al. in 1998: "An ontology is an explicit specification of a conceptualization" (Studer et al., 1998). The definition contains four elements: shareability, conceptualization, explicitness, and formalization of ontology. Ontology construction is a complex system engineering, which often needs the cooperation of domain experts, requirement analysts, and system analysts, according to certain methods and appropriate tools.

Perez et al. used taxonomy to organize ontology and summarized five basic modeling primitives (Gomez-Perez and Corcho, 2002): class (concept), relation, function, axioms, and instance.

1) Class (or concept) describes the common characteristics of a class of transactions. Semantically, it represents a collection of objects, which corresponds to the linguistic description of concepts.
2) Relation represents the interaction between concepts in a domain.
3) Function describes the mapping between concepts in the domain, which is a special kind of relationship.
4) Axioms are expressed as assertion.
5) Instance refers to the basic element of a concept class. From a semantic point of view, an instance is an object represented.

2.2 Fundamental relation of ontology

There are four basic relationships between ontology concepts: the classification relationship (kind-of), composition relationship (part-of), attribute relationship (attribute-of), and instance relationship (instance-of).

1) Kind-of: indicates the parent–child relationship between the concepts of A and B. For example, the subcategories of power plants include thermal power plants, hydropower plants, and wind farms, and they are all classified as "power plants."
2) Part-of: refers to the relationship between the whole part or global part between the concepts of A and B. For example, a wind turbine is composed of an engine room, wind wheel, a shaft, etc., and they constitute a compositional relationship with the "wind turbine."

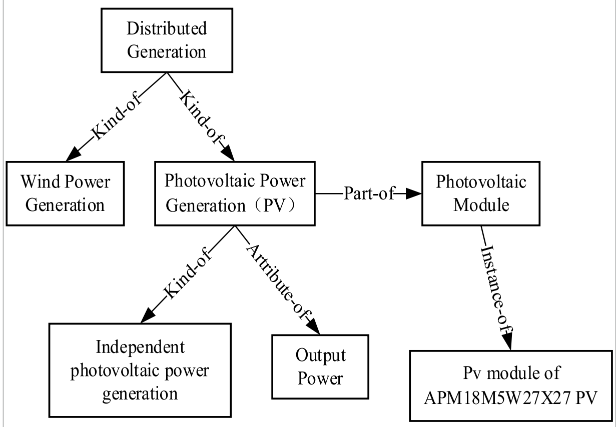

FIGURE 1
Sample diagram of distributed power supply ontology.

3) Attribute-of: attribute refers to the inherent properties of a thing, an inevitable, basic, inseparable characteristic of a thing, or the qualitative expression of a certain aspect of a thing. Two classes with this relationship represent that one class is a property or characteristic of the other class. Common attribute relationships in the field of the power system include the following:

i Inherent attribute, which describes the physical quantities and related physical properties of the object, such as the rated voltage, current, and capacity of the transformer.

ii Electrical properties, such as the schematic diagram of wind power generation and equivalent circuit.

iii Data attributes, such as static data on each element of the power grid, all kinds of parameter data, and output curve data on each power supply unit.

iv Related concepts, such as the operation mode, wiring mode, and fault type.

4) Instance-of: indicates that concept A is an instance of B, such as the SFPZ9-12000/110 transformer is an instance of transformers, and they constitute an instance relation.

A sample of distributed generation ontology is shown in Figure 1. "Distributed generation" has a classification relationship with "wind power generation" and "photovoltaic generation," that is, "wind power generation" and "photovoltaic generation" are both a kind of "distributed generation." "Output power" and "photovoltaic generation" constitute an attribute relationship, that is, "photovoltaic output power" is an attribute of "photovoltaic generation." "Photovoltaic module" and "photovoltaic power generation" constitute a composition relationship, that is, "photovoltaic module" is one of the components of "photovoltaic power generation". Also, the

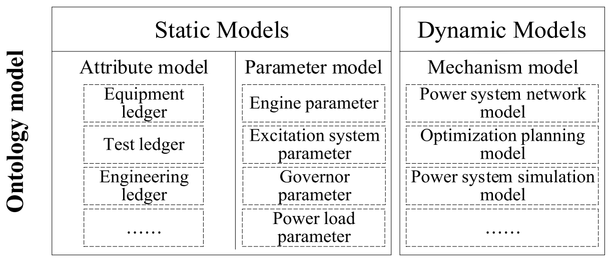

FIGURE 2
Ontology model structure.

"PV module of APM18M5W27 × 27" is an instance of a "photovoltaic module".

2.3 Ontology model structure

The operation of the power grid is a real-time and dynamic process. Therefore, the ontology model needs to gather the entire static and dynamic information about the power grid and the environment. The ontology model based on the dynamic characteristics of the power system should encompass two parts, namely, a static model and a dynamic model, as shown in Figure 2.

The most essential information in the power system is static information represented by a static description of the system's operating environment. The static model includes a static ledger model and a static parameter model. This part includes various attribute models and parameter models in the system. The dynamic model plays a significant role in the power system, which enables the real-time characteristics of the system to respond quickly. The expression form of the dynamic model is usually represented by constraints and rules. During the operation of the power grid, the dynamic mechanism model can combine the static model of the ontology with the real physical entity to form a dynamic evolution ontology knowledge chain driven by the mechanism model. The dynamic models at the mechanism level of time-series operation simulation include the distributed generation model, power load model, power flow model, and power balance model as shown in Eqs 1–4.

