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Real-time data exchange using web service with CIM for aging estimation of distribution transformers

Te-Tien Ku[1], Chia-Hung Lin[1*], Chao-Shun Chen[2], Kun-Lin Tsai[1], Tong-Yu Zhang[1], Yih-Der Lee[3], Chin-Chan Cheng[3], Zi-Chun Lin[3]
[1]Department of Electrical Engineering, National Kaohsiung University of Science and Technology, Kaohsiung, 807618, Taiwan; ttku@nkust.edu.tw (T.T.K.); chlin@nkust.edu.tw (C.H.L.).
[2]Department of Electrical Engineering, I-Shou University, Kaohsiung, 84001, Taiwan; cschen@mail.ee.nsysu.edu.tw (C.S.H.).
[3]National Atomic Research Institute, Taoyuan, 325207, Taiwan.

Abstract: This paper applies web services using the common information model (CIM) to exchange measurement data from the transformer terminal unit (TTU) to the distribution management system (ADMS) for the aging estimation of distribution transformers. An application programming interface (API) is designed by using web services such as simple object access protocol (SOAP) and representational state transfer (RESTful) for TTU measurement data exchange. The structured query language (SQL) and the not only SQL (NoSQL) databases are used to store historical TTU data for neural network (NN) model training. An optimization architecture of web service with the database is proposed to increase data exchange performance. The exchanged real-time TTU data is input into a trained NN model that can provide a reference aging factor for the utility crew to balance distribution transformer loading. Finally, the graphic user interface (GUI) is designed in this paper to display real-time information and achieve asset management of distribution transformers.
Keywords: *Aging estimation, Common information model, Data exchange, Web service.*

1. Introduction

The Taiwan Power Company (Taipower) has constructed multiple management systems that can execute corresponding workflows for distribution systems. The existing management systems are not integrated, and exchanging data is difficult. Therefore, Taipower has begun developing an ADMS to integrate different systems and assist staff in operating and maintaining the distribution systems. The ADMS can further improve distribution systems' operating efficiency and power quality, so data exchange is vital to ensure that ADMSs function normally. To reduce the complexity of data exchange, the International Electrotechnical Commission (IEC) has proposed the CIM as a method and standardized data models for exchanging data so that the required number of API programs and development costs can be reduced [1-2]. The CIM provides a method to standardize the data format based on unified modeling language (UML) and extensible markup language (XML), and then it uses web services such as SOAP or RESTful to exchange data.

To manage distribution transformers, Taipower has already installed TTU to measure voltage and current to calculate power parameters that provide necessary information to evaluate the state of health of distribution transformers. All TTUs measured data is transmitted to the transformer management system (TMS) to monitor the status of distribution transformers in real-time. For asset management of distribution transformers, the ADMS exchanges TTU data via web services from TMS and uses SQL or NoSQL databases to record TTU real-time information in XML format. To increase the efficiency of data exchange, the optimization architecture is crucial because SOAP and RESTful data exchange methods and SQL and NoSQL query methods are different. Therefore, to ensure real-time monitoring of distribution transformers for aging analysis in ADMS, the processing times of SOAP and RESTful are compared in this paper to show which web service is appropriate for data exchange. Also, the access

* Correspondence: ttku@nkust.edu.tw

time of SQL and NoSQL are compared which selected minimum query time to increase the performance of aging analysis.

To manage distribution transformers in ADMS, the installed TTUs at Yunlin District in Taipower are selected and use CIM as a basis model for the TTU information. Then web services such as SOAP and RESTful APIs were developed to ensure the reliability of the CIM during the data exchange between TMS and ADMS. Also, the databases are constructed for ADMS to evaluate SQL and NoSQL access performance and develop an application for the operation and management of distribution transformers. Finally, this paper also designs GUI to show the aging factors of the distribution transformers to achieve asset management of distribution systems and support smart grid applications.

2. Data Exchange Methods with CIM

A CIM is used as a standard data model because the CIM provides a universal and efficient data exchange format that enables different systems to share and exchange data. The CIM based on UML utilizes XML to perform data exchange of distribution systems [3-4]. Thus, different systems and applications can share and exchange information for power system operation and management. Most of the CIM is used in power plants, distribution systems, and operators between utilities and customers. Thus, the CIM is used for real-time data exchange of TTU for distribution transformer monitoring, and TTU transmits data to the TMS via the data concentrator unit (DCU). To analyze the aging factor of the distribution transformer, the ADMS received data from TMS using a web service to exchange real-time measurement information. To ensure data exchange performance between TMS and ADMS, this paper proposed a two-phase evaluation method based on CIM, including web service and database access. In the test phase of web service, SOAP and RESTful are used to exchange data and evaluate the required process time when requesting TMS to get TTU data for the ADMS. After ADMS receives TTU real-time information, the data is stored in the database, and the query and retrieval performance of SQL and NoSQL databases are compared using the designed API. In this phase, the query and retrieve time are recorded, and the performance of the two databases are compared for data exchange interface design. Figure 1 illustrates the performance evaluation flow for data exchange.

