International Information and Engineering Technology Association
Advancing the World of Information and Engineering

Journal Européen des Systèmes Automatisés
Vol. 58, No. 12, December, 2025, pp. 2603-2608
Journal homepage: http://iieta.org/journals/jesa

# Real-time Communications Network Modeling for Critical Virtual Power Plant Applications

Ahmed I. Alghannam[1*], Firas S. Alsharbaty[2]

[1] Department of Electrical Engineering, College of Engineering, University of Mosul, Mosul 41001, Iraq
[2] Department of Communications and Intelligent Digital Systems Engineering, College of Engineering, University of Mosul, Mosul 41001, Iraq

Corresponding Author Email: ahmed_edrees@uomosul.edu.iq

Copyright: ©2025 The authors. This article is published by IIETA and is licensed under the CC BY 4.0 license (http://creativecommons.org/licenses/by/4.0/).

https://doi.org/10.18280/jesa.581213

**Received:** 21 September 2025
**Revised:** 26 November 2025
**Accepted:** 1 December 2025
**Available online:** 31 December 2025

***Keywords:***
*communications network, IEC 61850, MMS message, real-time, VPP services*

**ABSTRACT**

A reliable two-way communication network is vital for the operation of a virtual power plant (VPP). It supports the continuous flow of monitoring and control information between distributed energy resources (DERs) and the VPP control center (VPPCC). The VPP provides a wide range of services through its DERs, and each service requires specific end-to-end (ETE) delay and data reliability. These requirements must be carefully considered when designing the communications network infrastructure. In this work, a communications network based on the IEC 61850 standard is proposed to meet the stringent requirements of time-critical services, such as emergency frequency support and emergency demand response. The performance of the proposed network was validated using a simulation model, with ETE delay and data reliability considered as key evaluation metrics. The simulation results show an ETE delay of 5.17 ms for MMS messages, while the reliability of the received data reaches 99.999%.

## 1. INTRODUCTION

The VPP concept is one of the most practical and promising solutions in modern energy management. It offers significant advantages by integrating communication networks and embedded systems into the power system. VPP enables real-time monitoring and improved energy efficiency through bidirectional energy flow and close coordination among all entities [1]. From a communications network perspective, a VPP is a group of interconnected entities that exchange operational information over a secure and reliable bidirectional communication network, designed to meet the needs of VPP applications [2]. These entities include DERs, VPPCC, transmission system operator (TSO), distribution system operator (DSO), and the energy market [3].

The communications network in VPP operates in two directions. The first, known as downstream communication, connects the VPPCC to the DERs. The second, referred to as upstream communication, links the VPPCC to the energy market as well as to the T&D system operators [4]. There are two main types of VPPs: the commercial VPP, which focuses on energy trading and participation in the energy market, and the technical VPP, which collaborates with T&D system operators to provide technical support services such as balancing and flexibility [5, 6]. Figure 1 illustrates the VPP's bidirectional communications network.

The VPPCC architecture consists of several units, including a control unit, an optimization unit, a reporting unit, a calculation unit, and a database unit. Each unit is responsible for specific tasks that integrate with the others to support effective monitoring and control of all DERs under the VPP's management [7]. In contrast, each DER contains a DER controller that stores the operating state, performs supervisory control, sets operating points, and manages the grid connection.

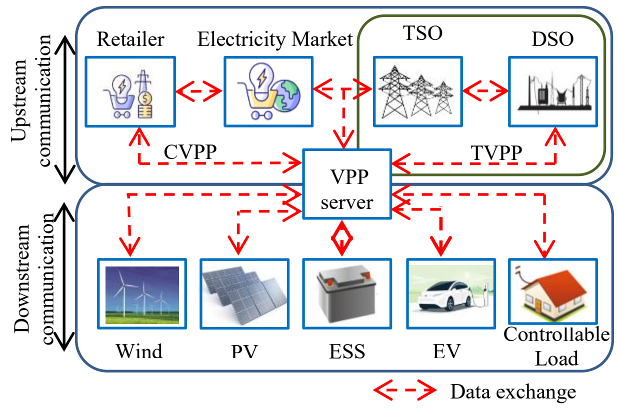


**Figure 1.** VPP communications network

Through a two-way communication network, the VPPCC receives information from DERs, such as capacity, generation output, and other operating parameters. It also sends commands to the DERs regarding on/off operations and power output adjustments [8]. The communication network used is a wide area network (WAN), providing extensive coverage and high data rates [9].

