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Performance of Communication Network for Monitoring Utility Scale Photovoltaic Power Plants

Ali M. Eltamaly [1,2,3,*], Mohamed A. Ahmed [4,5], Majed A. Alotaibi [6], Abdulrahman I. Alolah [6] and Young-Chon Kim [7]

1 Sustainable Energy Technologies Center, King Saud University, Riyadh 11421, Saudi Arabia
2 Department of Electrical Engineering, Mansoura University, Mansoura 35516, Egypt
3 Saudi Electricity Company Chair in Power System Reliability and Security, King Saud University, Riyadh 11421, Saudi Arabia
4 Department of Electronic Engineering, Universidad Técnica Federico Santa María, Valparaíso 2390123, Chile; mohamed.abdelhamid@usm.cl
5 Department of Communications and Electronics, Higher Institute of Engineering & Technology–King Marriott, Alexandria 23713, Egypt
6 Department of Electrical Engineering, College of Engineering, King Saud University, Riyadh 11421, Saudi Arabia; majedalotaibi@ksu.edu.sa (M.A.A.); alolah@ksu.edu.sa (A.I.A.)
7 Department of Computer Engineering and Smart Grid Research Center, Jeonbuk National University, Jeonju 561-756, Korea; yckim@jbnu.ac.kr
* Correspondence: eltamaly@ksu.edu.sa

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Abstract: The grid integration of large scale photovoltaic (PV) power plants represents many challenging tasks for system stability, reliability and power quality due to the intermittent nature of solar radiation and the site accessibility issues where most PV power plants are located over a wide area. In order to enable real-time monitoring and control of large scale PV power plants, reliable two-way communications with low latency are required which provide accurate information for the electrical and environmental parameters as well as enabling the system operator to evaluate the overall performance and identify any abnormal conditions and faults. This work aims to design a communication network architecture for the remote monitoring of large-scale PV power plants based on the IEC 61850 Standard. The proposed architecture consists of three layers: the PV power system layer, the communication network layer, and the application layer. The PV power system layer consists of solar arrays, inverters, feeders, buses, a substation, and a control center. Monitoring parameters are classified into different categories including electrical measurements, status information, and meteorological data. This work considers the future plan of PV power plants in Saudi Arabia. In order to evaluate the performance of the communication network for local and remote monitoring, the OPNET Modeler is used for network modeling and simulation, and critical parameters such as network topology, link capacity, and latency are investigated and discussed. This work contributes to the design of reliable monitoring and communication of large-scale PV power plants.

Keywords: large scale photovoltaic power plant; IEC 61850 Standard; communication architecture; wired communication; Ethernet

1. Introduction

Saudi Arabia is moving forward toward increasing the grid integration of large-scale photovoltaic (PV) power plants, supported by great opportunities of having long sunshine hours and high solar radiation intensity [1]. Different projects have been scheduled to be constructed, such as Qurrayat (200 MW), Alfaisalia (600 MW), Rabigh (300 MW), Jeddah (300 MW), Saad (300 MW), etc. [2].

These projects are expected to contribute to reducing the use of conventional fossil fuels and decreasing carbon dioxide emissions. Generally, the PV power systems are classified into three main categories: residential, commercial and utility scale. The residential types represent the smallest type of installations, with capacities less than 10 kW, usually used in private properties. The commercial installations are commonly used in commercial buildings with capacities ranging from 10 to 100 kW. This research targets the utility scale PV power plants (solar farms) with capacities above 100 kW [3]. As more and more PV power plants are integrated into the power grid, communication infrastructures will play an important role in the monitoring, protection and control of both PV power plants and the power grid.

Due to the intermittent nature of solar power generation, there are many operational and technical challenges including shading, soiling, cell aging, cell damage, multi-vendor equipment, etc. which make it difficult to identify and troubleshoot the abnormal conditions [3]. As most large-scale PV power plants are installed in remote sites over a large geographic area, communication infrastructures will play an important role in the monitoring, operating and controlling of PV power plants. The communication infrastructures enable the control center operator to detect any fault early before it causes a catastrophic problem, with the aim of increasing the PV power plant availability and decrease the operation and maintenance costs. With the absence of a unified communication architecture, different vendors and solar panel manufacturers are developing their own monitoring and control solutions according to their needs.

There are different configurations and topologies for large-scale PV power plants. The authors in [4] studied large scale PV power plants and provided a detailed description for the main electrical components (PV panels, PV inverters and transformers), the internal PV power plant configuration and the collection grid topologies (radial, ring and star). The authors in [5] presented various power conversion architectures (central inverter, string inverter, multi-string inverter and micro-inverter) and different strategies for reconfigurations of photovoltaic arrays in order to increase the output power under different conditions (mismatch condition and partial shading).

The basic elements of the PV monitoring system are sensors, data transmission, data storage and data analysis. The monitoring system for PV power plant can be divided into different levels: PV module level, string level, array level, and plant level. With respect to the PV module level, in order to enable efficient real-time monitoring and control, detailed information of each panel is required such as current, voltage, irradiance and temperature [6]. The authors in [7] presented a low-cost wireless monitoring system for PV modules in order to give details information for the performance of the PV panels. The collected information includes meteorological and electrical data from the PV system. Different types of sensor nodes are considered including module temperature, solar irradiance, current, and voltage. The authors in [8] developed a wireless solution for the remote monitoring of PV modules based on long range (LoRa) low power wireless area network (LPWAN) communication technology. However, the system performance in [7] and [8] considered a small-scale PV system with a small number of sensor nodes.

There are different studies regarding monitoring the behavior of PV modules and PV power plants. The authors in [9] developed a monitoring circuit which measures the operating voltage and the current of the PV panel. With the developed circuit, the behavior of the PV modules could be identified under normal/shading conditions. The authors in [10] investigated the appropriate number and the position of the irradiance sensors to be installed in large PV power plant. The authors in [11] developed a condition monitoring system for monitoring and control of a photovoltaic system consists of 60 PV modules and three inverters. The monitoring system consists of various sensor nodes including voltage, current and temperature. The communication system is based on ZigBee wireless network technology. The authors in [12] classified the condition monitoring of PV system into different levels including grid level monitoring, inverter level monitoring, array level monitoring, string level monitoring and module level monitoring. Among different monitoring methods, module level monitoring was capable of identifying the location of the faults and abnormality through sensor

nodes mounted on PV modules. However, a large volume of data needs to be communicated between PV modules and the control center.

