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A Community-driven Trinity Method of Data Model Framework, Connector Platform, and Operation Strategy to Connect Data Islands in Integrated Energy Systems

Yingya Zhou[1], Linwei Ma[1*],Weidou Ni[1]
1 State Key Laboratory of Power Systems, Department of Energy and Power Engineering, Tsinghua-BP Clean Energy Research and Education Centre, Tsinghua University, Beijing, China
(*Corresponding Author: malinwei@tsinghua.edu.cn)

ABSTRACT

Integrated energy management system (IEMS) is a must-have to ensure the operation of integrated energy systems (IES) and to provide foundation to advanced functions such as analysis, forecast and optimization. However, building an IEMS faces significant challenges, including the absence of unified data models across diversified disciplines, the dynamic and heterogeneous nature of IEMS, budget constraints for small-scale IESs, and the need for interdisciplinary cooperation. Previous research focused on proposing unified data model standards for each subfield of IES or particular IES projects. However, such approach inevitably struggles with the difficulties in covering vast and diverse topics encompassed by IES and the adoption in engineering practice. This research pivots away from attempting to create another data model standard but proposes a collaborative and software-aided method to foster community-driven data model and data integration. The method includes three key components: an IES data model framework, an IEMS data connector, and an operation strategy. The proposed method minimizes semantic ambiguity, translates human semantics to machine executions automatically, streamlines application interface connections, and fosters the development of a de-facto data model standard within the IES community. The method has been verified through a case study and theoretical criteria, offering a promising avenue for seamless data integration in IEMS.

Keywords: data model, integrated energy system, data integration

1. INTRODUCTION

Integrated energy system (IES) has been highly valued and deployed by academia and industry [1] . A lot of research has been focused on analysis, forecast, and optimization algorithms of IES. The smooth implementation of these research fruits, central to the success of IES, requires integrated energy management system (IEMS) as an infrastructure to integrate the traditionally independent energy supply and demand software applications [2, 3].

However, to build an IEMS becomes more and more challenging due to lack of unified data models across the traditionally independent disciplines, heterogenous combination of components in IES, dynamic data exchange need, interdisciplinary cooperation between IT, energy, and data science.

To deal with these challenges, previous research has spent efforts on standardizing data models across the subfields of IES, recognizing that data models are the bedrock for data interoperability, data exchange, and data reuse. A data model is a schematic representation of reality that can be used to organize metadata and produce tools [4]. Nevertheless, as an intersection of multiple energy disciplines, information technology disciplines and management disciplines, a unified data model encompassing the IES domain has not yet been discovered and generated [5].

Our research has shifted from working on a data model standard to proposing a collaborative and software-aided way for energy engineers to efficiently reach consensus on data models within an IEMS project and to translate the consensus into machine executable data exchange.

In detail, a triad of complementary components is proposed including an IES data model framework, a software platform named IEMS data connector, and an operation strategy of the IEME data connector. The IES data model framework serves as a kind of 'language', providing a hierarchical human-readable syntax for

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energy engineers to map out data supply and demand as well as agree on semantics of data models. The IEMS data connector acts akin to an 'Integrated Development Environment' (IDE), translating the semantics written in accordance with the IES data model framework into machine-executable data parsing. Furthermore, the IEMS data connector also offers rapid connection to applications without requiring prior knowledge on the data models. The operation strategy resembles community guidelines in an open-source project, ensuring continual integration and updates of the data model library through real-world application usage.

2. LITERATURE REVIEW

2.1 Previous research on data models of IES

2.1.1 CIM

CIM originated in 1990s from the field of electricity transmission grid [6] and is one of important standards adopted in power utilities worldwide. Many scholars have attempted to propose extensions of CIM into domains other than power transmission, such as power distribution[7, 8] and power system topology [9], and even sectors of other energy carriers, such as campus stream heating systems [10] and wind power [11].

However, the existing literature regarding CIM in the domain of IES faces certain limitations:

1) It fails to extend the CIM to the entire IES domain, as also stated in [12, 13].
2) Extensions proposed by different authors result in inconsistencies [13].
3) Many extensions were introduced in academic literature, with uncertain adoptions among IEMS software developers.

2.1.2 Ontology

In recent years, several studies have applied ontology to handle heterogeneous data in the energy field, such as the photovoltaic and weather analysis (PWA) ontology proposed in 2019 [14], the ontology for an industrial park including energy grid structures and demand-supply chains in 2020 [15].

Each of these studies focused on creating vocabularies for specific subfield within the IES domain, designed for particular IES projects or user groups, resulting in another layer of heterogeneity[16].

2.2 Data model challenges in the IES

According to the theory 'Apocalypse of the two elephants'[17], to achieve wide adoption, standards must be established when the target field is in the valley between the moment of invention and flourishment. IES is not a standalone new field but is a combination of incumbent energy disciplines and new technologies. Therefore, despite the efforts made in previous research in Section 2.1, the challenges in the engineering practice of data exchange and integration in the IEMS continue to persist, including data models created prior to the needs of data exchange, backward compatibility with existing models, and real-time automatic data exchange and integration between applications.

