Simulation of the 5G Communication Link Between Solar Micro-Inverters and SCADA System

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Abstract— **Integration of Distributed Generation (DG) into the existing grid, and communication being the lifeblood of any such system, is the answer to the rising demand for power. The characteristics of Wi-Fi are shared by 5G connections, which offers a peak speed of 1 gigabyte per second and extremely low latency (1ms), unlike 4G. To ensure an uninterrupted flow of power, this research focuses on investigating and establishing 5G communication protocols between the SCADA system and the solar micro-inverter of the solar power system. The 5G architecture protocol is designed on the NetSim simulator, which is utilized to gather and evaluate data, while the power system simulation is carried out in MATLAB Simulink. The simulation results show that 5G communication was successfully implemented between Solar Micro-Inverters and SCADA systems.**

Keywords—5G, microinverter, NetSim, SCADA, solar power system

I. Introduction

Solar Power systems have been increasing in popularity as a sustainable source of energy to combat issues that could affect future generations. Most sources of energy that are supplied in the U.S. are nonrenewable such as coal, and fossil fuels, which make up about 88%, and the other 12% comes from renewable sources that include solar [1]. It's necessary when working with any power system to integrate a monitoring and control system to collect measurements for voltage, current, and power which can be used for analysis and control to ensure that no problems are occurring when generating and distributing power. The implemented system is a Supervisory Control and Data Acquisition (SCADA) system, which is a generic name given for a computerized system capable of collecting and processing data of a complex industrial process over long distances and applying operational controls over it [2]. These systems typically gather data from Remote Terminal Units (RTUs) associated with Measurement Devices (MDs) and convey control signals to Programmable Logic Controllers (PLC) and Intelligent Electronic Devices (IEDs) for operating the system, and these systems benefit from transmitting and collecting data by implementing state of the art technologies for fast and reliable data transmission [2].

For the communications of the SCADA system to the Solar Power system, this paper presents the design and implementation of a 5G architecture to provide fast and reliable data transmission. 5G emerged as a cutting-edge type of mobile networking that offers connections that are quicker and more dependable to smartphones and other devices. The benefit of using 5G communications is that it is the fifth generation of mobile technology that provides diverse abilities and encourages full networking between different systems and industries [2][3]. El-Shorbagy et al. in their paper "5G technology and the future of Architecture" have mentioned that there are numerous problems the world faces that require creative tech-based solutions to make the future more livable for people [3]. 5G technology works by transmitting and receiving data with frequencies of 3 to 90 GHz which is useful for power systems that need to be monitored fast and reliably to prevent any errors from happening [2][3]. 5G can be implemented with power systems in two main levels which include Field Area Networks (FANs), which includes the communication of measurement data that is transmitted typically between measurement devices, and Wide Area Networks (WANs) which includes the communication of measurement data aggregated at substation level to a central controller [2]. The standard technology in transmitting data with 5G communications is 5G New Radio (NR) which allows high-speed connections with systems that have Internet of Things (IoT) devices, which can be integrated with power systems controlled by SCADA systems [4].

The goal and motivation of this work is to improve existing systems that are utilized for transmission of data, and to increase the demand and usability of solar power systems. Other works have been done to implement these types of communication systems in renewable energy systems for fast, and reliable transmission of data [5][6] Which is why this work will be to simulate the 5G communication link between solar-microinverters and SCADA.

The organization of this paper is as follows: Section II of the paper discusses the implementation of the Solar Power and SCADA system in MATLAB Simulink. Section III discusses the 5G Architecture and Communications designed using NetSim that is used to interface with the model in Simulink. Section IV discusses the MATLAB model integration with NetSim. Section V shows the results from the MATLAB Simulink model interfacing with the 5G Communication system simulated in NetSim, and section VI presents the conclusion and future recommendations.

II. Solar Power and SCADA System

A. Solar Power System

This paper presents that the main source of energy is solar energy, which is collected from Photovoltaic (PV) Arrays, based on the conditions of solar irradiance, and temperature. The ideal case for solar irradiance is 1000 W/m^2, and the temperature is 25 °C [7], then the PV Arrays can generate power. Because PV Arrays supply efficient power in these conditions, Battery Energy Storage Systems (BESS) are implemented to supply power during times when there is a decrease in solar energy, but because of the nonlinear characteristics of PV Arrays which can increase, or decrease the values for voltage and current, these systems are integrated with energy regulators to ensure that the BESS is charging properly with no overvoltage or overcurrent problems which can decrease the life expectancy or lead to the destruction of the BESS. The energy regulator that will be used will be a Buck-Boost Converter, which can increase or decrease the output voltage or current based on the Duty-Cycle of a Pulse-Width Modulated (PWM) signal used to control a switch [8].