Recently, the application of the internet of things (IoT), computer vision and unmanned aerial vehicle (UAV) have received great attention in remote monitoring of PV power plants. The authors in [13] presented an IoT architecture for remote monitoring of a solar photovoltaic system. The monitoring system consists of a PV module attached with different sensor nodes and measurement devices including pyranometer, voltage, current, temperature, humidity and video camera. The authors in [14] presented the application of computer vision and UAV for remote condition monitoring for photovoltaic systems. The system consists of a drone with a radiometric thermal camera and an algorithm for the detection of hotspots. The authors in [15] investigated hybrid communication networks for distributed energy resources (DER) with the focus on rooftop solar PV panels using network simulator 3 (NS3). The hybrid communication architectures included different technologies such as Ethernet, WiFi and WiMAX, and the performance was evaluated with respect to latency, throughput and packet loss rate. The authors in [16] presented modeling intelligent electric devices (IEDs) for different types of DERs based on IEC 61850 standard and simulation of communication configuration using OPNET Modeler for a microgrid system. The performance of the communication network was evaluated with respect to end-to-end delay and throughput.

Considering the previous research work related to the monitoring system of PV systems, as given in Table 1, there is a knowledge gap regarding the performance of the communication infrastructures associated with monitoring large-scale PV power plants with respect to network topology, network traffic and application definition, which have not received much attention in the literature. This work aims to study the performance of the communication infrastructure associated with remote monitoring and control of large-scale PV power plants. The major elements of a PV power plant are PV arrays, PV inverters, feeders, buses, meteorological masts, substations, and the control center. The communication infrastructure comprises measurement devices (sensor nodes, meters and intelligent electronic devices) and networking components (network switches, cables, and servers). Monitoring parameters are classified into different types: environmental information, status information and electric information based on IEC 61724 standard. In order to design the communication network, many factors should be determined, including the number and types of sensor nodes and the generated amount of data. Network topology, link capacity, and latency are critical parameters investigated and discussed. The main contributions of this research are as follows:

- Design a communication network architecture for remote monitoring of large scale PV power plants based on the IEC 61850 Standard. The proposed architecture consists of three layers: the PV power system layer, the communication network layer, and the application layer.
- Classify monitoring parameters into different types: environmental information, status information and electric information based on IEC 61724 standard.
- Propose a communication model for the PV power system and define data types, data size and the number of sensor nodes.
- Build communication network models for the PV system using OPNET Modeler and evaluate the network performance with respect to end-to-end delay for a single PV power plant and a group of PV power plants from different regions in Saudi Arabia.

Table 1. Comparison among monitoring system used in photovoltaic (PV) power plant.

Ref.	PV Monitoring System			Comments	
	Sensors	Data Transmission	Storage and Analysis		
[3]	No	Yes	No	RS-485 → Between inverter and data logger Ethernet, WiFi, ZigBee → local monitoring RS-232 and USB → On-site configuration	Overview of communication systems for grid integration of PV power plants
[6]	No	No	Yes	Application of machine learning and computer vision for improving the reliability of PV arrays	
[7]	Yes	Yes	No	RF data transmission between sensor nodes (for electric data and meteorological data) and the gateway	Low cost wireless monitoring system for PV module
[8]	Yes	Yes	No	Long range communication using LoRa for remote monitoring of PV systems	
[9]	Yes	No	No	Monitoring system for individual panels in PV system including operating voltage and current, open circuit voltage and short circuit current	
[10]	Yes	No	No	Define the number of irradiance sensors and the position in large PV system	
[11]	Yes	Yes	No	ZigBee wireless network for remote condition monitoring for PV operation	Sensor nodes include voltage, current, irradiance and temperature
[12]	No	No	Yes	Fault detection of PV power plant including string fault, module bypassed and partial shading	
[13]	Yes	Yes	Yes	IoT-based architecture for remote monitoring of solar PV system including the backend and web server application	Monitoring parameters include camera, voltage, current, irradiance and temperature
[14]	No	No	Yes	The PV monitoring system includes an algorithm with a thermal camera for hot spot detection	
[15]	No	Yes	No	Different communication technologies including Ethernet, WiFi, WiMAX	Simulation of hybrid communication models for rooftop solar PV panels

2. Photovoltaic Power Plant Architectures

2.1. PV Power System Layer

The basic components of a typical large-scale PV power plant are PV panels, PV inverters, transformers and protection devices [17]. The PV panels (a number of solar cells connected in series and encapsulated with a special frame) convert solar energy into electricity. PV panels are arranged in groups and are connected together to form module strings. If there is a fault in any single module or shading, the output voltage of PV panels will be affected, which may degrade the system output [18]. The outputs from the PV panels are connected to PV inverters. The PV inverters are electronic devices used to allow the conversion from DC to AC. This can be done through one stage (DC/AC) or two stages (DC/DC, DC/AC). Transformers are used to step up the output voltage from the PV inverters and to connect the PV power plant to the grid.

Figure 1 shows different configurations for the interconnection between PV panels and inverters such as central, string and multi-string [4,5]. The selection among different configurations is based on the cost, reliability, and power quality. In the central configuration, all the PV panels are connected to one inverter. The PV panels are clustered into PV arrays. Each PV array consists of many PV strings connected in parallel and each string consists of many PV panels connected in series. In the string configuration, each string is connected to one inverter. In the case of multi-string configuration, the PV strings are connected to a DC/DC converter and each group of DC/DC converters are connected one DC/AC inverter.