Industrial automation systems utilize several communication protocols, including Distributed Network Protocol 3 (DNP3), Modbus, Message Queuing Telemetry

Transport (MQTT), and IEC 61850. Each protocol has specific strengths and suitable applications. Modbus is characterized by its simplicity and low cost. It is widely used in process control and SCADA systems for data exchange. However, it lacks encryption and authentication, making it vulnerable to various security threats. DNP3 is designed for communication between a SCADA/HMI as master device and remote PLC/RTU as slave device. MQTT is suitable for sending non-critical monitoring data from substations to enterprise applications or Internet of Things (IoT) systems. Finally, IEC 61850 is an international standard for substation automation that establishes unified communication protocols to ensure compatibility and seamless integration across devices from different vendors. It employs secure communication protocols between SCADA systems and IEDs/RTUs, such as circuit breakers and smart meters [10].

To ensure smooth data exchange and interoperability, standardized communication protocols are applied. Among all standards used in VPP communications, IEC 61850 is the most important because of its strong interoperability features [11, 12].

There is limited literature on IEC 61850-based VPP communications from a communications network perspective. Sun et al. [13] proposed an information model for monitoring DERs in a VPP based on the IEC 61850 standard. In addition, the Jabber protocol was studied and tested to enable real-time communication services. Xiang and Zheng [14] presented a method for evaluating delays in both idle and online states, considering the communication links of a VPP. A communications network model was developed using a simulation program, and the results showed that this method can meet the real-time requirements of some VPP services. Etherden et al. [15] presented a conceptual framework for interoperability requirements between entities within a VPP and conducted a comparative study of how existing communications technologies address these requirements. Their work compared the needs of VPPs with the capabilities of the IEC 61850 standard and proposed extending the standard to improve the interaction between VPPs and DERs.

The main contributions of this research are:

1) Design and configuration of a reliable bidirectional communication network that meets the time-critical service requirements of a VPP network.

2) Modeling IEC 61850-based MMS data messages exchanged between a VPPCC and DERs over TCP.

3) Simulating and evaluating the proposed communication network using key performance metrics, including data reliability and ETE delay.

## 2. METHODS AND MATERIALS

### 2.1 VPP system description

To evaluate the performance of the communications network supporting VPP services in terms of ETE delay and data reliability, a VPP model was used. It consists of five DER units spread over a geographical area of 50 × 50 kilometers. These units include photovoltaic systems, a generator, a wind turbine, a controllable load, and an energy storage system. The VPPCC is located in the center of the region. It is responsible for monitoring and regulating the operation of all DERs units through a secure and reliable two-way communication network.

### 2.2 The adopted communication protocol

The international standard IEC 61850 provides data modeling and communication services. Communication services for information exchange defined in this standard are delivered through three main protocols: Sampled Values (SV), Generic Object-Oriented Substation Events (GOOSE), and Manufacturing Message Specification (MMS) [16, 17]. The MMS Messaging Protocol is an application-layer protocol primarily designed for remote control and monitoring of devices [18]. MMS establishes a messaging process that supports real-time devices and functions modeling, data exchange, processing, and control information management among applications or devices in a network [19]. This protocol is built on the OSI model to ensure interoperability between communication devices and uses ISO-defined basic protocols for encapsulating network layers data, as presented in Figure 2 [20].