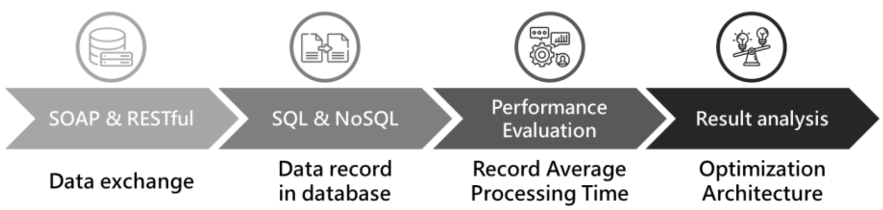

Figure 1.
Performance evaluation flow for data exchange.

To verify web service performance, the API is designed to record time-tag before and after data exchange. In the API, the functions of web service consist of SOAP and RESTful modes. When working in SOAP mode, it does not support the extended universal resource identifier (URI) that needs to get a request from the Body section of SOAP. In RESTful mode, it supports extended URIs to simplify request procedures and respond quickly. Before and after exchanging data, the API records the time-tag that analyzes the average execution time for performance evaluation. The performance evaluation flow of web service is shown in Figure 2(a). After exchanging data from TMS, the TTU information is also recorded in the database for distribution transformer aging analysis. The mean time of accessing data from those two databases is recorded to verify SQL and NoSQL queries and retrieve performance. In this evaluation phase, the SQL must convert XML to relational data format for database access because SQL does not support XML format. The NoSQL is different from SQL because it is nonrelational and can directly access XML, so NoSQL can improve the database's access performance. Figure 2(b) shows the access performance evaluation flow for databases.

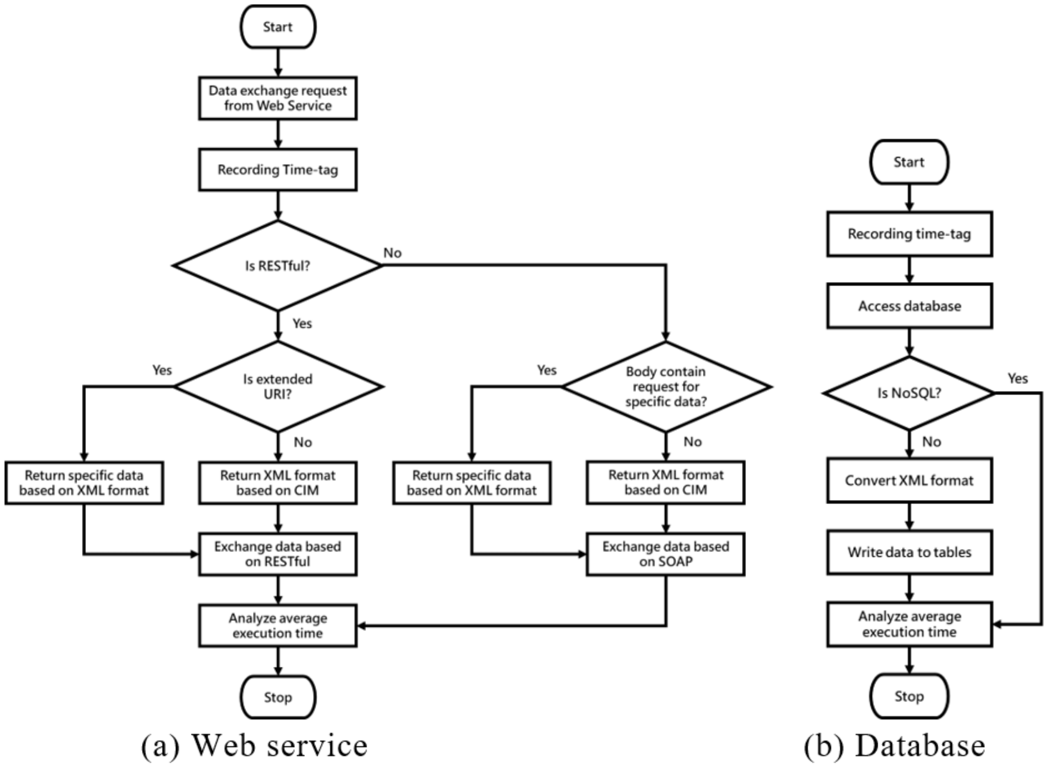

Figure 2.
Performance evaluation flows of web services and databases.

3. Distribution Transformer Monitoring

To prevent distribution transformer overload and reduce the voltage variation of the feeder with high-penetration of renewable energy in distribution systems. The TTUs are installed to monitor the voltages, currents, and loadings of distribution transformers. Long-range (LoRa) wireless communication is used to transmit TTU measurement data to the DCU, and the 4G mobile wireless communication is used to transmit DCU data to TMS to monitor the status of distribution transformers in real time. Then, the web service of TMS is used as the interface to exchange data for ADMS. Figure 3 shows the communication architecture, including TTU, DCU, TMS, and ADMS, for real-time monitoring of distribution transformers.