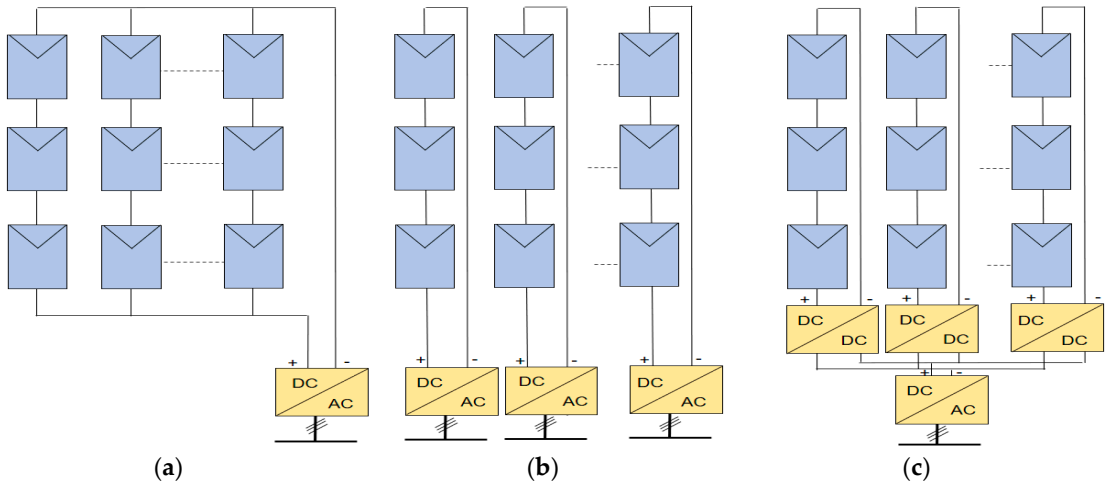


Figure 1. Different configurations for PV inverter topologies. (**a**) Central, (**b**) string, (**c**) multi-string.

The internal topology of a PV power plant represents the electrical connections among PV panels, PV inverters and transformers. Different topologies and configurations could be considered based on output power, cost, and reliability such as central topology, string topology and multi-string topology. There are different configurations for connecting the internal DC collection grid and the AC collection grid, such as radial, star, and ring [4,5].

- Radial topology considers a group of PV generators connected to one feeder. This topology is simple and cheap but has low reliability. In the case of a fault in the first generator connected to the feeder, all the string will be disconnected.
- Ring topology is based on the radial topology configuration but adds an extra feeder to the string from the other side. This enables connection to the PV generators even in the case of a PV generator fault. However, this configuration brings more complexity and cost for the installations.
- Star topology offers higher reliability compared with radial and ring. Each PV generator is connected to the main controller through a feeder connection. The connections between PV generators and feeders increase the total cost of the star topology configuration.

2.2. *Data Communication of PV Power Plants*

In PV power plants, supervisory control and data acquisition (SCADA) systems play an important role in the remote monitoring and control of field devices (sensors, smart meters, remote terminal units (RTUs), intelligent electric devices (IEDs), etc.) [19,20]. A typical SCADA system consists of data acquisition units, RTUs, communication networks, and system servers. Data acquisition units measure and collect monitoring parameters such as voltage, current, temperature, irradiance, etc., and then transmit it through the communication infrastructure to the control center. As the control center represents the core of the SCADA system, there are several application servers, such as front-end servers, historian servers, web servers and human–machine interfaces, where monitoring data are analyzed and visualized. The front-end servers are responsible for collecting data from the field devices, while the historian servers are used for data storage. Figure 2 shows the communication network for a PV monitoring system. Each local control center is dedicated to the monitoring and control of a PV power plant. All control centers are connected to a wide area network via routers.

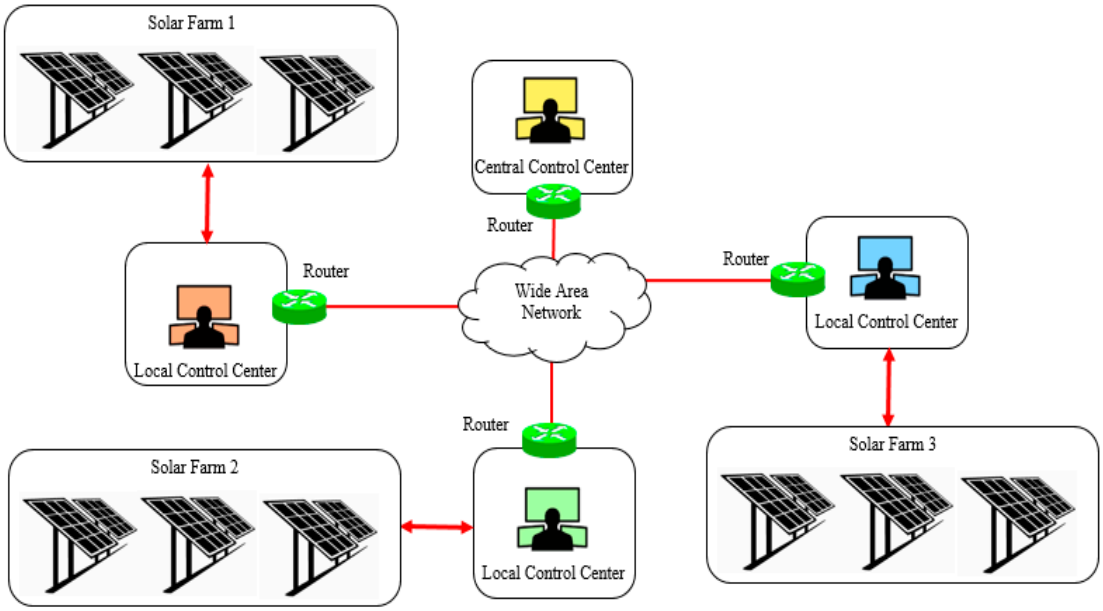


Figure 2. Communication network for a PV monitoring system.

3. Communication Network Architecture for Large Scale Photovoltaic Power Plants

The proposed communication network architecture for large-scale PV power plant consists of three layers: the PV power system layer, the communication network layer and the application layer, as shown in Figure 3.