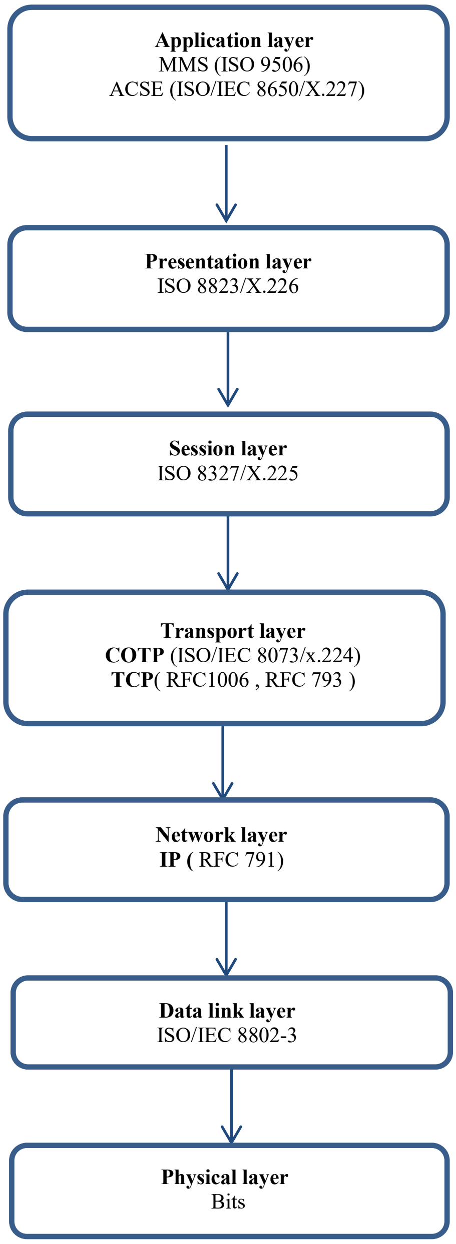


**Figure 2.** MMS Protocol over the OSI model

An MMS message contains an IP header and can be simply routed over a WAN network [21]. Therefore, it is used to monitor and control DERs through a client-server connection between DER unit controller and the VPPCC. The MMS architecture takes the form of a client-server model. Smart industrial devices act as the MMS server, allowing the MMS client to access, monitor, and control information. This makes the MMS client potentially an application or HMI in the control center. Consequently, the DER unit controller acts as the MMS server and the VPPCC acts as the MMS client. In the monitoring process, power measurements from the DER unit controller are transmitted to the VPPCC, while in the control process, control signals are transmitted from the VPPCC to the DER unit controller. In the MMS server there is a Virtual manufacturing Device as shown in Figure 3. It provides a comprehensive view of the server to the client and includes the current state of the devices through variables in the form of objects. The mechanism of access to the objects by the client through several services such as read, write, define, and manage variables [22].

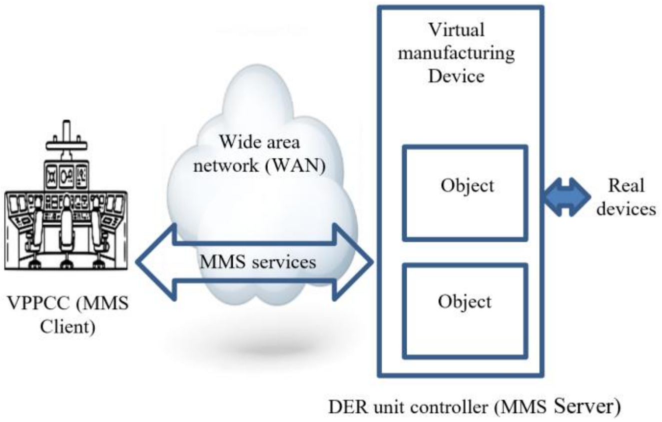


**Figure 3.** MMS messaging protocol structure

To exchange information between the VPPCC (MMS Client) and DER unit controller (MMS Server) via MMS messages, three main steps are performed [23]:

1) Establish a TCP socket connection.

2) Initiate a transport association via the Connection-Oriented Transport Protocol (COTP).

3) Initiate the exchange of MMS messages.

Figure 4 depicts the sequence of messages involved in MMS data exchange. After the standard three-way TCP handshake between the MMS client and the MMS server, the Connection- COTP layer establishes a connection or a path for ISO protocols over TCP. This process involves a Connection Request message initiated by the MMS client and a Connection Confirm message returned by the MMS server.

Subsequently, the MMS Initiation/Bind procedure is carried out. In this phase, the MMS Initiation Request is mapped onto the Application Association Request data unit of the ACSE layer and transmitted through the COTP layer. The MMS server replies with an Initiation Response, which is mapped to the Application Association Response data unit of the ACSE layer, likewise transmitted via the COTP layer. Upon receipt of this Initiation Response, the MMS client completes the establishment of the MMS connection, enabling the client and the server to commence MMS data exchange. The MMS message type 2 used, where the transmission time for a type 2 message must be less than 100 msec.