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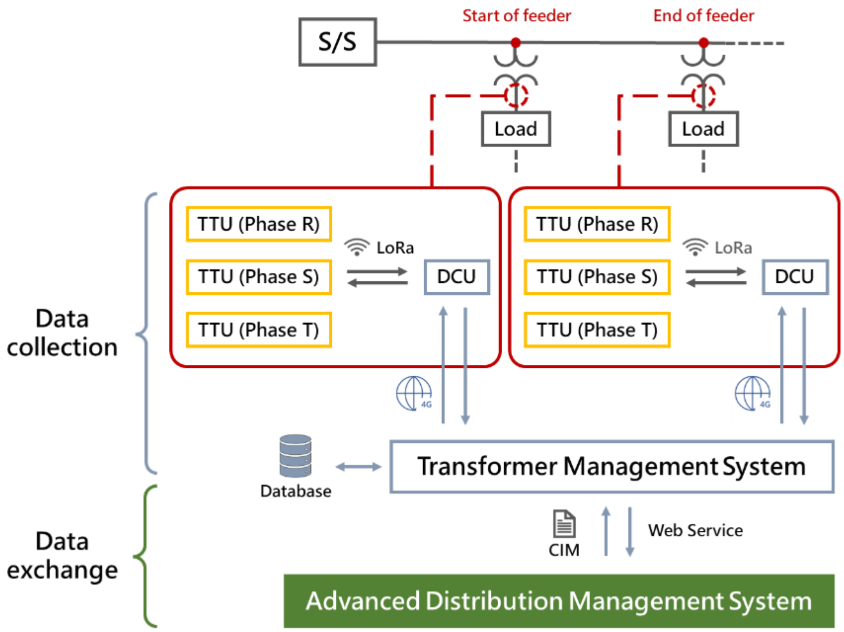
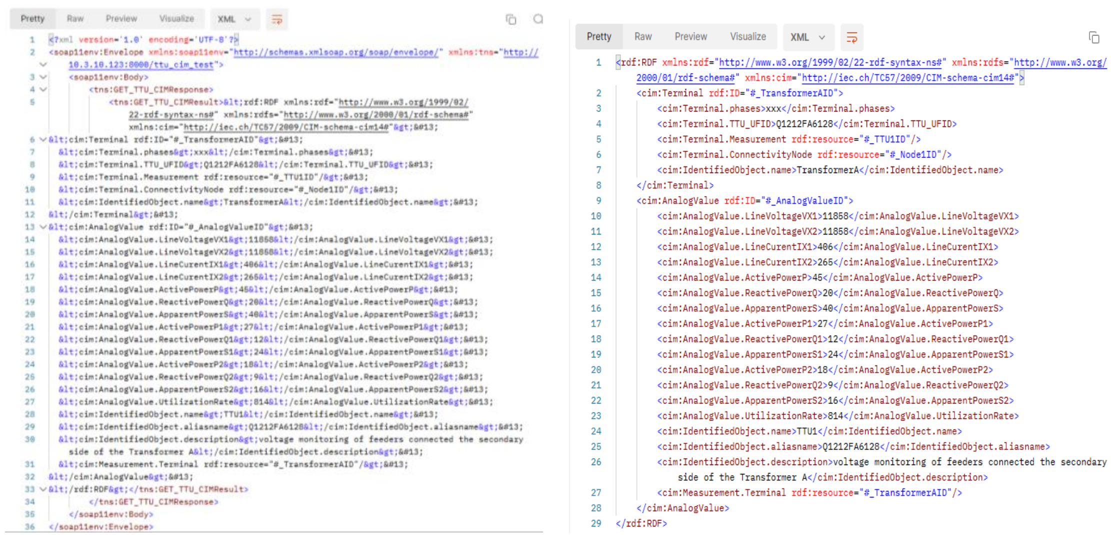


Figure 3.
The communication architecture for distribution transformer monitoring.

To exchange data, the CIM is utilized as a model between TMS and ADMS. The CIM includes basic information such as the phase of a distribution transformer and utility facility identification (UFID). Also, the measured power parameters such as line voltage (LineVoltageVX1), line current (LineCurrentIX1), active power (ActivePowerP1), and reactive power (ReactivePowerQ1), etc. are included in the CIM. To convert TTU data to CIM in TMS, the access module is designed in API and includes a subroutine that converts TTU raw data to XML format. Then, the web services such as SOAP or RESTful are used for data exchange. Before data exchange between TMS and ADMS, the API also designed an authorization module with an account and password to prevent unauthorized logins.

4. Performance Evaluation of Data Exchange

The performance of SOAP and RESTful are compared in this paper to evaluate which web service is more efficient for data exchange between TMS and ADMS. In the SOAP, it utilizes the POST method to exchange data.[5] The envelope of the SOAP includes the XML format based on CIM to exchange information between the TMS and the ADMS under the security certification. When TMS receives a data request from ADMS, the TMS retrieves TTUs data and appends it to the Body section in an envelope, then transmits it to the ADMS. Different from SOAP, RESTful uses a URI based on the Hypertext Transfer Protocol (HTTP), which includes three aspects: (a) security certification for data accessing, (b) IP address and port number management system, and (c) extended URI for accessing specific information such as TTU's UFID.[6] To exchange specific information about TTU from TMS, the URI path can be defined based on CIM, such as reading all of TTU measurement information or only reading line voltage. Figure 4(a) and Figure 4(b) show the TTU information using SOAP and RESTful for data exchange respectively.