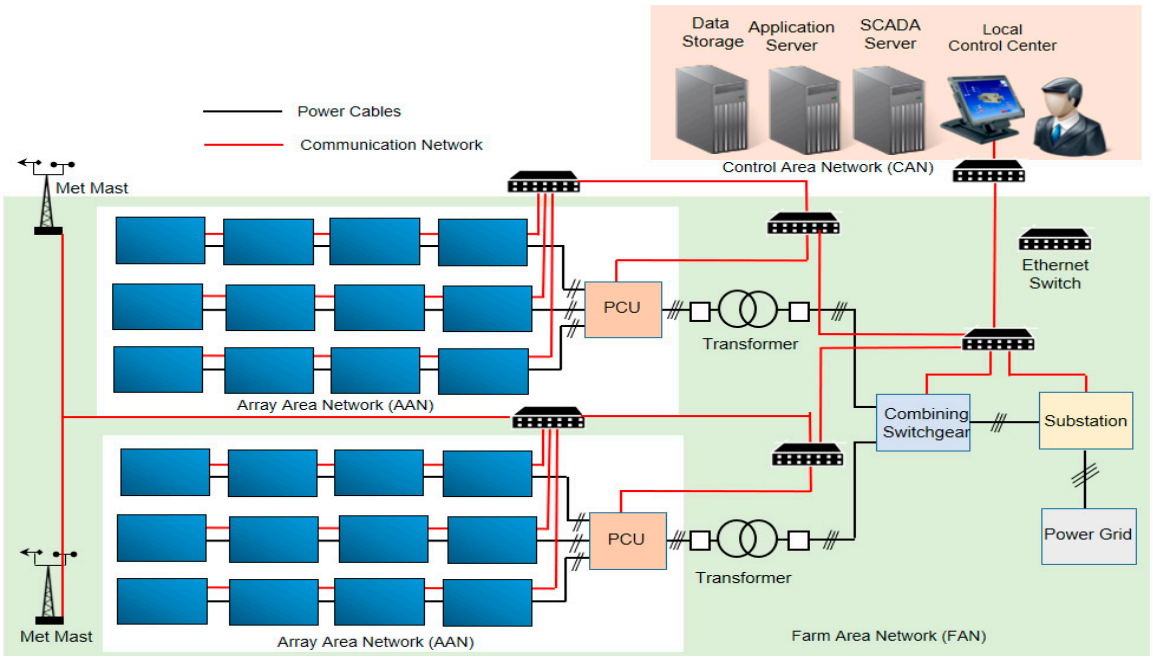


Figure 3. Layout of grid integration of a large-scale PV power plant.

3.1. PV Power System Layer

The PV power system layer consists of all physical devices including PV modules, junction boxes, circuit breakers, protection devices, PV inverters, power cables, grid connection, transformers, the substation, etc. PV modules are connected in series to form a module string. Groups of strings are connected together in a string combined box. The string combiner boxes are connected to a power

condition unit (PCU), which plays an important role in the PV power plant as it inverts the output DC voltage from PV panels to AC and is connected to a transformer based on PV power plant topology.

3.2. Communication Network Layer

The communication network layer enables two-way communications between PV power plant subsystems and the local control center. It consists of various communication devices connected with communication links. There are different types of sensor nodes and measurement devices interfacing with the power system layer. For example, pyranometers are used for measuring solar radiation, while anemometers are used for measuring wind speed and wind direction. Other measurements include modules temperature, air humidity, ambient temperature, atmospheric pressure and rain. Monitoring data from the PV subsystem and meteorological parameters are transmitted to the control center via the communication network layer. The communication network layer in PV power plant can be divided into subnetworks: the PV array area network (AAN), PV farm area network (FAN) and control area network (CAN). Each sub-network has different requirements in view of network configuration, coverage range and data rate. The main applications are given below:

- SCADA system: Used for monitoring the performance of the PV power plant for documentation and analysis. This includes monitoring DC and AC parameters (voltage, current and power), PV modules, total generation from panels.
- Meteorological system: Used for collecting meteorological information such as solar irradiance, ambient temperature, humidity and wind speed.
- Protection and control system: Used for PV power plant protection. It interconnects among all protection and control IEDs in a PV power plant, which are responsible for safety and protection of the utility's hardware components.
- Metering the grid interface system: Used for measuring the electrical parameters at the point of interconnection. This could be done by monitoring real and reactive power, voltage and connection status at the point of interconnection in order to ensure the grid quality assurance.

The IEE 1646 Standard defines different requirements for data transmission for different applications [21]. Table 2 shows the requirements for data delivery time based on IEEE 1646 Standard. The requirements of data delivery for the protection information required strict delay compared with monitoring and control.

Table 2. Requirements for data delivery time based on IEEE 1646 Standard [21].

Information Type	Internal to Substation	External to Substations
Protection	4 ms	8–12 ms
Monitoring and control	16 ms	1 s
Operation and Maintenance	1 s	10 s
Image Files	10 s	60 s
Audio and Video	1 s	1 s

3.3. Application Layer

The control center is responsible for the monitoring and controlling the operation the PV power plant including PV panels, inverters, transformers, grid connection point, etc. Data collected from sensor nodes, measurement devices are processed and stored in system servers, and appropriate control actions are taken accordingly.

4. Modeling Photovoltaic System Based on IEC 61850-7-420 Standard

In a typical PV power plant, there are many factors that affect the plant operation, such as faults, cell damage, shading, dust, degradation, etc. [22]. Most of these factors are hidden and difficult to identify in a large-scale PV power plant. Supervisory control and data acquisition (SCADA) system represent an essential element for remote monitoring and control of PV power plant. It ensures a reliable and a safe operation for PV power plant subsystems as it enables the control center operator to analyze the performance, detect operation issues and identify faults during abnormal conditions. The PV power plant can be divided into different levels: the module level, string/array level, inverter level and grid level.

- The module level monitors the voltages and current in each module. The status of each PV module can be determined and faults in any module can be identified.
- The string/array level monitors the voltages and current in each string/array. Faults in any string/array can be identified.
- The inverter level monitors the array output power and the performance of the section connected to that inverter. In the case of a malfunction, both the array and the inverter can be identified.
- The grid level monitors the total performance of the PV power plant.

The IEC 61724 standard defines the general guideline for monitoring the overall performance of the PV system including in-plane irradiance, array output and energy storage system [23]. The required parameters to be measured are shown in Table 3, where all parameters should be continuously measured. The amount of data generated from sensor nodes are calculated based on the sampling rate, the sample size and the number of channels. The data rate was calculated given the assumption that each data sample is represented with 2 bytes (16 bit) [24].

Table 3. Measured parameters for the photovoltaic system based on IEC 61724 standard.