2.3.1 Power flow model

$$\begin{cases} P_i(t) = V_i(t)\sum_{j\epsilon i} V_j(t)\left(G_{ij}\cos\theta_{ij} + B_{ij}\sin\theta_{ij}\right) \\ Q_i(t) = V_i(t)\sum_{j\epsilon i} V_j(t)\left(G_{ij}\sin\theta_{ij} - B_{ij}\cos\theta_{ij}\right) \end{cases} \quad (1)$$

where $P_i(t)$ and $Q_i(t)$ are the active power and reactive power injected into node i at time t; $V_i(t)$ is the voltage of the node i at time t; G_{ij} and B_{ij} are the real and imaginary components of the branch admittance matrix; and θ_{ij} is the voltage phase angle difference between nodes i and j.

2.3.2 Power balance model

$$P_{DG}(t) + P_{ESS}(t) + P(t) + P_{dr}(t) = P_{load}(t) \quad (2)$$

where $P_{DG}(t)$ is the output of the photovoltaic at time t; $P_{ESS}(t)$ is the output of the ESS at time t; $P(t)$ is the power provided by the upper power grid at time t; $P_{dr}(t)$ is the output of the controllable user at time t; and$P_{load}(t)$ is the load at time t.

2.3.3 Grid load model

$$\begin{cases} P_j^{load}(t) = P_{j,0}^{load}(t)\left(\alpha_j^A \frac{V_j^2(t)}{V_{j,0}^2} + \alpha_j^B \frac{V_j(t)}{V_{j,0}(t)} + \alpha_j^C\right) \\ Q_j^{load}(t) = Q_{j,0}^{load}(t)\left(\beta_j^A \frac{V_j^2(t)}{V_{j,0}^2(t)} + \beta_j^B \frac{V_j(t)}{V_{j,0}(t)} + \beta_j^C\right) \end{cases} \quad (3)$$

where $P_j^{load}(t)$ and $Q_j^{load}(t)$ are the active power and reactive power of the node j at time t; $P_{j,0}^{load}(t)$ and $Q_{j,0}^{load}(t)$ are the active and reactive power ratings of the node j at time t; $V_{j,0}(t)$ is the voltage rating of the node j at time t; α_j^A, α_j^B, and α_j^C are ZIP coefficients of constant impedance, constant current, and constant power load in the active power, respectively; and β_j^A, β_j^B; and β_j^C are ZIP coefficients of constant impedance, constant current, and constant power load in the reactive power, respectively.

2.3.4 Distributed photovoltaic model

$$P_{PV}(t) = I_r(t) \times P_{mpp} \times F_T \quad (4)$$

where $P_{PV}(t)$ is the output of the photovoltaic at time t; $I_r(t)$ is the irradiance at time t; $P_{mmp}(t)$ is the output of the photovoltaic array under unit irradiance at a certain temperature; and F_T is the output power coefficient.

3 Modeling method for the time-series operation simulation ontology model

Ontology modeling requires certain methods to support, for example, the skeleton method, TOVE method, IDEF5 method, seven-step method, etc. Most of these methods are proposed based on a specific project, whose versatility is poor, and the two key issues of ontology quality and consensus cannot be effectively resolved. The fact-oriented two-layer ontology modeling method introduced in the following section can effectively solve these two key issues (Pan, 2011).

3.1 Basic modeling method of ontology

This article uses natural language as a communication medium to construct domain ontology by enumerating and analyzing real facts and fact-related assertions in the domain. In natural language, a word or term contains a concept, and a concept is an abstraction of a certain class of objects, which are all instances of this concept. The set of all objects satisfying the natural language interpretation of a certain term is the space of possible instances of the concept referred to by the term. A fact indicates that an object has a certain property or a certain relationship among objects, so the fact type is an abstraction of a certain property of the same class or the same type of relationship existing among objects. From the perspective of natural language, domain ontology is composed of various concepts, fact types, and constraints related to the domain. The key of ontology modeling is to list all kinds of terms (concepts), propositions (facts), and assertions (constraints).

In the real world, all kinds of things are interconnected, and there is no completely independent object, that is, every object will be related to at least one fact. Therefore, if you want to find all the objects in the field, you only need to enumerate all the possible facts in the real world, and then, abstract the concepts, fact types, and constraints.

The structured pseudo-natural language sentences, called “fact templates,” can be employed to express fact types and constraints. For example, the fact that “the rated voltage level of a power grid is 10 kV” can be expressed as “the rated voltage level of [power grid] is [voltage level]."

The fact type expressed by the fact template not only preserves the natural language structure of the fact but also clearly explains the meaning of the fact type. It can be said that the fact template is the natural language interpretation of the fact type. By using the fact template as the bridge of communication, domain experts can better participate in ontology modeling activities and in the convenient cooperation among the modeling team, which can effectively improve the quality and application efficiency of ontology.

Based on the aforementioned introduction, one of the fact-oriented ontology modeling language called FOOL (Studer et al., 1998) is used for modeling in this article. The modeling language FOOL is constructed on the basis of ORM (object-role modeling), and the first-order logic is used to formalize semantic modeling, which is detailed in Pan (2011).