(a) SOAP (b) RESTful

Figure 4.
TTU basic and measurement information in different web services.

To record TTU real-time information, this study selects the SQL and NoSQL databases to compare their access performance. The results provide a database selection for accessing XML format when exchanging data based on CIM. In the SQL database, data cannot be directly accessed in XML format. The conversion program is developed in this paper to convert XML and insert data into relational tables.[7] To increase access performance in XML format, an open-source native XML database called NoSQL is selected, and it has an XML editor that features XQuery to enable rapid query and analysis of XML format. Also, the NoSQL offers authenticated users for data security and integrity. The query engine of NoSQL specializes in efficiently processing large quantities of XML data [8-9]. Figure 5 shows that the TTU data is stored in the NoSQL database.

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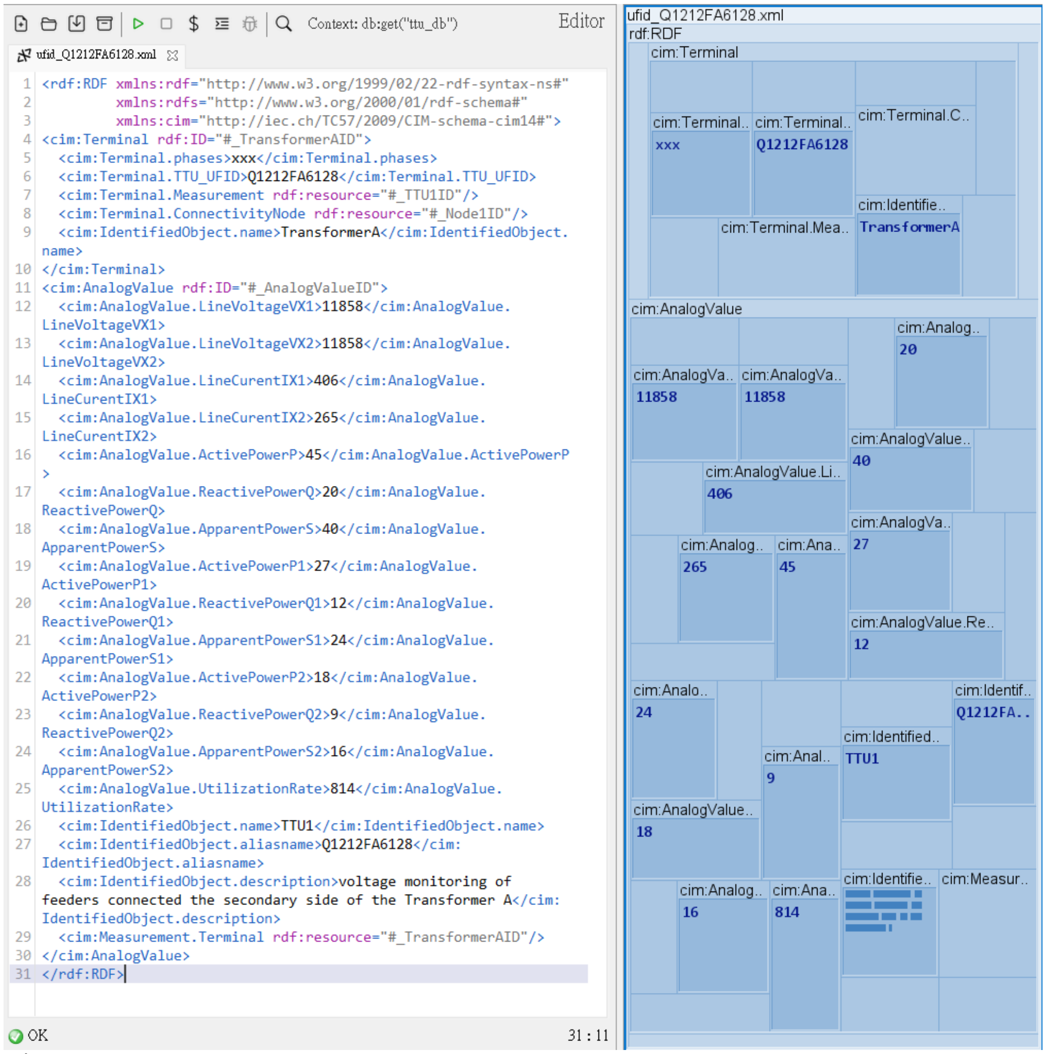

Figure 5.
TTU data is stored in the NoSQL database.