Level	Parameters	Symbol	Unit	Sampling Rate	Channel Number	Data Rate
PV Array	Output voltage	V_A	V	360 Hz	1	720 bytes/s
	Output current	I_A	A	360 Hz	1	720 bytes/s
	Output power	P_A	kW	5 Hz	1	10 bytes/s
	Module temperature	T_m	°C	1 Hz	1	2 bytes/s
	Tracker tilt angle	$Ø_T$	degree	3 Hz	1	6 bytes/s
	Tracker azimuth angle	$Ø_A$	degree	3 Hz	1	6 bytes/s
Utility Grid	Utility voltage	V_U	V	2048 Hz	3	12,288 bytes/s
	Current to utility grid	I_{TU}	A	2048 Hz	3	12,288 bytes/s
	Current from utility grid	I_{FU}	A	2048 Hz	3	12,288 bytes/s
	Power to utility grid	P_{TU}	kW	5 Hz	1	10 bytes/s
	Power from utility grid	P_{FU}	kW	5 Hz	1	10 bytes/s
Meteoro-logical	Total irradiance	G_I	Wm^{-2}	100 Hz	1	200 bytes/s
	Ambient air temperature	T_{am}	°C	1 Hz	1	2 bytes/s
	Wind speed	S_w	m/s	3 Hz	1	6 bytes/s
	Wind Direction	D_w	degree	3 Hz	1	6 bytes/s

IEC 61850-7-420 standard defines the general data model for distributed energy resource (DER) systems. The standard describes the information model of the photovoltaic system including PV panels, conversion system, circuit breakers, protection devices, and metering devices. Figure 4 shows the architecture model of the photovoltaic system based on IEC 61850-7-420 standard [25]. A photovoltaic array controller (DPVC) and a PV tracking controller (DTRC) represent the logical nodes of the PV

panels, as shown in Equation (1). In order to maximize the output power of the PV system, the output voltage and current are adjusted through the maximum power point tracking.

$$PV_{LN} = \{DPVC, DTRC\}, \quad (1)$$

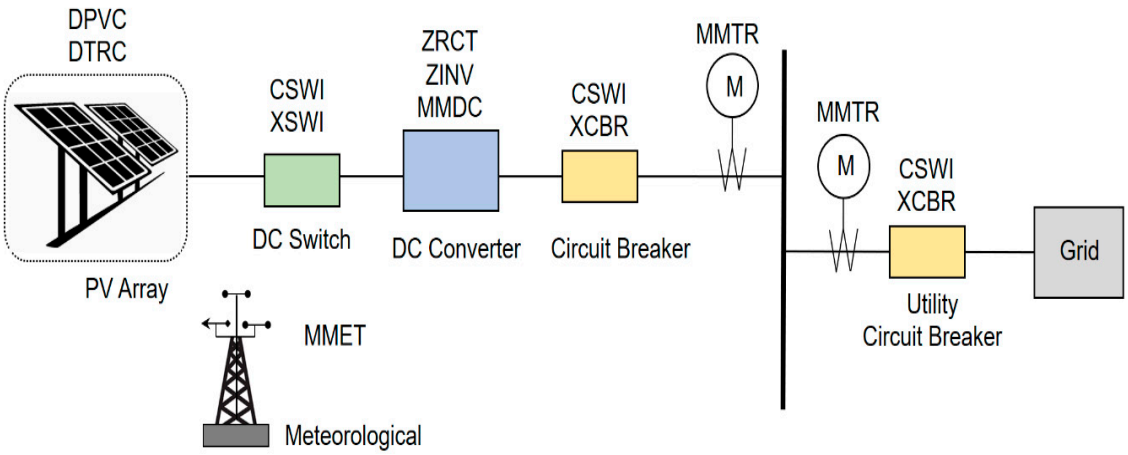


Figure 4. Logical nodes associated with photovoltaic system based on IEC 61850-7-420 standard.

The main operation of the switchgear is to monitor and control the operation of circuit breakers and switches. The logical nodes of the DC switch (SW_{LN}) is represented with a circuit breaker (CSWI) and a switch controller (XSWI) while the circuit breaker (CB_{LN}) is represented with a circuit breaker (CSWI) and a circuit switch (XCBR), as shown in Equations (2) and (3).

$$SW_{LN} = \{CSWI, XSWI\}, \quad (2)$$

$$CB_{LN} = \{CSWI, XCBR\}, \quad (3)$$

The rectifier (ZRCT), inverter (ZINV) and DC metering (MMDC) represent the logical nodes of the inverter (INV_{LN}), as shown Equation (4).

$$INV_{LN} = \{ZRCT, ZINV, MMDC\}, \quad (4)$$

The electric measurements are represented with the logical node metering (MMTR). The logical node MMXU represents the metering of the AC current while MMDC represents the DC current. The logical node (MMET) represent the meteorological measurements, which includes monitoring parameters of meteorological information such as solar irradiation and ambient temperature. The list of logical nodes associated with the photovoltaic system is given in Table 4.

There are three types of IED: circuit breaker CB-IED, merging unit MU-IED, and protection and control P&C IED. The CB-IED monitors the status of the circuit breaker and sends status information for the P&C IED. The MU-IED measures the current and voltage signals and transmits it to the P&C IED. The P&C IED manages and supervises the operation of all IEDs. Based on IEC 61850 standard, the P&C system can be divided into three levels: the process level, bay level and station level.

Table 4. List of logical nodes associated with photovoltaic system based on IEC 61850-7-420.

Name	Logical Node	Description
Photovoltaic Array	DPVC	Photovoltaic array controller
	DTRC	Photovoltaic Tracking controller
DC Switch	CSWI	Switch Controller
	XSWI	Circuit Switch
DC Converter	ZRCT	Rectifier
	ZINV	Inverter
	MMDC	DC Measurement
Circuit Breaker	CSWI	Switch Controller
	XCBR	Circuit Breaker
Metering	MMTR	Metering
Meteorological Tower	MMET	Meteorological Information

5. Network Modeling and Simulation Results

5.1. Single PV Power Plant Scenario

This section explains the simulation models that were developed to evaluate the performance of the communication network of a PV power plant. The simulation models were built using OPNET Modeler based on a real project (Layla solar plant (10 MW), phase 1) in Saudi Arabia. The developed model consists of 80 PV strings, two feeders, two power conditioning units (PCU), one bus, one transformer, two meteorological masts and a local control center, as shown in Figure 5. The main components of the PV power plant and IEDs are summarized in Tables 5 and 6, respectively.