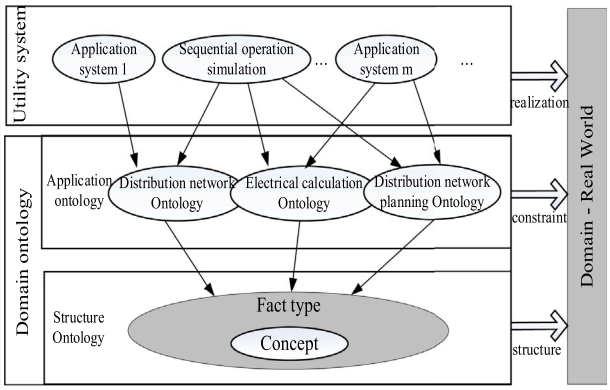

FIGURE 3
Two-layer ontology modeling system architecture.

3.2 Two-layer ontology modeling framework

Figure 3 shows the two-layer ontology modeling framework (Pan, 2011). The domain ontology is divided into one structure ontology and multiple application ontologies.

The structure ontology only contains the concepts and fact types related to the field, that is, the structure ontology of the power system has all the concepts and fact types related to the power system. The application ontology contains the relevant knowledge of a certain type of business application, including business-related concepts, fact types, and various constraints. Also, different application ontologies are independent of each other. The concept set in application ontology is a subset of structure ontology, which can be obtained by directly reusing a part of structure ontology.

In the two-layer ontology modeling framework, structure ontology and application ontology are modeled separately. The advantage of the two-layer modeling framework is that it enables domain experts and business personnel to reach consensus on ontology. It is conducive to establishing interoperability between different systems. In addition, modeling based on a two-layer modeling framework is beneficial to the application and promotion of ontology. The details are described in the following section.

Structure ontology modeling is carried out first; at this stage, there is no need to consider the constraints required to realize any business, so it is easier to obtain the consensus of the relevant personnel in the domain. After consensus is reached on the structure ontology, the application ontology of different types of businesses can be constructed. At this time, only the constraints of relevant business need to be considered, and domain-level knowledge need not be considered. At this stage, the application ontology is mainly for a corresponding business service, so it is easy to obtain the consensus of business-related personnel.

TABLE 1 Power system structure ontology.

Power system structure ontology

Concept		Fact type
Power system composition	[Power plant]	1) [Power system] is composed of the [power plant], [transmission grid], [distribution network], and [power user]. 2) [New energy] includes [wind power generation], [solar power generation], [tidal power generation], and [biomass power generation]. . .. . .
	[Transmission grid]	
	[Distribution network]	
	[Electricity users]	
New energy	[Wind power]	
	[Solar energy generation]	
	[Tidal power generation]	
	[Biomass power generation]	
	....	
Primary equipment	[Power generation assembly]	
	[Switchgear]	
	[Compensation equipment]	
	[Transformer]	
. .. . .		

Therefore, the two-layer modeling framework can effectively solve the problem that domain ontology is difficult to reach consensus. In this way, data messages and domain knowledge can be exchanged between different systems. Knowledge in the power system is accurately conceptualized by ontology modeling, which makes communication more effective by eliminating misunderstandings.

The power system structure ontology and the business ontology model based on the two-layer ontology modeling framework have strong universality and can generally obtain the consensus of domain experts and business experts. In the beginning, only structural ontology and application ontology that meet the requirements of existing applications need to be constructed. When there are new ontology application requirements, the domain structure ontology can be evolved according to the application requirements, and the corresponding application ontology can be developed, which is beneficial to the application and popularization of the ontology model.

The power system domain ontology is constructed based on the two-layer ontology modeling framework. First, the power system structure ontology containing only the domain knowledge is constructed. Structure ontology is a natural language to describe its related concepts and fact types, including all the concept knowledge in the power system and their relations. Table 1 shows the description form of part of the power system structure ontology constructed.

Then, to build application ontologies only related to business, the application ontologies are formed by describing their related application concepts, fact types, and constraints. Table 2 shows the description form of the application ontologies.

In this article, Protégé software is used to construct ontology model. Figure 4 and Figure 5 show partial examples of the power system structure ontology and the distribution network application ontology.

3.3 Time-series operation simulation ontology model

After constructing the structure ontology and application ontology, the time-series operation simulation ontology model can be constructed by the dynamic ontology construction method. The dynamic ontology construction method can be used to construct the ontology model according to the specific requirements. At present, the definition of dynamic ontology has not been unified. Liu et al. (2014) put forward the definition: dynamic ontology refers to a temporary ontology built on the basis of multiple domain ontologies, which is used to simplify knowledge requirements and form target knowledge resources. The dynamic ontology mentioned in this article is to build real-time applications based on user needs and domain ontology resources.

The steps of dynamic ontology modeling are shown in Figure 6, which mainly includes five steps (Zhou et al., 2014).

According to the specific application requirements proposed by users, this method matches the required parts from several constructed application ontologies. Then, they carry out the application ontology resource integration work. Therefore, it is not necessary to start ontology construction from scratch for different requirements but only need to build temporary ontologies based on the constructed ontology resources, which

TABLE 2 Application ontologies.