The performance comparisons of the two web services are achieved by evaluating the required time. Figure 6(a) illustrates SOAP and RESTful web services performance comparisons. The results show that the RESTful web service's data exchange time is 0.009ms less than 0.016ms of the SOAP. Besides, this study also performs the access performance evaluation with the XML format by using the designed API for SQL and NoSQL databases. In the SQL database, a conversion process is needed to convert XML format, but NoSQL differs from SQL because it does not require a data conversion process and can directly access XML data. The results revealed that more access time is needed to access XML format for SQL 0.054ms than NoSQL 0.019ms due to the conversion time required. Figure 6(b) shows the time required to access databases, including the data conversion process.

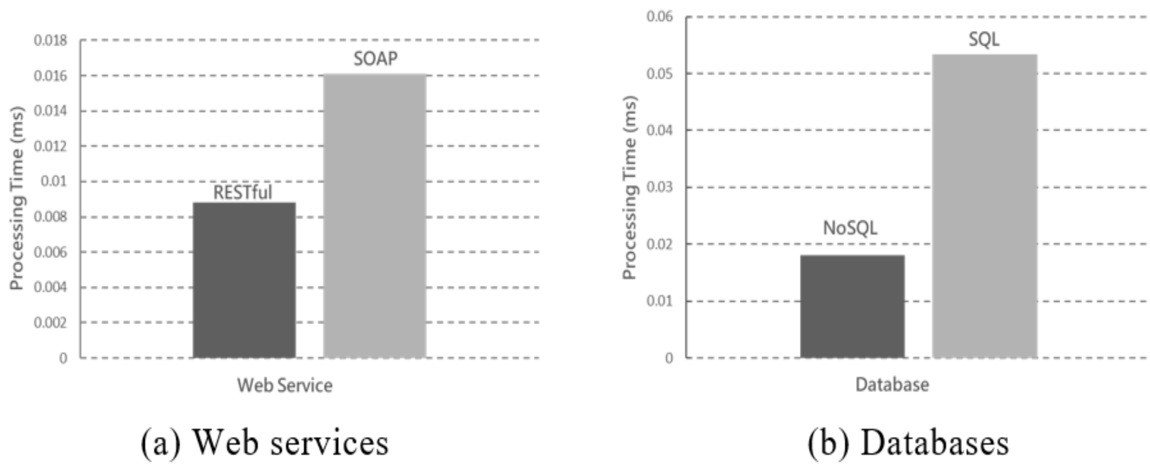

Figure 6.
TTU data is stored in the NoSQL database.

5. Aging Estimation of Distribution Transformers

In this study, the real-time monitoring of the distribution transformer can support utility staff in operation and maintenance by using the proposed CIM via RESTful and recorded information in NoSQL for aging analysis. The real-time data of TTUs are used to analyze and visualize the aging factor of distribution transformers to prevent customer outages. To extend the life cycle of the distribution transformers, excellent insulator performance and materials are essential to ensure the transformers' safe and reliable operation. Statistics reveal that insulator deterioration is the primary cause of 85% of failure or malfunction cases in Taipower's distribution transformers. The aging of a distribution transformer includes many factors, such as operation duration, oil temperature, and load, that cause deterioration in the performance of insulators. Therefore, evaluating and monitoring insulator deterioration is crucial for distribution transformer management.

The IEEE Std. C57.91 standard provides specific regulations and methods for evaluating the aging of oil-immersed transformers.[10] The aging equation indicates that the relation of insulation deterioration to time and temperature follows an adaption of the Arrhenius reaction rate theory. Modern oil-immersed transformers can minimize the effects of humidity and oxygen content on insulator performance. Therefore, temperature is used as an independent variable in this study. The temperature within the transformer is not distributed uniformly, and components typically exhibit the most damage when operating at the highest temperature. So, the insulator aging is assessed by focusing on aging at the highest temperature. The aging of the insulator deterioration factor can be defined as eq. (1).

$$f_{ag} = T_b \times e^{\left(\frac{A_r}{\theta_H + 273}\right)} \quad (1)$$

where T_b is the per unit value based on 110°C, A_r is the aging rate, and θ_H is the highest temperature in the transformer coil.

The equation (1) indicates the relation between the aging of a transformer insulator and the maximum temperature of the winding. In this equation, temperature is the main variable affecting a transformer's aging. Equation (2) illustrates the effects of load and temperature on distribution transformers where θ_A is the ambient temperature at a specific load, $\Delta\theta_{TO}$ is the temperature rise between ambient temperature and oil, and $\Delta\theta_{TC}$ is the temperature rise between coil and oil. In the $\Delta\theta_{TO}$ and $\Delta\theta_{TC}$, the oil temperature depends on the loading, so it affects the transformer's insulator deterioration factor.