3. A TRINITY METHOD OF COMMUNITY-LED IEMS DATA INTEGRATION

A trinity method is proposed to establish a coordinated, collaborative, self-evolving and community driven way to agree on IES data models and to implement a data exchange between heterogeneous existing applications in the IEMS.

Overall, as depicted in Fig.1, the traditional point-to-point integration of applications involves point to point discussions and mutual agreement between each pair of application providers on the data exchange needs, data models, data exchange mechanism, protocols, etc. Each application provider then translates the agreement in natural language to development specification. The development specification is then realized by the hard-coded programs to complete the automatic data exchange between each pair of applications.

In contrast, the IES data model framework frames an efficient communication between engineers on the supply and demand as well as data models. The IEMS data connector translates the human-readable configurations to machine-executable data parsing. Meanwhile, the IEMS data connector also provides easy linkage to each application to serve as a bridge between applications. More importantly, all the contents in communications between humans, human and machine, and machines can be dynamically configured without much involvement on human discussion and re-programming. As more IEMSs are integrated on IEMS data connector, the operation strategy makes sure the data models across different IEMSs to converge.

3.1 *IES data model framework*.

Based on extensive experience in system integration projects dealing with various data formats, models and content, an IES data model framework containing seven parts is proposed. The first three parts manage the basic data, attributes and data models that are globally valid and can be used by different IES:

1) Basic data management defines the basic components including unit of measurement and enumeration values that an attribute can cite.
2) Attribute management defines the name, explanation, unit and data type of attributes that a data model can cite.
3) Data model management defines the name, explanation, attributes of data models.

The remaining four parts manage the entities, data twins, applications and devices that are specific for each IES:

4) Entity management defines physical or virtual entities in an IES. Each entity can be associated with a data model.
5) Data twin management defines the topology of entities.
6) Application association management defines which application can input or output data of which entity of which data twin.
7) Device association management defines a list of physical devices in an IES and can associate each device to an entity.

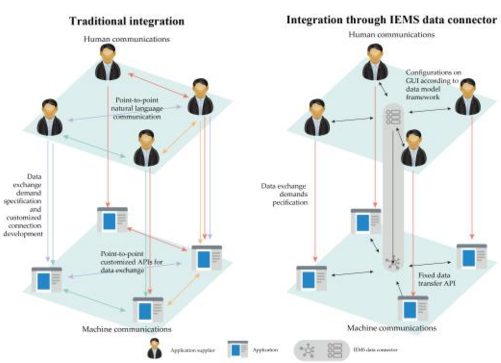

Fig.1. Comparison between traditional application integration and integration via the IES data model framework and IEMS data connector

The hierarchical structure of the IES data model framework reflects the data management nature of IEMS. It helps to overcome the difficulties during the integration of multiple applications in the IEMS: Energy managers or equipment maintenance personnel usually have a list of energy appliances, while each application provider has a list of data points. With all the data supply and demand depicted using the IES data model framework, it is intuitive for everyone to co-edit the entities of IEMS they know without any prior training or data engineering background. Moreover, an overview of the entities can be clearly stated that are described by data in the IEMS. Lastly, the framework lays common ground for engineer, product managers and developers to align on which entity they are referring to without semantic ambiguities.

3.2. IEMS data connector

The IEMS data connector provides a GUI for IES stakeholders to facilitate the expression and documentation of data supplies and demands according to the IES data model framework, the translation of human language to machine language, and to speed up the data connection and exchange between machines. Moreover, the IEMS data connector has to connect the dynamically changed data exchange needs and the hard-coded way of software programs.

The overall structure of the IEMS data connector is depicted in Fig.2, which involves three functional parts:

1) A flexible part that includes a GUI for the users to configure according to IES data model framework

2) A fixed part of API connection and API services

3) The data hub that bridges the above two parts by transforming and storing data received by API according to the configuration set in the user GUI