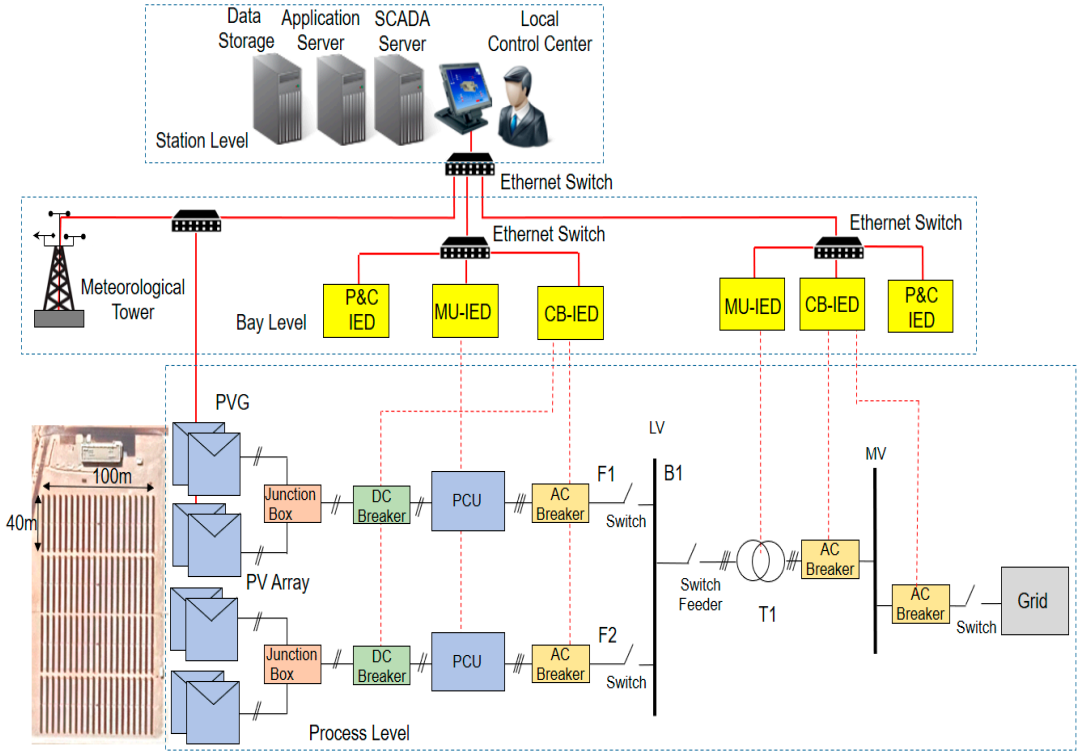


Figure 5. Proposed communication network model for the PV power plant. PVG: PV generator; PCU: power conditioning unit F: feeder; B: bus; T: transformer, LV: low voltage; MV: medium voltage.

Table 5. Summary of the system components for the developed model of the PV power plant.

Components	Number	Comments
PV Strings	80	Every string consist of 20 modules
DC Box	8	Every 10 strings are connected to one DC box
PCU	2	Every 4 boxes are connected to one PCU
Transformer	1	Every PCU is connected to one transformer

Table 6. Intelligent electric device (IED) configurations for the developed model of the PV power plant.

Components	CB IED	MU IED	P&C IED
Transformer (T1)	2	1	1
Collector Bus (B1)	1	1	1
Collector Feeder (F1 and F2)	1	1	1
PV generator (PVG)	1	1	1

In a real PV power plant, independent communication networks are used to support different applications (sometimes from different service providers) where all subnetworks are connected together via a common backbone network. In this work, independent communication networks (independent communication links and switches) are considered to support different applications (PV arrays, protection and control and utility grid).

Figure 6 shows the OPNET simulation model for the PV power plant. It consists of seven octagons representing four PV arrays, two meteorological masts and one control center. The configuration is based on the actual PV power plant dimensions. Two scenarios are considered: fixed mounted PV arrays (no tracker tilt angle nor tracker azimuth angle) and PV arrays with sun trackers (each PV sun tracking unit is equipped with a pyranometer). Two different link capacities are considered for local area communication (LAN): 10 BaseT and 100 BaseT. The traffic configuration, including the source and destination, is given in Table 7. The performance of the proposed communication network is evaluated for a switched Ethernet architecture in view of bandwidth and end-to-end delay. Tables 8 and 9 show the end-to-end delay for different scenarios of PV arrays with different channel capacities. Each PV array is modeled with an Ethernet LAN of 20 workstations in a switched topology. The results of latency are compared with different numbers of PV arrays.

Table 7. Traffic configuration of the PV power plant.

Traffic Type	Source	Destination
Photovoltaic Array	PV_A1, PV_A2, PV_A3, PV_A4	SCADA Server
Meteorological	MET1, MET2	SCADA Server
Protection	Feeder, bus and transformer (MU IED, CB IED)	PCI Server
Utility Grid	PVPP_PCC	Utility Server

Table 8. Internet Protocol (IP) end-to-end delay (ms) for fixed mounted PV arrays (without sun trackers) with different link capacity.

Scenario	10 Mbps				100 Mbps			
	Array 1	Array 2	Array 3	Array 4	Array 1	Array 2	Array 3	Array 4
1 PV Array	0.501	-	-	-	0.053	-	-	-
2 PV Arrays	0.493	0.624	-	-	0.053	0.066	-	-
3 PV Arrays	0.518	0.698	0.825	-	0.054	0.066	0.079	-
4 PV Arrays	0.575	0.697	0.818	0.909	0.053	0.067	0.081	0.092