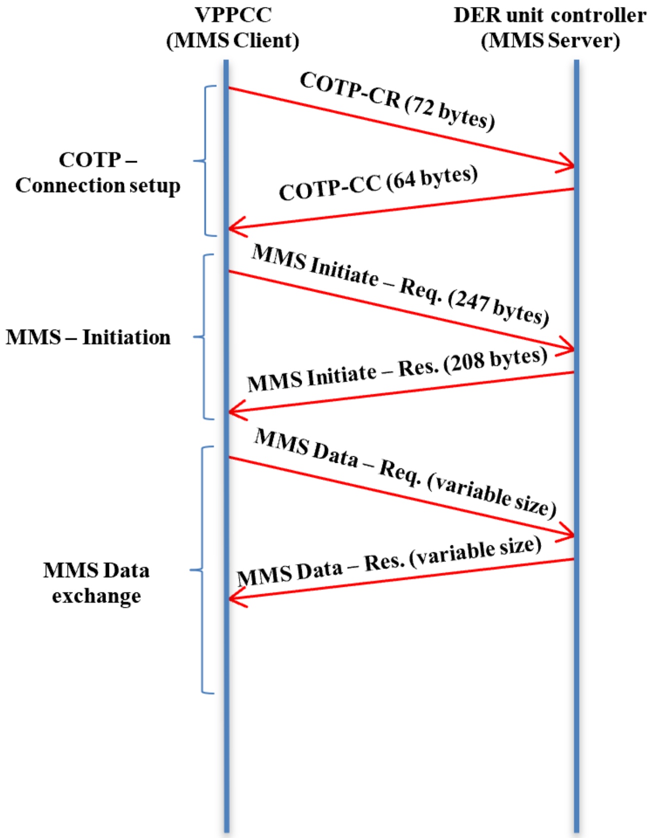


**Figure 4.** MMS data exchange between VPPCC and DER unit controller

### 2.3 VPP services requirements

The VPP plant participates in several services in the energy market provided by its DERs [24]. Some of these services include demand response, peak load regulation, frequency control, and the energy trading market. Each service has time requirements related to response time, required ETE delay, and data reliability according to IEEE and IEC standards. Table 1 shows the requirements for these services, ranked from lowest ETE delay to highest ETE delay. Emergency frequency support and emergency demand response appear to require the least ETE delay compared to the other services. Therefore, providing a communication network that meets the requirements of this service is critical.

**Table 1.** VPP services [25]

| VPP Services | Required ETE Delay | Reliability | Event Types |
|---|---|---|---|
| Emergency frequency support | Less than 20 msec | 99.999% | Event-triggered |
| Emergency demand response | Less than 50 msec | 99.999% | Event-triggered |
| Normal demand response | 0.5 - 1.1 sec | 99.999% | Periodic (minutes) Time-triggered |
| Peak regulation | Less than 6 sec | 99.99% | Periodic (seconds) Time-triggered |
| Energy trade market | Less than 10 sec | 99.99% | - |

It is worth mentioning that studies evaluating ETE delay in the communication network for time-critical services such as frequency regulation through emergency demand response have shown that an ETE delay greater than 500 msec can lead to frequency instability. It is also noted that most studies consider an ETE delay of about 20 msec to be an acceptable value [26].

### 2.4 Proposed communications network

The proposed wired communication network for the virtual power plant model is designed in accordance with IEC 61850, as illustrated in Figure 5. The model consists of five DER unit controllers and a VPPCC, each connected to the backbone network via an Ethernet switch and a gateway. A 100 Mbps link is used for all connections in the communication network. OPNET modeler 14.5 is used to model the suggested communications network. The main model configuration parameters are described in Table 2.