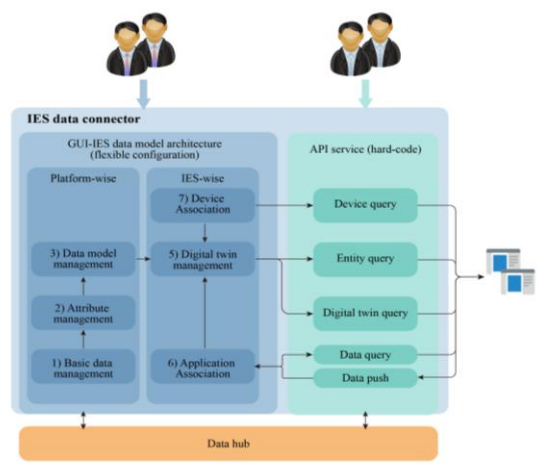

Fig.2. Structure of the IEMS data connector

3.3. Operation strategy of IEMS data connector

Since it is hard to get an ex-ante unified and universal list of basic data, attributes and data models across all kinds of IES subfields, this research turns to define an IES data model framework in which different stakeholders can express their data models unambiguously in the same hierarchical and hence co-create the landscape of all data assets in each specific IEMS. Meanwhile, as more applications of more IEMSs express their data structure according to the IES data model framework in the IEMS data connector, the attributes and data models, under proper operation strategy, accumulating in the attribute management and data model management of the IEMS data connector, will evolve into a de-facto standard where survival of the fittest applies: the attributes and data models with the most quotes prevail and become a standard in practice, by the IES community and for the IES community.

4. VERIFICATION

4.1. By theoretical framework and platform criteria

There are currently few established or standardized verification criteria for data model framework. The closest reference is [18], which proposed seven verification criteria for assessing data model frameworks and platforms for microgrid systems. The first five verification criteria are also suitable for the verification of the IES data model framework and IEMS data connector proposed in this research:

1) Interoperability of information exchange
2) Interoperability of interfaces, communication pattern, and network
3) Cybersecurity
4) Evolvability
5) Scalability

The proposed IES data model framework and the IEMS data connector fulfill the above five criteria.

4.2 By a case study

To show the feasibility and effect, a case study on one of a real integration project using IEMS data connector is provided. In the IEMS for an IES in an industrial park in Jiangsu Province, China. 14 different software applications in Phase 1.1 and another one software application in Phases 1.2 had to be integrated. The data exchange needs within the IEMS are shown in Fig.3.

This case study verified several key advantages of using the proposed IES data model framework and the IEMS data connector for integrating applications in the IEMS:

1) Semantic and interface interoperability: The integration achieved semantic, synaptic, and interface-wise interoperability for data exchange between 15 applications and their respective data models.
2) Efficiency gains: During Phase 1.1 of the integration, more than 61% of the integration development workload was saved. When extending the IEMS to incorporate a new application (Phase 1.2), the proposed approach saved more than 67% of the development workload.
3) Simplified integration: The IES data connector offered an intuitive graphical user interface for 15 application providers to express their data supply and demand.

5. LIMITATIONS

When the data exchange demand deviates from typical scenario, the present design of IEMS data connector may not be optimal but can be extended with other complementary designs: In the case where applications in the IEMS have to exchange large amounts of unstructured data such as pictures and videos, the type of the database used in the IEMS Data Connector has to be correspondingly changed or extended. If the application providers still want to enjoy the loose coupling, scalability and evolvability of IEMS data connector while requiring the real-time data transfer, the present IEMS data connector should be extended to incorporate a synchronous data bus service to satisfy the need.

6. CONCLUSIONS

This manuscript addresses to the multifaceted challenges surrounding the data integration between different applications in the IEMS by offering a collaborative and software-aided method comprised of three components: IES data model framework, IEMS data connector, and the operation strategy of the IEMS data connector.

The verifications by theoretical framework and platform criteria and a case study provide evidence that this method is a significant step towards achieving greater interoperability and efficiency in the integration within IEMS.

Looking ahead, future research can be made on several directions. First, continued efforts to expand the

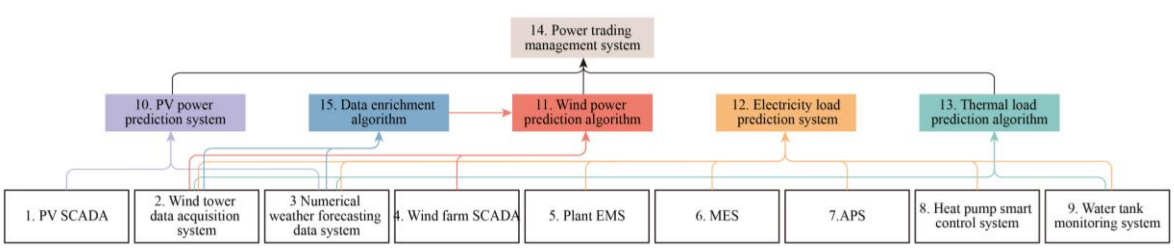

Fig.3. Illustration on the need of data exchange between the applications for phase 1.1 and 1.2

proposed method are necessary to ensure its adaptability to a wide range of scenarios including exchange of unstructured data and milli-second automation. Second, intelligent analysis using artificial intelligence on the data models across different IEMSs based on existing quote and usage data of data models on the IEMS data connector can be pursued. Lastly, the further application of information theory or management theory in this energy engineering area may broadens the horizon and guide new ways.

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DECLARATION OF INTEREST STATEMENT

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. All authors read and approved the final manuscript.

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