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$$\theta_H = \theta_A + \Delta\theta_{TO} + \Delta\theta_{TC} \tag{2}$$

In the equation (2), the $\Delta\theta_{TO}$ can be represented as eq. (3), which consists of loading rate K_L, loss ratio R, and temperature rise between ambient temperature and oil $\Delta\theta_R$ when transformer loading is rated. In this factor, the loading rate K_L is calculated by real-time TTU information.

$$\Delta\theta_{TO} = \Delta\theta_R \times \left(\frac{K_L \cdot R + 1}{R+1}\right)^{0.8} \tag{3}$$

Also, the IEEE Std. C57.91 defines the lifespan of a distribution transformer that operates at 110°C as 20.55 years. In this condition, the θ_H is 110°C, and the aging factor F_{AA} equals 1 p.u. as shown in eq. (4). When the temperature exceeds 110°C, the aging factor is larger than 1 p.u., which increases the aging of insulators. Otherwise, if the temperature is below 110°C, the aging factor is less than 1 p.u. and can increase the lifespan of the distribution transformer.

$$F_{AA} = e^{\left(\frac{15000}{110+273} - \frac{15000}{\theta_H + 273}\right)} \tag{4}$$

To estimate the aging rate of distribution transformers, this study focuses on transformer loading and leverages neural networks (NN) to predict F_{AA}. The 70% of the TTU history data from ADMS is used as a training dataset to train the NN model and the 30% history data is used to test and verify the performance by using mean squared error (MSE) to validate its performance. The MSE is defined in eq. (5) where e_{rr} is the error between estimation and actual values. Finally, the real-time information of TTU is used as the input for NN to predict the distribution transformers F_{AA}. The NN model is shown in Figure 7.

$$MSE = \frac{1}{n}\sum_{n=1}^{N} e_{rr}^2 \tag{5}$$

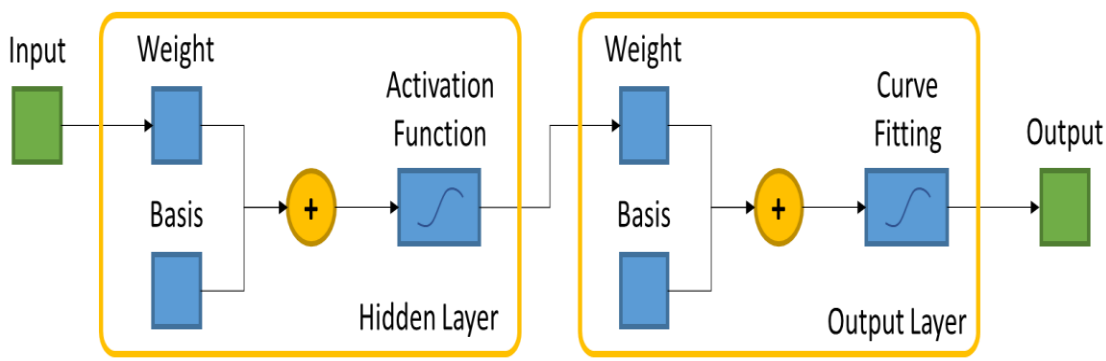

Figure 7.
The structure of the NN model.

To understand the impact of different hidden layers and neurons of the NN model, this study used 70% of TTU history data from ADMS to train and validate model accuracy when the NN is different. The accuracy results are shown in Table 1. Considering the calculation time and simplifying the NN model, the number of hidden layers is selected as 3 layers, and each layer contains 2 neurons, with an accuracy result of 96.61% in this study.

Table 1.
The accuracy results from different hidden layers and neurons.

Neurons / hidden layers	1	2	3	4	5	6	7
1	6.78%	96.05%	96.05%	94.92%	94.92%	96.05%	96.61%
2	7.91%	94.92%	95.48%	95.48%	94.92%	94.92%	94.92%
3	6.78%	96.61%	94.92%	96.05%	94.92%	94.92%	94.92%
4	6.78%	96.61%	95.48%	94.92%	94.92%	94.92%	96.05%
5	7.91%	93.22%	94.92%	94.92%	94.92%	95.48%	95.48%
6	7.91%	94.92%	96.61%	95.48%	95.48%	94.92%	94.92%
7	6.78%	2.26%	95.48%	96.61%	96.05%	94.92%	94.92%

After the training process of the NN model is achieved, the real-time TTU information is used as an input dataset for the NN, and then the aging factor F_{AA} can be estimated. The NN prediction and actual results of the aging factor are shown in Fig. 8. In the figure, the load pattern is different on weekdays and weekends when the distribution transformer serves residential customers. The oil temperature changes based on the transformer loading because heavy loading causes more copper loss in the transformer. The maximum aging factor is 0.198 p.u. on Tuesday noon, and the minimum aging factor is 0.032 p.u. on Monday early morning during a week. This week, the average MSE was 0.03%, which shows the good performance of the proposed NN model for predicting the aging factor of the distribution transformer.