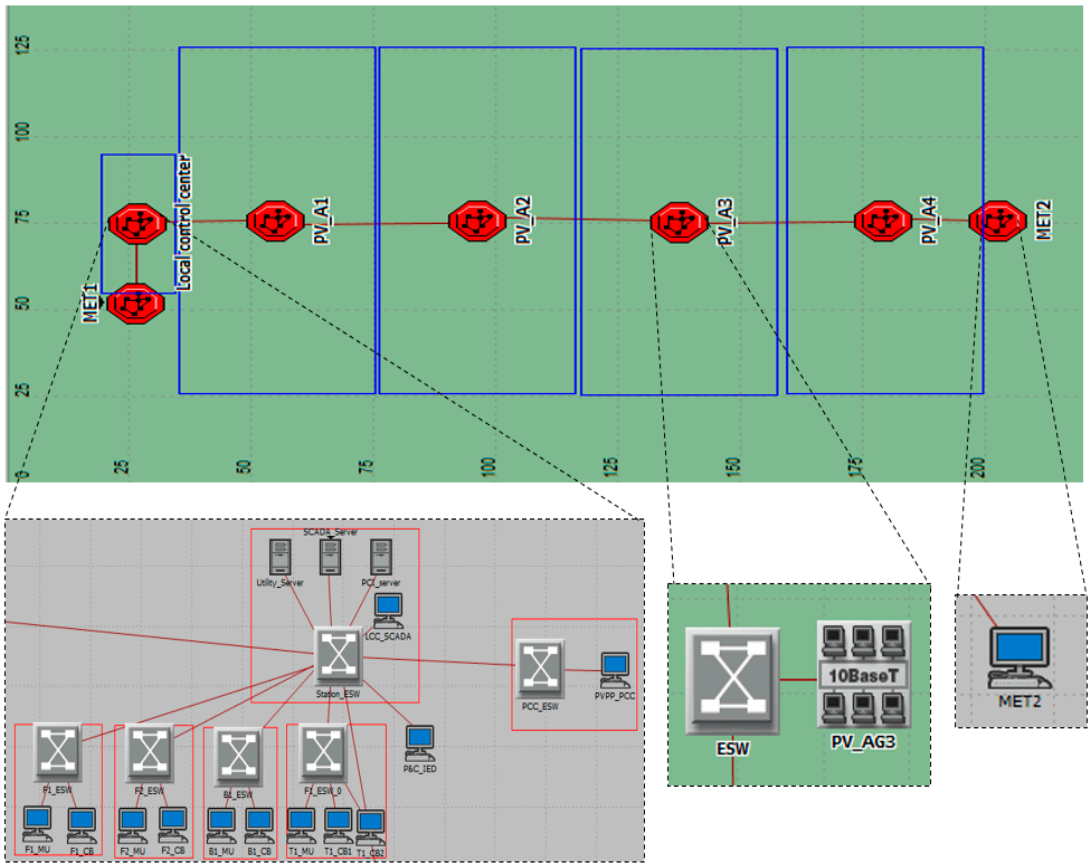


Figure 6. OPNET model for communication network of the PV power plant.

Table 9. IP end-to-end delay (ms) for PV arrays (with sun trackers) with different link capacity.

Scenario	10 Mbps				100 Mbps			
	Array 1	Array 2	Array 3	Array 4	Array 1	Array 2	Array 3	Array 4
1 PV Array	0.423	-	-	-	0.046	-	-	-
2 PV Arrays	0.458	0.558	-	-	0.047	0.058	-	-
3 PV Arrays	0.494	0.563	0.703	-	0.047	0.058	0.070	-
4 PV Arrays	0.471	0.660	0.744	0.930	0.047	0.059	0.069	0.081

In general, the architecture of the substation automation system consists of a process level, protection and control level, and station level. In this work, the substation automation system of the PV power plant is implemented using different IEDs. These different IEDs include PV generator, collector feeder, collector bus and transformer which are interconnected through a communication network. The model of the transformer IEDs consists of two CB IED, one MU IED and one P&C IED. The models of collector bus and collector feeders consist of one CB IED, one MU IED and one P&C IED. The communication network is configured as a star topology. A PCI server is used to represent the station level, while the bay level includes different protection and control IEDs. The data generated from IEDs are transmitted to the PCI server. Note that the protection and control functions require a fast response time compared with SCADA monitoring. Two scenarios are considered for the substation communication using LAN with 10 Mbps and 100 Mbps. The end-to-end delay for different protection and control IEDs are shown in Table 10.

Table 10. End-to-end delay for different protection IEDs.

	Dedicated Network		Shared Network	
	10 Mbps	**100 Mbps**	**10 Mbps**	**100 Mbps**
F1-MU	22.65 ms	2.26 ms	25.82 ms	2.31 ms
F1-CB	4.34 ms	0.44 ms	4.79 ms	0.54 ms
F2-MU	22.40 ms	2.24 ms	25.31 ms	2.27 ms
F2-CB	4.31 ms	0.42 ms	4.61 ms	0.47 ms
B1-MU	22.30 ms	2.22 ms	24.92 ms	2.25 ms
B1-CB	4.09 ms	0.40 ms	4.21 ms	0.45 ms
T1-MU	22.93 ms	2.29 ms	26.09 ms	2.33 ms
T1-CB1	2.97 ms	0.28 ms	3.34 ms	0.34 ms
T1-CB2	4.78 ms	0.47 ms	4.61 ms	0.52 ms

5.2. PV Power Plants Scenario

This work considers the planned PV power plants in Saudi Arabia based on the Renewable Energy Project Development Office (REPDO) [26]. Table 11 shows a list of the planned solar power projects across the kingdom. The projects have been divided into three rounds: round 1 includes one project (Sakaka PV project, 300 MW), round 2 includes six projects (1.47 GW) and round 3 includes four projects (1.2 GW). Al-Faisaliah project is the largest among them, with a generation capacity of about 600 MW. Figure 7 shows the locations of PV power plants. The solar PV power plants are distributed among different regions, where all projects will be connected to the national electricity grid.

Table 11. Summary of future PV power projects in Saudi Arabia [20].

Round	Status	Solar PV Projects	Capacity (MW)	Region
Round 1 300 MW	Operating	Sakaka Project	300	Al Jouf
Round 2 1470 MW	Pre-Developed	Qurayyat Project	200	Al Jouf
		Rabigh Project	300	Mecca
		South Jeddah Project	300	Mecca
		Al-Faisaliah Project	600	Mecca
		Rafha Project	20	Northern Borders
		Madinah	50	Medina
Round 3 1200 MW	Pre-Developed	Layla Project	80	Riyadh
		Wadi Al Dawaser Project	120	Riyadh
		Saad Project	300	Riyadh
		Al Rass Project	700	Riyadh

The proposed communication network model was developed for the wide monitoring of PV power plants. It consists of 12 subnetworks (each subnetwork is represented by an octagon) and a central control center. Each PV power plant is configured to transmit the monitoring data of the point of common coupling (PCC) including voltage, current and power to the central control center (CCC), where monitoring data are stored and used by other applications such as an energy management system. As the computer systems are the core part of the control center, the system must be sized to receive, process and store the necessary information. The main elements are front-end units (industrial servers), a historian server, operator consoles, a web server and a video wall [27]. The front-end units are responsible for receiving information from PV power plants. Additional front-end units are added as the number of PV power plants increases. Historical servers are used to store the information received from the front-end units. The decision regarding the type of historical database in the control center is based on the amount of information to be stored, the scan rate and the speed required in data access using reports. The new control centers are moving toward virtual machines with the target of decreasing the amount of equipment, reducing maintenance costs, and reducing energy consumption and wiring, etc.