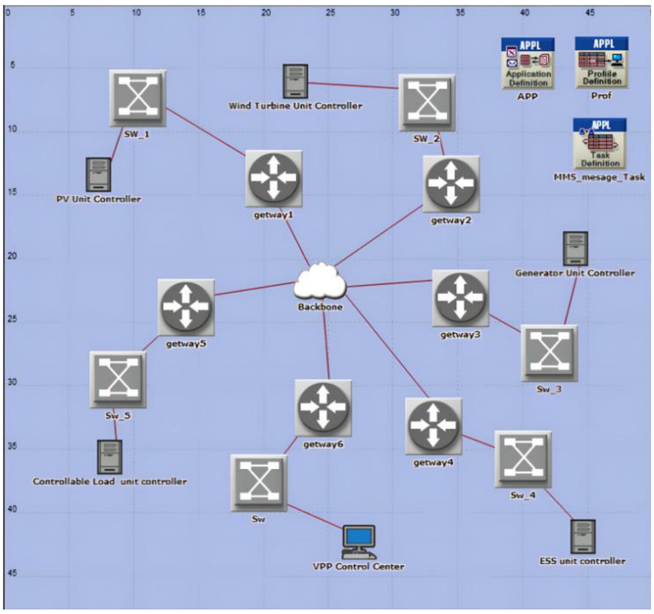


**Figure 5.** Proposed wired network topology

**Table 2.** Configuration model parameters

| Parameters | Description |
|---|---|
| Protocol | TCP/IP |
| Interval time | 30 sec |
| Start application time | 250 sec |
| Traffic request / node | 14.3 byte/sec |
| Traffic response /node | 20.3 byte/sec |
| Simulation time | 3500 sec |
| Node type | Ethernet (wired) |

The MMS messages are modeled to enable data exchange between all DER unit controllers and the VPPCC.

## 3. RESULTS AND DISCUSSIONS

To verify the performance of the proposed communication network in meeting the services requirements for ETE delay and data reliability, a simulation scenario was developed using the OPNET modeler 14.5.

The exchange of data process via MMS messages between the VPPCC and the DER unit controller occurs in three phases. Figure 6 shows the ETE delay in the communication network for each phase, while Figure 7 shows the total ETE delay. The total ETE delay is approximately 5.17 milliseconds, which is significantly lower than the minimum ETE delay required for critical VPP services, such as emergency frequency support and emergency demand response.

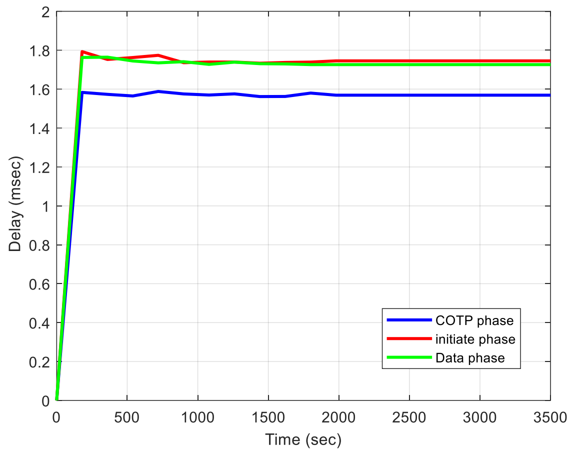


**Figure 6.** MMS message phase ETE delay

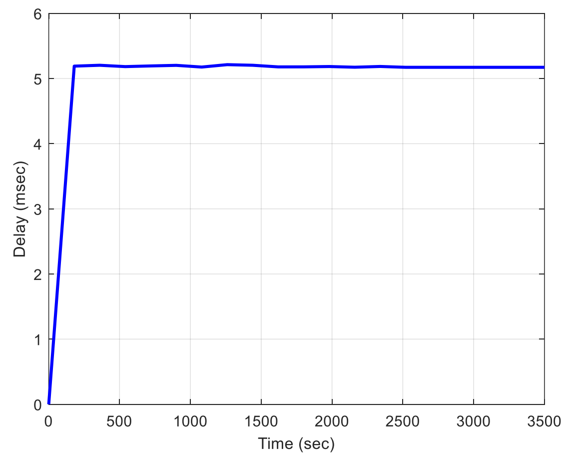


**Figure 7.** Total MMS message ETE delay

Based on ETE delay analysis, the reliability of the communication system was also evaluated. The traffic load was first sent as a request from the VPPCC (MMS client) to the DER unit controller (MMS server) and received without any data loss at a data rate of 14.3 bytes/second, as shown in Figure 8. Subsequently, the traffic load was sent as a response from the DER unit controller (MMS server) to the VPPCC (MMS client), as shown in Figure 9, and was also received without any data loss at a data rate of 20.3 bytes/second.