Distribution network application ontology		
Concept		**Fact type**
Composition of the distribution network	[Overhead line] [Cable] [Distribution transformer] [Switchgear] [Tower] [Reactive power compensation capacitor]	1) [Distribution network] consists of the [overhead line], [cable], [tower], [distribution transformer], [switchgear], [reactive compensation capacitor], and some auxiliary facilities. 2) The [radial] structure uses the [single power supply] mode. ......
. . .. . .		
Related constraints		
1) [Distribution network] generally adopts [closed-loop design] and [open-loop operation], and the structure is [radial]. 2) The design of the [distribution network] needs to meet the development of [load demand].		
Electrical computing application ontology		
Concept		**Fact type**
Electrical calculation composition	[Power flow calculation] [Short-circuit calculation] [Reliability calculation]	1) [Electrical calculation] consists of [power flow calculation], [short circuit calculation], and [reliability calculation]. 2) The operation state parameters to be calculated in [power flow calculation] include [voltage amplitude] and [phase angle] of bus node, [power distribution] of each branch, and [power loss] of the network. ......
Electrical calculation algorithm	[Newton method] [Z-bus algorithm]	
. . .. . .		
Related constraints		
1) [Power flow calculation] needs to meet the [power balance constraint]. 2) [Power flow calculation] needs to meet the [voltage deviation constraint].		
Distribution network planning application ontology		
Concept		**Fact type**
Distribution network planning composition	[Load prediction] [Substation optimization] [Network optimization] [Power flow calculation] [Fail-safe analysis]	1) The main contents of [Distribution network planning] include [Load prediction], [Substation optimization], [Network optimization], [Power flow calculation], [Fail-safe analysis], etc. ......
Planning basic data	[Economic society] [Electricity supply and demand] [Power grid operation]	
. . .. . .		
Related constraints		
1) [Distribution network planning] needs to improve the [reliability] and [security] of the grid. 2) [Distribution network] needs to meet ["N-1" criterion]. 3) [Distribution network] needs to meet [power supply safety criteria].		
. . .. . .		

greatly reduces the time cost of ontology construction and improves the efficiency of modeling.

Through the aforementioned steps, the final distribution network time-series operation simulation ontology can be obtained, as shown in Figure 7.

Finally, ontology instance construction for specific businesses can be implemented, and the ontology model can be applied. Data exchange between the real system and the ontology model is achieved by driving the dynamic mechanism model, as shown in Eqs 1–4.

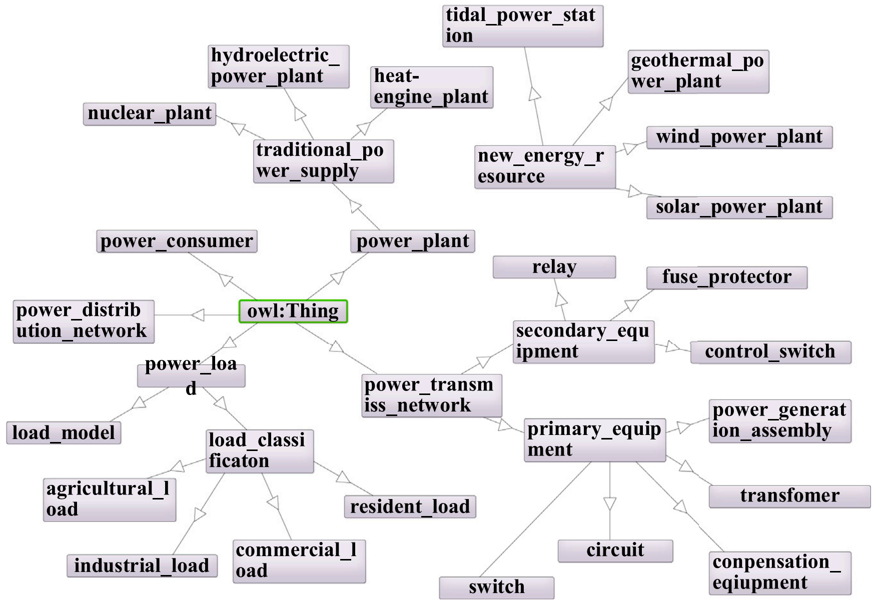

FIGURE 4
Structure ontology of the power system.

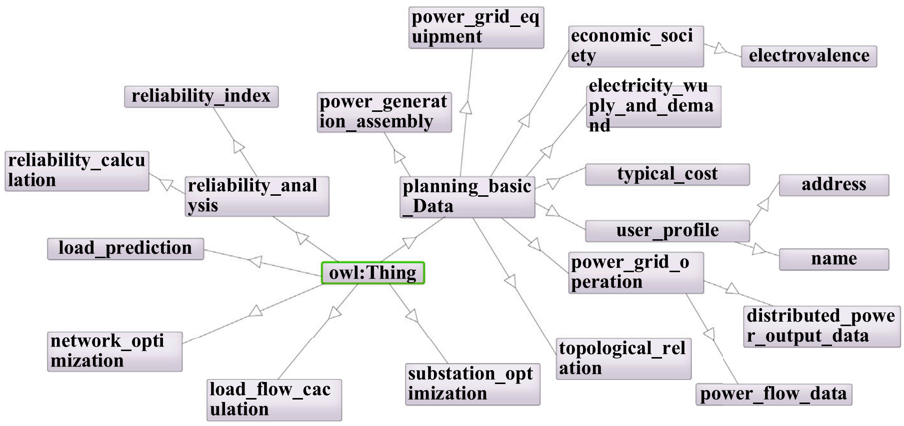

FIGURE 5
Application ontology of distribution network planning.