An inverter is used to convert DC power to AC power by controlling switching devices [9], and for this paper, a Three-Phase inverter is implemented to convert the DC power from the PV Arrays, and BESS to AC power, which can be used to distribute power. Fig. 1 shows the schematic for a Three-Phase Solar Power System that will include the PV Arrays, Buck-Boost Converter, BESS, and Three-Phase Inverter which will be simulated in MATLAB Simulink to supply power to a load rated for 6250 VA and a power factor of 0.8.

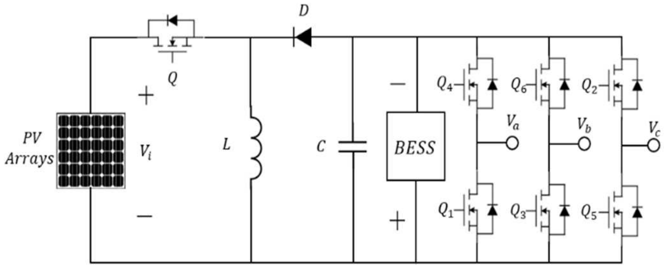

Figure 1. Three-Phase Solar Power System

B. SCADA System

The role of the Solar Power system is to distribute power from PV Arrays and a BESS, but as stated before without any monitoring and control for these systems they will become unstable, and eventually fail. Therefore, a SCADA system is used to monitor and collect data for analysis and to detect any errors that might occur in the Solar Power system. In this work, the role of the SCADA system is to collect Power, Voltage, and Current data. It also monitors the status of the BESS. Fig. 2 shows the model for the Solar Power system that is simulated in MATLAB Simulink to collect the necessary data for the SCADA system.

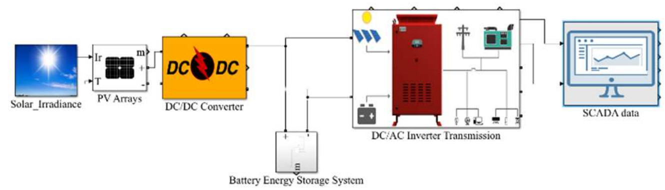

Figure 2. MATLAB Simulink Model

III. 5G Architecture and Communications

Many elements of the proposed 5G architecture are implemented to improve 5G networking. with Radio Access Networks (RAN) that are no longer limited by base station proximity or intricate infrastructure, 5G Network uses a more intelligent architecture. The virtualized, disaggregated, and flexible RAN that 5G pioneers added more data access points through novel interfaces. User Equipment (UE) and base station/towers (gNB) using 5G's NR technology can be used for direct communication.

The architecture in Fig. 3 includes access and mobility management functions, session management functions, and user functions as the main 5G networking components [10]. Three 5G Core Devices are present. The first 5G Core device is the Access and Mobility Management Function (AMF), which only handles connectivity and mobility-related duties. [11] It gets all connection and session-related data from the User Equipment. Its deployment has a standalone mode. This mode's Network Functions (NF) are deployed with specific microservices with separate namespaces in Kubernetes. The interface compiles a detailed 3GPP specification based on the corresponding compliance version. The RAN and SMF use N2 and N11 when interfaced with an AMF. The core device's second component, the Session Management Function (SMF), oversees establishing the link between the user equipment and the data network [11]. The User Plane Function (UPF), which manages the connection between the user equipment and the data network, is also tied to it [11]. The UPF uses an N6 and N4 interface with a router and SMF, and it establishes a connection between the external protocol data unit session point and the data network [11]. This 5G network system has data forwarding, packet routing, quality of service management, and traffic utilization among its many features. The UEs are used for data in a variety of ways, including receiving data from MATLAB, sending data to the power system and SCADA system for control and network monitoring, and receiving data from MATLAB for transmission to the 5G core networks [10].