Finally, VPP applications inherently exhibit variations in the size of data transmitted via MMS messages. Therefore, the communication network was evaluated under high data traffic, as shown in Figure 10. This high data traffic represents the worst-case scenario for the communication network, illustrating the impact of load variations on network performance. The results showed that the network remained stable, with data reception reliability reaching 99.999%, and ETE delay consistently remaining well below the acceptable threshold.

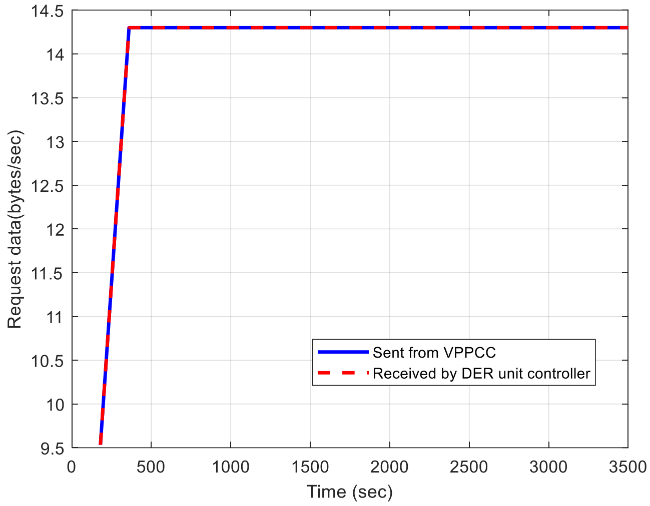


**Figure 8.** MMS data request

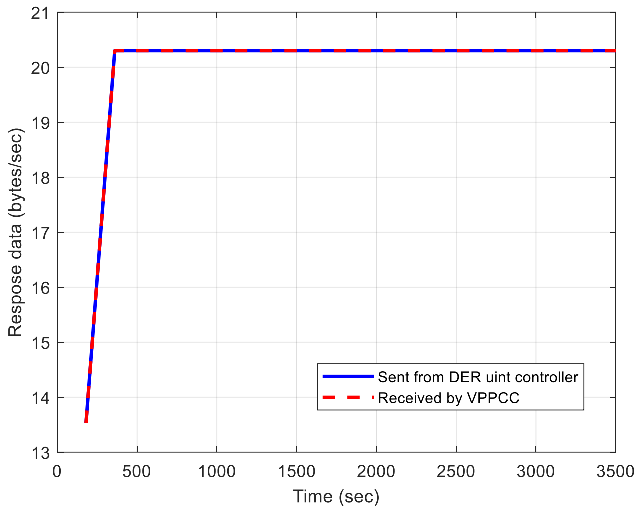


**Figure 9.** MMS data response

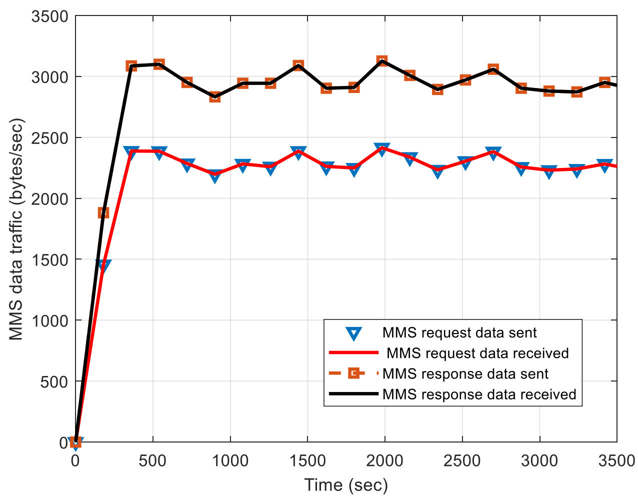


**Figure 10.** MMS sent and received data

The results indicate, the proposed communications network of the VPP leverages high performance to enhance the stability of electrical power systems and support broader sustainability goals. It also facilitates the integration of clean energy sources into the electrical grid and delivers cost-saving benefits to Prosumers.

## 4. CONCLUSIONS

Designing a communications network that meets the ETE delay and data reliability requirements for VPP services is essential. Certain services have stringent time constraints, such as emergency frequency support and emergency demand response, which require network ETE delays of no more than 20 milliseconds and 50 milliseconds, respectively, to function effectively. Therefore, the design of the communications network including routers, switches, servers, transmission lines, and their characteristics, must comply with these requirements.