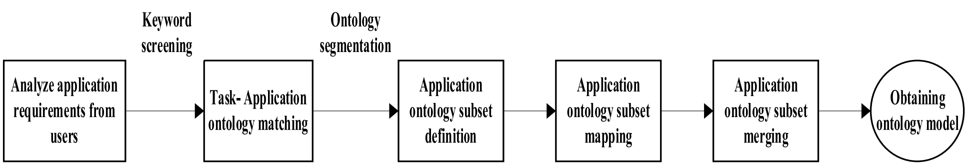

FIGURE 6
Dynamic ontology construction steps.

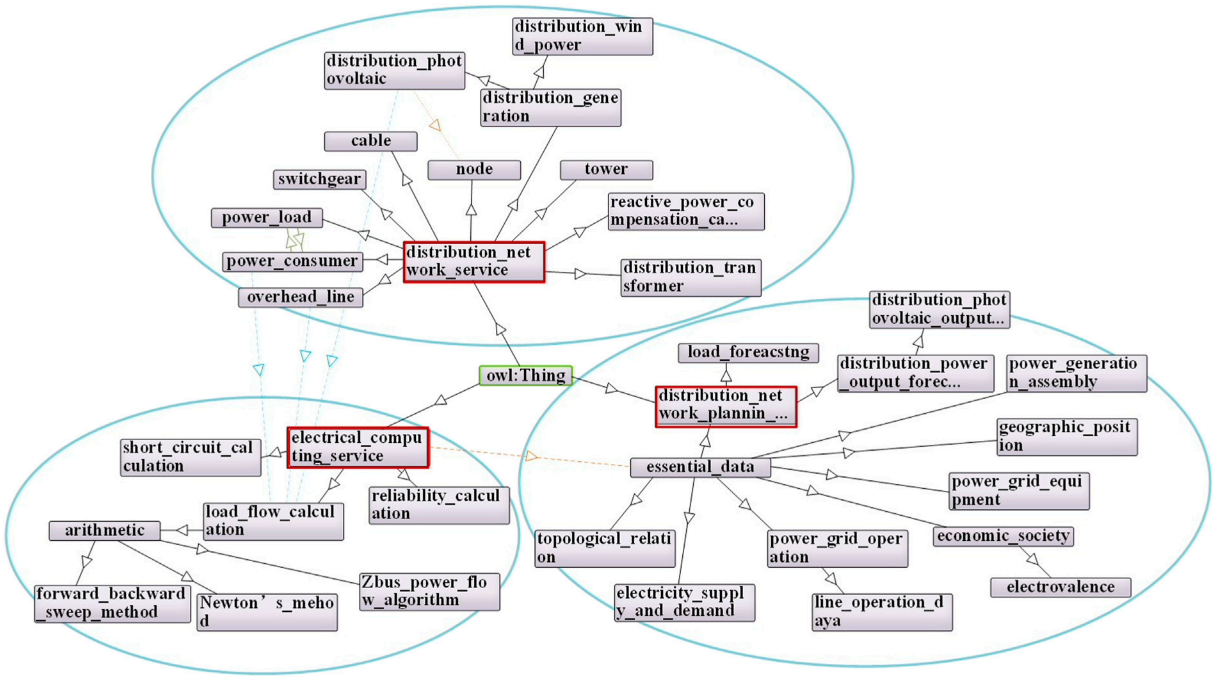

FIGURE 7
Schematic diagram of time-series operation simulation ontology of the distribution network.

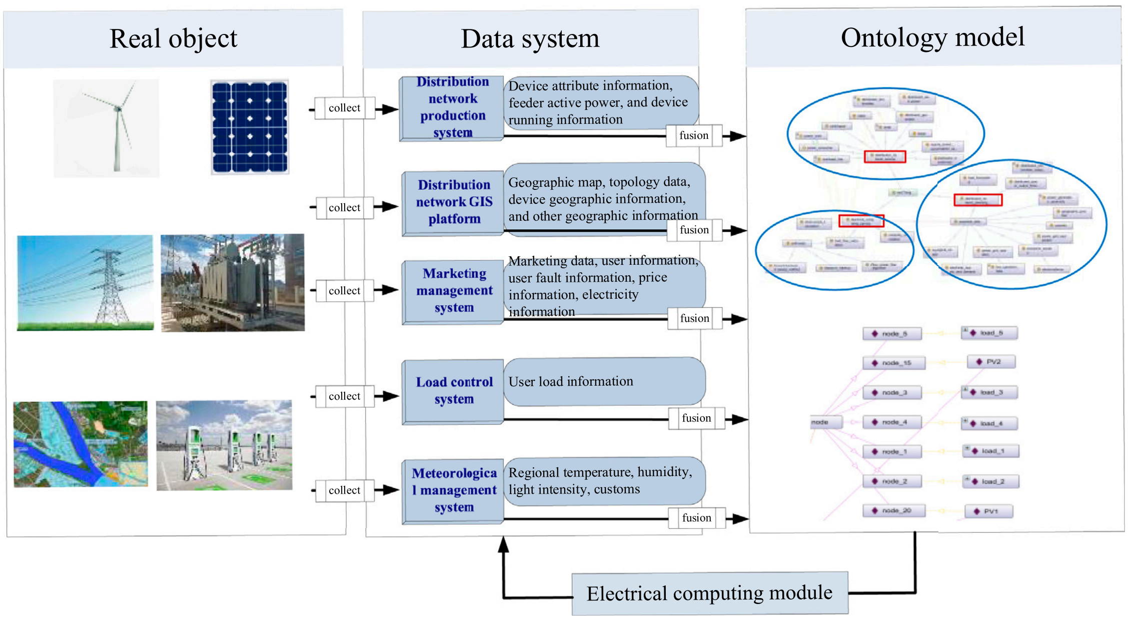

FIGURE 8
Schematic diagram of data flow.