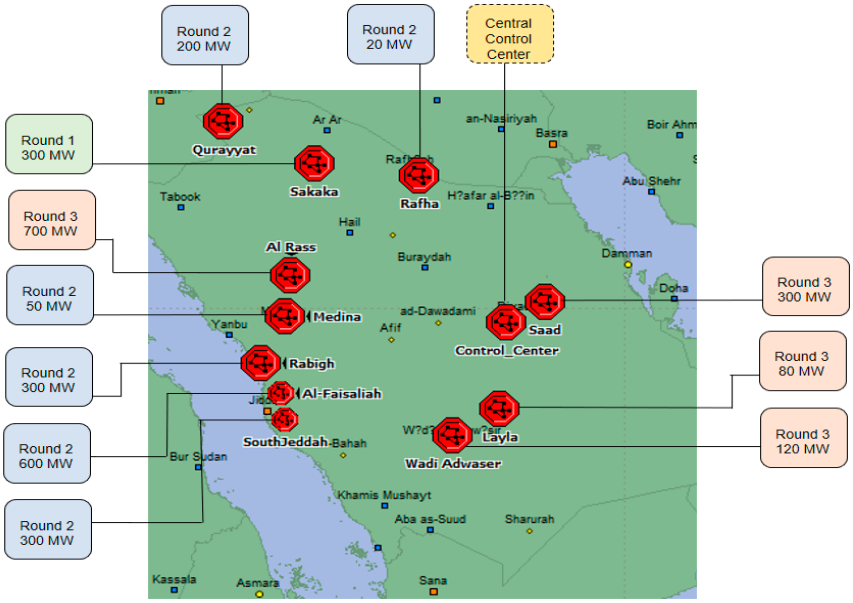


Figure 7. Geographical location of future PV power projects across Saudi Arabia.

All PV power plants communicate with the CCC through the public communication network. Figure 8 shows the developed OPNET model for the grid integration of 11 PV power plants. The communication networks inside all subnetwork are configured as local area networks. Each subnetwork contains an Ethernet Switch, a workstation and a router. The communication among the subnetworks and the CCC is configured using the internet, which is represented by the internet protocol (IP) cloud. The communication links between each PV power plant and the IP cloud is configured with PPP-DS3 with a link capacity of 44.736 Mbps.

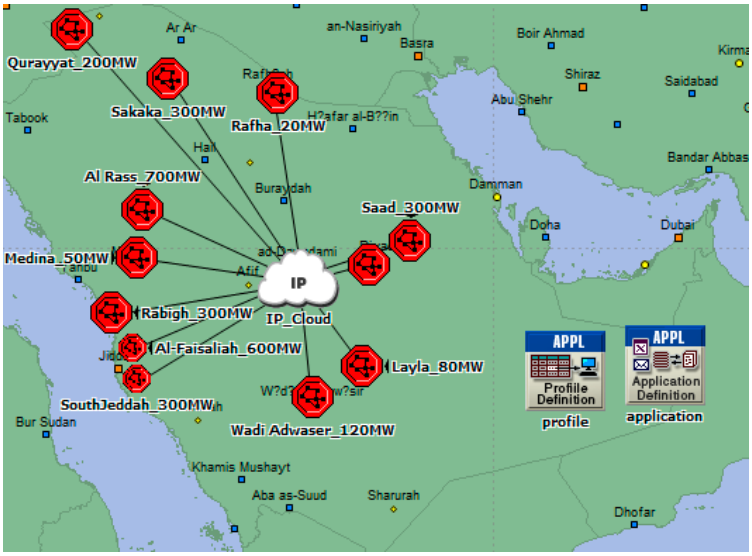


Figure 8. OPNET simulation model for grid integration of PV power plants.

Considering the measured parameters at the grid side, the amount of the received traffic for voltage, current and power are 12,288, 12,288 and 10 bytes/s, respectively. The total amounts of traffic received at the control center are 270,336, 135,168 and 220 bytes/s, for current, voltage, and power, respectively. All monitoring data are received successfully.

Table 12 shows the end-to-end delay between PV power plants and the central control center using a link capacity of 44.736 Mbps. The packet discard ratio (PDR) of the IP cloud has been configured at

1%, which specifies the percentage of packets dropped (ratio of dropped packets to the total submitted packets to this cloud). In case of no PDR, the end-to-end delay was about 7.79 ms for Qurayyat PV power plant, while about 5.83 ms for Saad PV power plant. With the PDR of 1%, the end-to-end delay was about 7.93 ms for Qurayyat PV power plant, while about 5.90 ms for Saad PV power plant. The difference in end-to-end delay among different projects is due to the location of each PV power plant.

Table 12. End-to-end delay between PV power plant and the central control center. PDR: packet discard ratio.

LCC	Link Capacity (DS3)		
	No PDR	**PDR (1 %)**	**Background Traffic (50 %)**
Sakaka Project	7.50 ms	7.67 ms	8.06 ms
Qurayyat Project	7.79 ms	7.93 ms	8.21 ms
Rabigh Project	6.97 ms	7.19 ms	7.43 ms
South Jeddah Project	7.22 ms	7.28 ms	7.59 ms
Al-Faisaliah Project	6.38 ms	6.48 ms	6.93 ms
Rafha Project	7.73 ms	8.01 ms	8.31 ms
Madina Project	6.32 ms	6.67 ms	7.16 ms
Layla Project	6.08 ms	6.17 ms	6.51 ms
Wadi adwaser Project	7.441 ms	7.448 ms	7.99 ms
Saad Project	5.83 ms	5.90 ms	6.37 ms
Al Rass Project	6.73 ms	6.94 ms	7.42 ms

6. Conclusions

Reliable communication networks play an important role in supporting the grid integration of large scale PV power plants. The underlying communication infrastructures are responsible for real-time monitoring and have a direct impact on the performance of the PV power plants as well as the capability for meeting the target application requirements. This work proposed communication network models for the PV power system in order to evaluate future scenarios of PV power plants. Various scenarios have been considered in order to evaluate the performance of the communication network, including a single PV power plant and a group of PV power plants from different regions in Saudi Arabia. The monitoring measurements are communicated to a local control center in a single PV power plant scenario, and to a central control center in the multiple PV power plants scenario for further assessment. The proposed model considered 11 PV power plants which are geographically distributed in different regions and the proposed communication models have been evaluated with respect to end-to-end delay for different applications using OPNET Modeler. The simulation results in a single PV power plant scenario show that the maximum end-to-end delay for protection data was less than 4 ms considering a channel capacity of 100 Mbps. In the case of multiple PV power plants, the simulation results show that the background traffic and packet discard ratio have a direct impact on the end-to-end delay. Future works aim to evaluate the performance of the proposed communication network using different wireless communication technologies.

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