To achieve interoperability between communication interfaces, the IEC61850 standard is used. This standard defines communication services and data models, and specifies MMS messages for communication between the VPPCC (MMS client) and the DER unit controller (MMS server). In this research, a communications network was proposed that connects the VPPCC as an MMS client to five DERs, each equipped with a DER unit controller as an MMS server. Simulation results demonstrate that the proposed IEC 61850-based network achieves an ETE delay of 5.17 milliseconds and a data reliability of 99.999%, while ensuring interoperability between components. Finally, under conditions of heavy traffic, the network maintained stable performance, achieving 99.999% data reliability, while ETE delay percentages consistently stayed well below the acceptable threshold.

The future work will focus on addressing the cybersecurity issues of the proposed VPP communications network, broader integration with clean energy modules and consumers, large-scale scalability testing, and the integration of advanced technologies such as edge computing and AI-based optimization strategies.

## ACKNOWLEDGMENT

The authors are grateful for all the support that was provided by the University of Mosul.

## REFERENCES

[1] Rouzbahani, H.M., Karimipour, H., Lei, L. (2021). A review on virtual power plant for energy management. Sustainable Energy Technologies and Assessments, 47: 101370. https://doi.org/10.1016/j.seta.2021.101370

[2] Ruan, G., Qiu, D., Sivaranjani, S., Awad, A.S., Strbac, G. (2024). Data-driven energy management of virtual power plants: A review. Advances in Applied Energy, 14: 100170. https://doi.org/10.1016/j.adapen.2024.100170

[3] Nafkha-Tayari, W., Ben Elghali, S., Heydarian-Forushani, E., Benbouzid, M. (2022). Virtual power plants optimization issue: A comprehensive review on methods, solutions, and prospects. Energies, 15(10): 3607. https://doi.org/10.3390/en15103607

[4] Kolenc, M., Ihle, N., Gutschi, C., Nemček, P., et al. (2019). Virtual power plant architecture using OpenADR 2.0 b for dynamic charging of automated guided vehicles. International Journal of Electrical Power & Energy Systems, 104: 370-382. https://doi.org/10.1016/j.ijepes.2018.07.032