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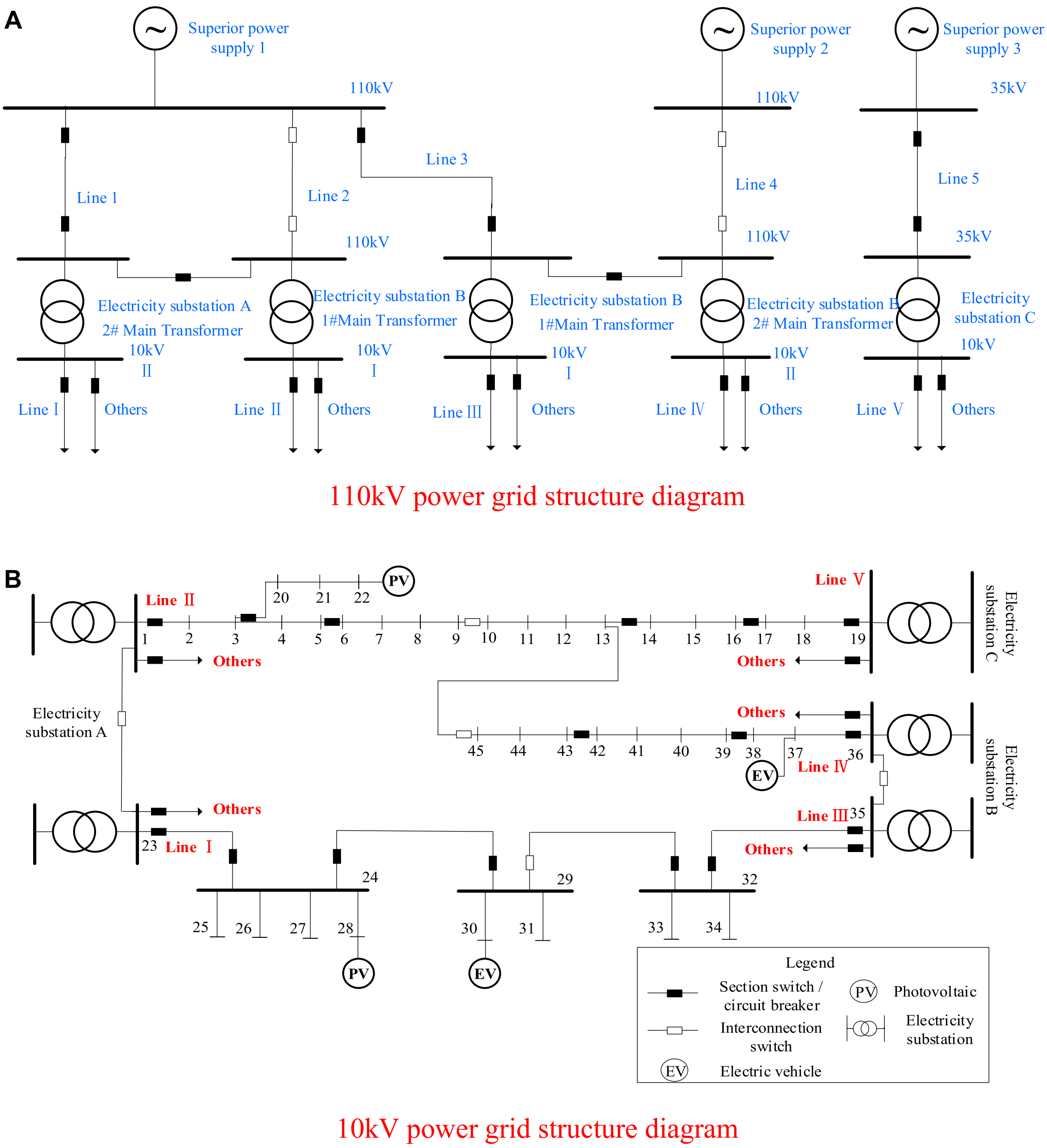

FIGURE 9
Typical power grid structure diagram. **(A)** 110-kV power grid structure diagram. **(B)** 10-kV power grid structure diagram.

Figure 8 is a schematic diagram of the data flow of the power grid, and the arrow represents the flow of data, which represents the conceptual objects in ontology, the actual objects in reality, and the application relations among various data sources of the power grid. All kinds of static data, parameter data, and text data collected from the real power system are stored in the data documents of different data systems. By querying conceptual objects in the ontology model, relevant data can be obtained from data documents. The electrical calculation module performs electrical calculations by querying the network model, algorithm, and related data required by relevant concepts in the ontology model, and the obtained calculation data results are updated and stored in the data document. At the same time, all kinds of calculated data can be queried and applied by the ontology model in real time. This circular mode can realize the dynamic following of the real characteristics of the system.