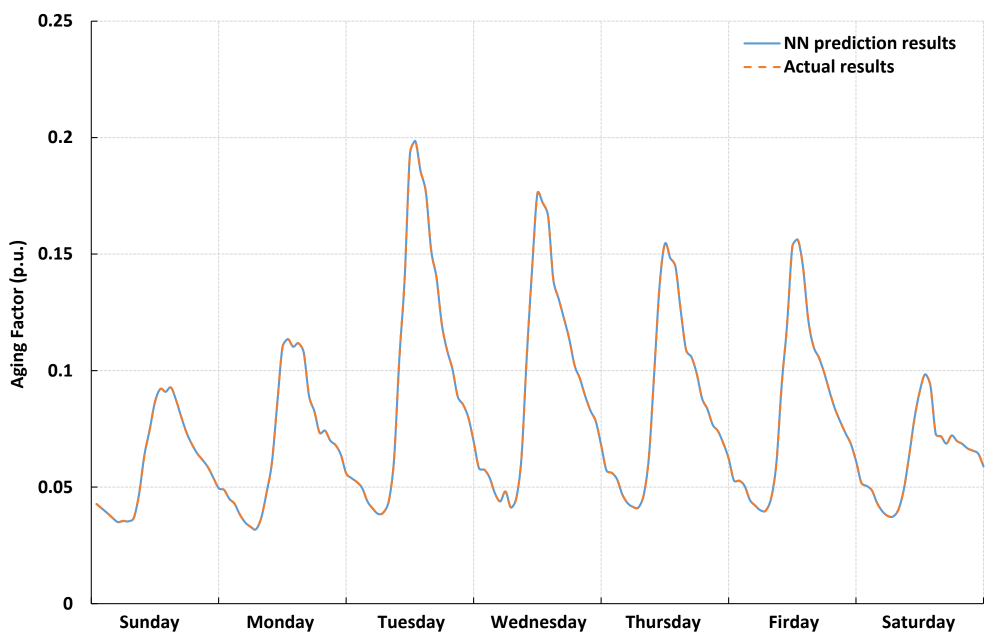

Figure 8.
The NN prediction and actual aging factor during a week.

A graphical user interface (GUI) is developed by PyQt6 for the operation and maintenance of distribution transformers. With the GUI, the maintenance crews perform the operation and maintenance of distribution systems by real-time monitoring. The functions of the front-end in GUI include real-time monitoring. Also, the GUI back-end processes data exchange through the RESTful web service and NN prediction. When receiving TTU information from TMS, the GUI can evaluate the aging factor of the distribution transformer in real-time. Figure 9 shows the aging factor and the health

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status of the distribution transformer with the designed GUI.

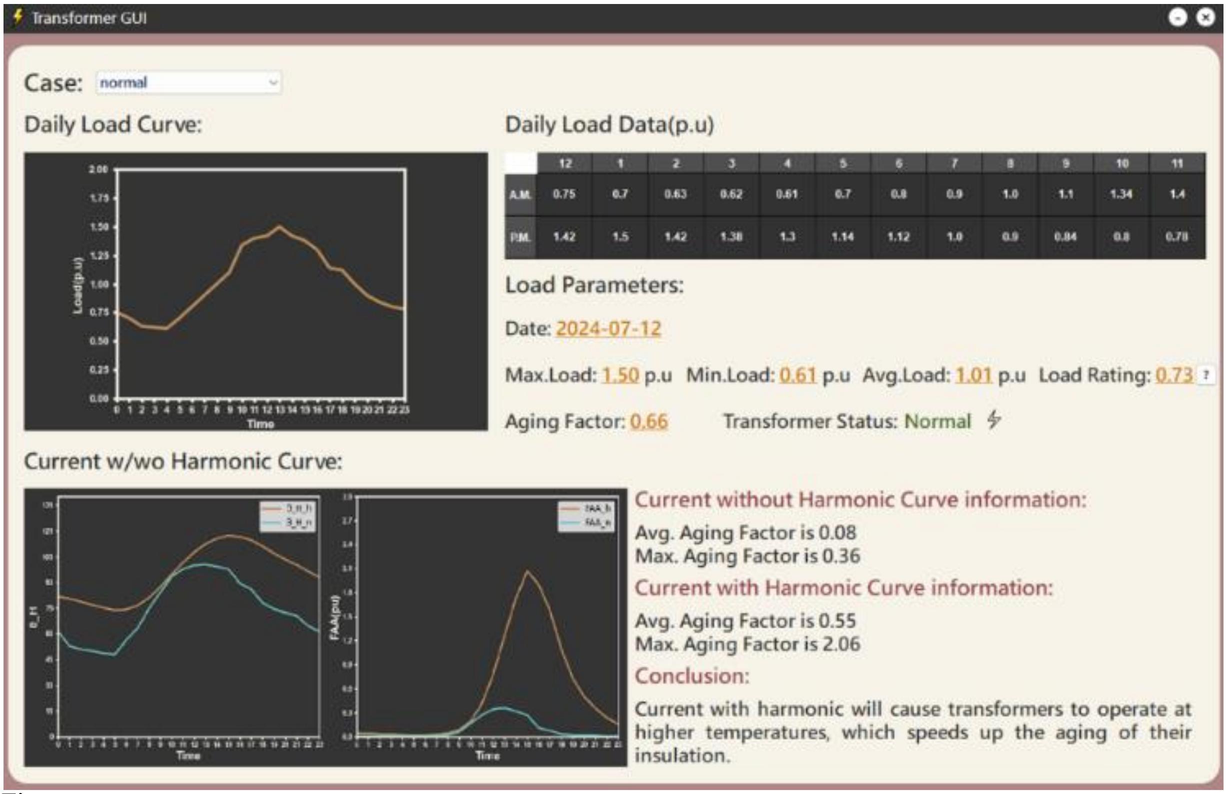

Figure 9.
Designed GUI for aging factor evaluation of distribution transformer.