[5] Venegas-Zarama, J.F., Muñoz-Hernandez, J.I., Baringo, L., Diaz-Cachinero, P., De Domingo-Mondejar, I. (2022). A review of the evolution and main roles of virtual power plants as key stakeholders in power systems. IEEE Access, 10: 47937-47964. https://doi.org/10.1109/access.2022.3171823
[6] Naval, N., Yusta, J.M. (2021). Virtual power plant models and electricity markets-A review. Renewable and Sustainable Energy Reviews, 149: 111393. https://doi.org/10.1016/j.rser.2021.111393
[7] Zajc, M., Kolenc, M., Suljanović, N. (2019). Virtual power plant communication system architecture. In Smart Power Distribution Systems, pp. 231-250. https://doi.org/10.1016/B978-0-12-812154-2.00011-0
[8] Bhuiyan, E.A., Hossain, M.Z., Muyeen, S.M., Fahim, S.R., Sarker, S.K., Das, S.K. (2021). Towards next generation virtual power plant: Technology review and frameworks. Renewable and Sustainable Energy Reviews, 150: 111358. https://doi.org/10.1016/j.rser.2021.111358
[9] Kuzlu, M., Pipattanasomporn, M., Rahman, S. (2014). Communication network requirements for major smart grid applications in HAN, NAN and WAN. Computer Networks, 67: 74-88. https://doi.org/10.1016/j.comnet.2014.03.029
[10] Muhammad, M., Alshra'a, A.S., German, R. (2024). Survey of cybersecurity in smart grids protocols and datasets. Procedia Computer Science, 241: 365-372. https://doi.org/10.1016/j.procs.2024.08.049
[11] Das, N., Haque, A., Zaman, H., Morsalin, S., Islam, S. (2024). Exploring the potential application of IEC 61850 to enable energy interconnectivity in smart grid systems. IEEE Access, 12: 56910-56923. https://doi.org/10.1109/access.2024.3390713
[12] Tan, H.C., Mohanraj, V., Chen, B., Mashima, D., Nan, S.K.S., Yang, A. (2021). An IEC 61850 mms traffic parser for customizable and efficient intrusion detection. In 2021 IEEE International Conference on Communications, Control, and Computing Technologies for Smart Grids (SmartGridComm), pp. 194-200. https://doi.org/10.1109/smartgridcomm51999.2021.9632304
[13] Sun, L., Chen, Y., Du, Q., Cheng, Q., Ding, R., Liu, Z. (2024). Virtual power plant for monitoring of distributed energy resources using extensible messaging and presence protocol. Sustainable Energy, Grids and Networks, 38: 101365. https://doi.org/10.1016/j.segan.2024.101365
[14] Xiang, J.N., Zheng, Q.R. (2023). A method for measuring network channel delay for virtual power plant aggregation control. In 2023 IEEE 11th Joint International Information Technology and Artificial Intelligence Conference (ITAIC), Chongqing, China, pp. 1505-1508. https://doi.org/10.1109/itaic58329.2023.10409004
[15] Etherden, N., Vyatkin, V., Bollen, M.H. (2015). Virtual power plant for grid services using IEC 61850. IEEE Transactions on Industrial Informatics, 12(1): 437-447. https://doi.org/10.1109/tii.2015.2414354
[16] Farooq, S.M., Hussain, S.S., Ustun, T.S. (2019). Performance evaluation and analysis of IEC 62351-6 probabilistic signature scheme for securing GOOSE messages. IEEE Access, 7: 32343-32351. https://doi.org/10.1109/access.2019.2902571
[17] Ustun, T.S., Hussain, S.S. (2019). Implementation of IEC 61850 based integrated EV charging management in smart grids. In 2019 IEEE Vehicle Power and Propulsion Conference (VPPC), pp. 1-5. https://doi.org/10.1109/vppc46532.2019.8952263
[18] Ushakov, V.Y., Rakhmonov, I.U., Askarov, A.B., Nikitin, D.S. (2025). Digitalization of Electrical Power Engineering: Scientific and Technical Fundamentals and Achieved Advantages. Springer. https://doi.org/10.1007/978-3-031-95705-5
[19] Gaj, P., Sawicki, M., Kwiecień, A. (Eds.). (2019). Computer Networks: 26th International Conference, CN 2019, Kamień Śląski, Poland, June 25-27, 2019, Proceedings (Vol. 1039). Springer. https://doi.org/10.1007/978-3-030-21952-9
[20] Ma, Q., Cong, Z., Shi, Z., Chen, F., Li, J. (2021). Design of cyber security monitoring system for smart substation. In International Conference on Genetic and Evolutionary Computing, pp. 125-136. https://doi.org/10.1007/978-981-16-8430-2_12
[21] Ali, I., Hussain, S.S. (2017). Control and management of distribution system with integrated DERs via IEC 61850 based communication. Engineering Science and Technology, an International Journal, 20(3): 956-964. https://doi.org/10.1016/j.jestch.2016.11.017
[22] Alipour, H., Fazaeli, M.H., Keramat, M.M. (2022). Over view on virtual manufacturing device in substation automation. In 2022 International Conference on Protection and Automation of Power Systems (IPAPS), Zahedan, Iran, Islamic Republic of, pp. 1-5. https://doi.org/10.1109/ipaps55380.2022.9763239
[23] Gautam, A., Ashok, S. (2019). Problem diagnostic method for IEC61850 MMS communication network. In Advances in Control, Signal Processing and Energy Systems: Select Proceedings of CSPES 2018, pp. 41-54. https://doi.org/10.1007/978-981-32-9346-5_4
[24] Plancke, G., De Vos, K., Belmans, R., Delnooz, A. (2015). Virtual power plants: Definition, applications and barriers to the implementation in the distribution system. In 2015 12th International Conference on the European Energy Market (EEM), pp. 1-5. https://doi.org/10.1109/eem.2015.7216693
[25] Wu, J., Liu, C., Tao, J., Liu, S., Gao, W. (2023). Hybrid traffic scheduling in 5G and time-sensitive networking integrated networks for communications of virtual power plants. Applied Sciences, 13(13): 7953. https://doi.org/10.3390/app13137953
[26] Pourmousavi, S.A., Nehrir, M.H. (2012). Real-time central demand response for primary frequency regulation in microgrids. IEEE Transactions on Smart Grid, 3(4): 1988-1996. https://doi.org/10.1109/tsg.2012.2201964