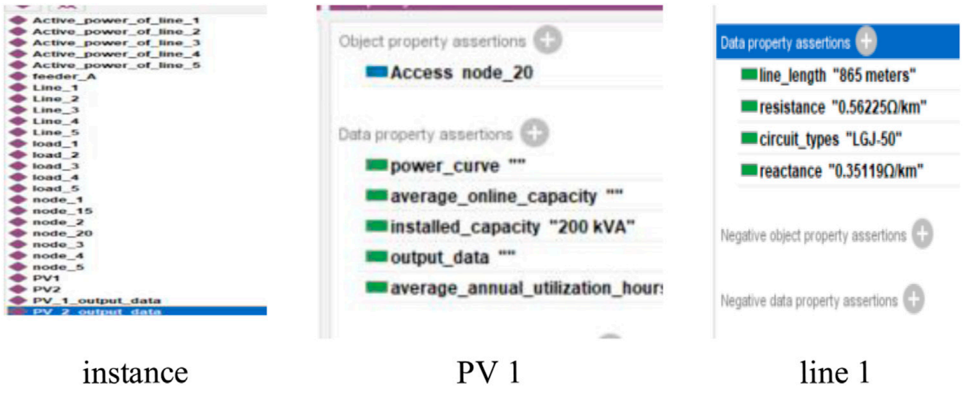

FIGURE 10
Instances built and properties of instance (example).

4 Application of ontology modeling for time-series operation simulation of distribution networks

4.1 Case introduction

Time-series operation simulation ontology can be used in distribution network planning. For the modules of load forecasting, substation location, network planning, electrical calculation, state analysis and evaluation of current distribution network, operation simulation of planned distribution network, etc., the ontology model can be configured directly by using a separate configuration tool to meet the needs without reprogramming software one by one. On the basis of the constructed time-series operation simulation ontology, software can be developed for different application systems. Parameters of traditional application systems are always relatively fixed and cannot be dynamically changed according to specific application scenarios. For application systems developed based on the ontology method, the parameters can be configured and loaded dynamically. It greatly reduces the time cost of modeling and improves the efficiency of business implementation.

In this article, a typical distribution network in North China, as shown in Figure 9, is taken as an example. There are two 110-kV substations and one 35-kV substation in the system. Figure 10 shows the constructed instance of a particular feeder and its attributes (example).

Traditionally, when developing different software modules with different functions such as state analysis and evaluation of distribution networks and network planning of distribution networks, it is generally necessary to develop their own customized database, algorithm, and functional interfaces, etc.,

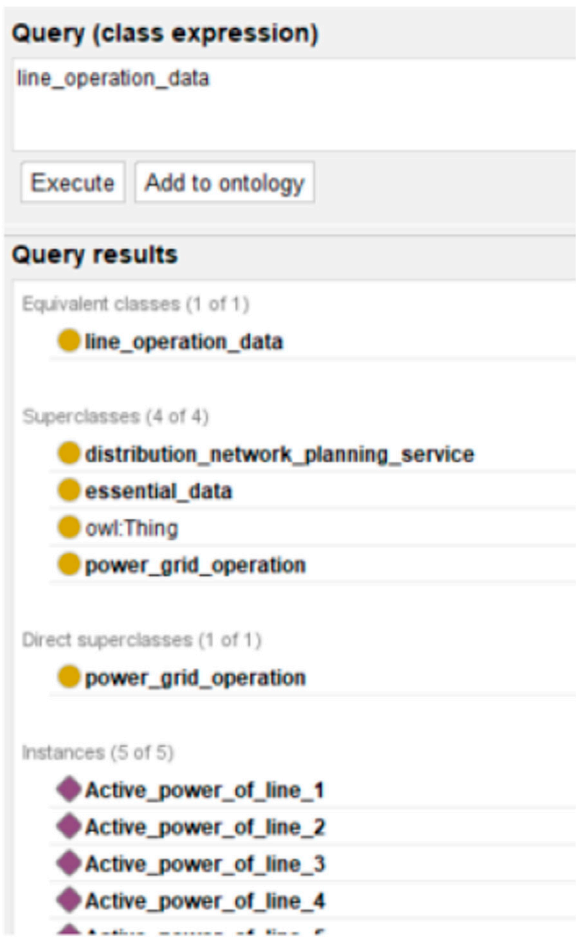

FIGURE 11
Result of querying line running data.

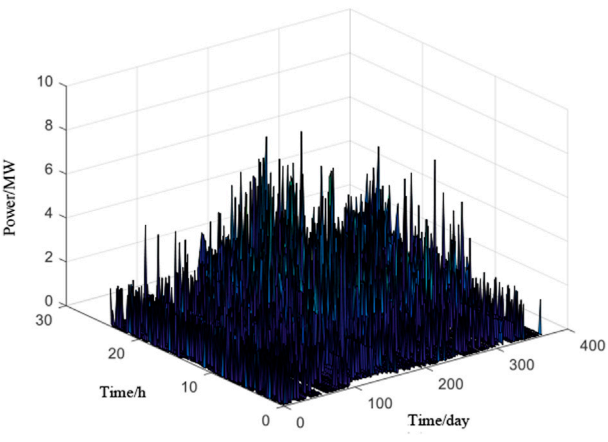

FIGURE 12
Schematic diagram of 1-year sequential active power of transformer.

for each independent module separately. Obviously, the similar function of time-series simulation analysis of the distribution network in different modules cannot be shared with each other, and part of the developing work is repeated, and resources are also wasted unnecessarily. When developing software based on the ontology method, we only need to develop algorithms for specific requirements and configure the database and functional interfaces quickly, which can avoid duplication of work like rebuilding the database and lots of others.