6. Conclusions

This paper proposes an optimized data exchange approach with CIM by using RESTful for data exchange and NoSQL for data recording of TTUs. The real-time information of TTUs is used to evaluate the aging factor of distribution transformers by trained NN model to assist utility crew to management facility of distribution transformers. The conclusions of this study are as follows:

(1) RESTful utilities use simpler formats than SOAP and thus provide higher efficiency and scalability for data exchange.
(2) In the performance evaluation of databases, a NoSQL database exhibits higher compatibility and efficiency for processing the XML format based on CIM.
(3) The combination of RESTful and NoSQL is proposed as the optimal solution for data exchange between TMS and ADMS for distribution transformer aging estimation.

The proposed method can improve the efficiency of the data exchange process among various management systems and serve as a crucial reference for future research and applications. Also, this study investigates the operation and maintenance of distribution transformers based on the IEEE Std. C57.91 standards. The ADMS history data of TTU is used to train the NN model to estimate the aging factor of distribution transformers. Finally, the GUI is developed to display the aging factor of distribution transformers to achieve real-time monitoring and provide a reference for the utility crew to achieve the asset management of distribution systems.

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References

[1] Electric Power Research Institute (EPRI), "Common Information Model Primer", Dec. 2011.

[2] R. Santodomingo et al., IEC 61970 for Energy Management System Integration. 2016. doi: 10.1002/9781118755471.sgd094.

[3] W3C Recommendation, "RDF Schema 1.1", https://www.w3.org/TR/rdfschema/#ch_summary.

[4] W3C Recommendation, "W3C XML Schema Definition Language (XSD) 1.1 Part 1", https://www.w3.org/TR/xmlschema11-1/.

[5] W3C Recommendation, "SOAP 1.2 Part 1: Messaging Framework", https://www.w3.org/2000/xp/Group/1/08/29/soap12-part1.html.

[6] W. Khan, T. Kumar, Z. Cheng, K. Raj, A. M. Roy, and B. Luo, "SQL and NoSQL Databases Software architectures performance analysis and assessments - A Systematic Literature review," arXiv.org, Sep. 14, 2022. https://arxiv.org/abs/2209.06977v1 (accessed May 08, 2023).

[7] J. V. De Barros and J. B. Leite, "Development of a Relational Database Oriented on the Common Information Model for Power Distribution Networks," 2021 IEEE URUCON, pp. 63–66, Jan. 2021.

[8] A. Meier and M. Kaufmann, SQL & NoSQL Databases: Models, Languages, Consistency Options and Architectures for Big Data Management. Wiesbaden: Springer Fachmedien Wiesbaden, 2019.

[9] Lendak, E. Varga, A. Erdeljan, and M. Gavric, "RESTful web services and the Common Information Model (CIM)," 2010 IEEE International Energy Conference, Manama, Bahrain: IEEE, pp. 716–721, Dec. 2010.

[10] "IEEE Guide for Loading Mineral-Oil-Immersed Transformers and Step-Voltage Regulators," IEEE Std C57.91-2011 (Revision of IEEE Std C57.91-1995), pp. 1–123, Mar. 2012.

[11] H. F. M. Mantilla, A. Pavas, and I. C. Durán, “Aging of distribution transformers due to voltage harmonics,” 2017 IEEE Workshop on Power Electronics and Power Quality Applications (PEPQA), pp. 1–5, May 2017.

[12] Lingming Kong, Wenxiong Mo, Xinyuan Ge, Tian Liu, Fanke Zhou and Haitao Chen, “Application of Insulation Aging Evaluation Method for Distribution Transformers in Practice,” 2020 IEEE International Conference on High Voltage Engineering and Application, pp. 1-4, 2020.

[13] Jiefeng Liu, Qingyin Wang, Xianhao Fan, Yiyi Zhang and Hui Hwang Goh, “Effects of Temperature Gradient Induced Aging and Moisture Distribution on Dielectric Response Measurement for Transformer Insulation,” IEEE Transactions on Instrumentation and Measurement, vol. 71, pp. 1-10, Apr. 2022.

[14] Mohammed Z. Hussain, Samir Gupta, William Brown and Qais Alsafasfeh, “Nonlinear Load Harmonics and Their Impact on Aging in Dry-Type Transformers,” 2024 IEEE/PES Transmission and Distribution Conference and Exposition, pp. 1-5, May, 2024.

[15] Haifei Wang, Tingkang Wang, Manyu Xue, Jianming Sun, Wei Xiong and Yuning Hou, “Research on Overload Capability of Dry Distribution Transformer Based on Hot Spot Temperature Model,” 2019 22nd International Conference on Electrical Machines and Systems, pp. 1-5, Aug. 2019.

[16] Harold Francisco Mazo Mantilla, Andrés Pavas and Iván Camilo Durán, “Aging of distribution transformers due to voltage harmonics,” 2017 IEEE Workshop on Power Electronics and Power Quality Applications, pp. 1-5, May 2017.