4.2 Result analysis

By using the time-series operation simulation ontology model, the operation of the distribution network can be simulated at different time scales according to different simulation requirements. The data include static data, parameter data, and load/generation curve data. These data include network topology data, geographical location data, and attribute data, which remain unchanged on an annual scale. It also contains data that change continuously in 24 h a day, such as the operation data on distributed generation, meteorological data, and system power flow data.

Driven by the dynamic mechanism model in the ontology model, each dynamic process of power grid operation has a corresponding ontology knowledge chain. When invoking the dynamic knowledge concept, we only need to search the corresponding knowledge chain according to the search engine to obtain the relevant equipment, system status, and other information during the dynamic operation of the power grid. For example, query "Line Operation data" during the dynamic operation of the power grid; the result is shown in Figure 11.

According to the query result, the corresponding time series data are matched, and the data curve is automatically generated, which can describe the time-series power flow of the distribution system. Figure 12 shows the 1-year sequential active power of a transformer.

The time-series operation simulation ontology model can standardize the representation of digital data, pictures, formulas, text descriptions, and other data objects related to conceptual objects and actual objects. Also, it can effectively realize the requirement of data sharing after data fusion. Query through the ontology model can accurately locate the required data resources so as to quickly obtain and update the scattered storage information and achieve a fast dynamic simulation of the real physical world.

When developing software systems for the business needs of power distribution system optimization calculation and planning analysis, about 90 tables and 1,000 fields need to be created to develop a power distribution network operation optimization system. When developing a distribution network planning system, 120 tables and about 1,500 tables need to be created. The two systems contain a general timing operation simulation module, which needs to create 63 tables and 407 fields (Tianjin University, 2021). When applying the ontology model for software development, the 63 tables and 407 fields shared by the distribution network operation optimization system and distribution network planning system do not need to be created repeatedly. At this time, it is enough to develop their own unique functional algorithms and integrate and reuse the timing operation simulation modules. Therefore, the ontology modeling method greatly improves the modeling efficiency and effectively shortens the software development time.

4.3 Comparison of modeling methods

The traditional modeling method is oriented to the specific needs and mostly adopts the "one case one discussion" method. Different modeling standards and data formats inevitably exist among multiple application systems, resulting in repeated construction of the same part of the system and a low resource reuse rate.

Ontology modeling is a more generalized modeling method for multiple applications, including model representation, data organization, data preparation, application logic, and application achievement presentation. This method belongs to the "Middle Platform" modeling idea (Liu et al., 2020), which extracts the common parts of multiple application systems for ontology modeling and can be shared by everyone. In addition, ontology modeling with a dynamic mechanism model can overcome the disadvantages that a traditional static model cannot be combined with the dynamic evolution process of

TABLE 3 Comparison between traditional modeling methods and ontology modeling methods.

	Traditional modeling	Ontology modeling
Modeling ideas	"One case one discussion"	"Middle Platform" modeling idea
Modeling method	Single modeling	Generalized modeling
Disadvantage	Low resource reuse rate; repetitive modeling; high modeling time cost; static model modeling; and cannot be combined with dynamic evolution	The construction is complex; the engineering is large; and the construction process is difficult to reach consensus
Advantage	Simple operation and limited engineering	High resource reuse rate; avoiding repeated construction; low modeling time cost, including the dynamic mechanism model; and can be combined with the dynamic operation state of the power grid

the power grid. This method can describe the real-time dynamic operation state of the power grid. So the ontology modeling method provides feasible ideas for constructing electric power digital twins.

For example, multiple services in different application systems (such as the distribution network optimization planning system and the distribution network operation optimization system) have similar requirements for time-series operation simulation. With the traditional modeling method, it is necessary to build the system for each module, such as the data integration module, power flow calculation module, short-circuit calculation module, and result display module, which has the problem of repeated construction inevitably. The generalized ontology modeling method only needs to extract the common high-frequency modules for integration and reuse without the need to be reprogrammed. For the application of modeling methods, table 3 shows the comparison between traditional modeling methods and ontology modeling methods.

5 Conclusion

In this article, an ontology modeling method applied to the simulation modeling of distribution network time-series operation is proposed. Based on the framework of two-layer ontology modeling, the structure ontology of the power system and the business-based application ontology are constructed, which realizes the standardized expression of power grid data and concepts. Then, combined with the requirements of the time-sequence operation simulation of the distribution network, the time-series operation simulation ontology is constructed dynamically. Taking a typical distribution network as an example, it shows that the ontology modeling method can greatly save the time cost of power grid modeling and improve the modeling efficiency. At the same time, it can effectively integrate and fuse a large amount of heterogeneous data to realize data sharing. The results show that the ontology modeling technology provides a research basis for the unified modeling of electric power digital twins and the presentation of high-fidelity twins, which has reference significance for future research on electrical power digital twin technology.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material; further inquiries can be directed to the corresponding author.

Author contributions

FL: supervision, conceptualization, and writing—review and editing. SF: methodology, software, data curation, and writing—original draft. YY, ZA, XL, and YC: writing—review and editing.

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Conflict of interest

Authors YY, ZA, XL and YC were employed by the company Digital Grid Research Institute of China Southern Power Grid.

The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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