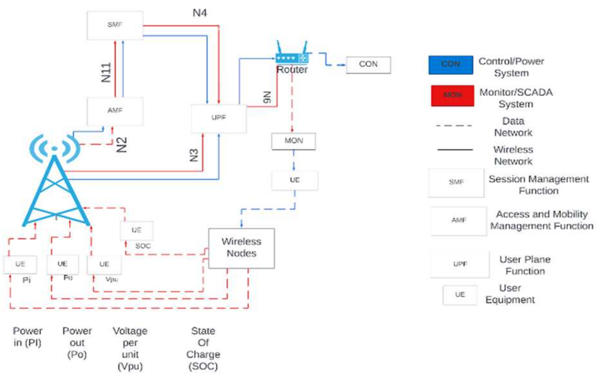

Figure 3. 5G Communication Architecture

IV. MATLAB SIMULINK AND NETSIM INTEGRATION

To get the desired results it is required that MATLAB and NetSim be integrated [13]. Interfacing NetSim and MATLAB initializes a MATLAB engine process in parallel with NetSim. The process executes MATLAB [13] workspace commands and passes the parameters to the workspace. It is where they are read, and results generated.

V. SIMULATION RESULTS

A. MATLAB Simulink

For this work, the MATLAB Simulink model presented in Fig. 2 is simulated for 6 seconds, and the values for input power, output power, output voltage, and SOC of BESS are measured. The collected data is then used by the SCADA system for monitoring and analysis purposes. The Simulink results for the input power, output power, output voltage, and BESS SOC are displayed in Fig. 4 through Fig. 7, respectively. The input power is shown to have a peak of about 1,600 W at 3 seconds and decreases to 0 W after 6 seconds, while the output power is shown, in Fig. 5, to have a constant value of 7000 W. This is because the system supplies power from both the BESS and from the PV Arrays. This system relies on the power from the BESS when the power from solar is low and relies on the power from solar when the power from the input is high, which is shown in Fig. 7 where the BESS's SOC is increasing when the power from solar is increasing and is constant when the power from solar is decreasing. The output is shown in Fig. 6 to have a rms voltage value of about 115 V which is to simulate the voltage seen from the consumer's side after distribution. These results demonstrate the proper execution of the Solar Power System which is collecting SCADA data that is sent through the 5G Communication Architecture which is simulated in NetSim.

B. NetSim MATLAB Interface

The NetSim model shown in Fig. 8 simulates and generates how the packets would move throughout the model and displays the metric results indicated in tables I and II. In Fig. 8, the 5G core devices are mandatory for every 5G network.

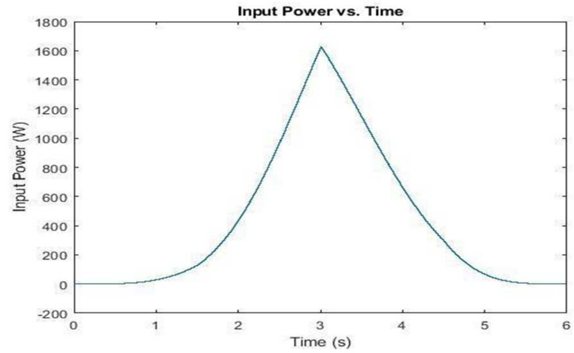

Figure 4. Input Power

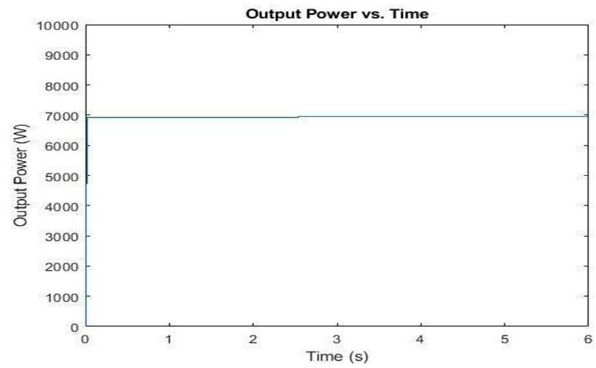

Figure 5. Output Power

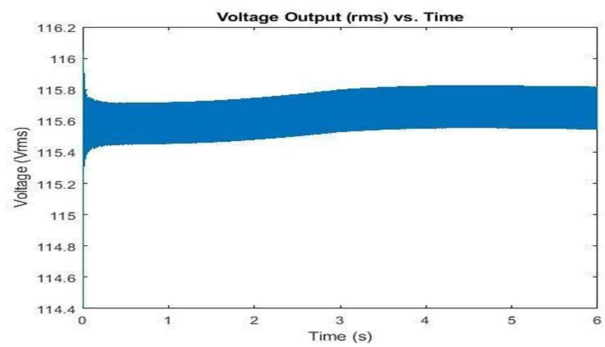

Figure 6. Output Voltage

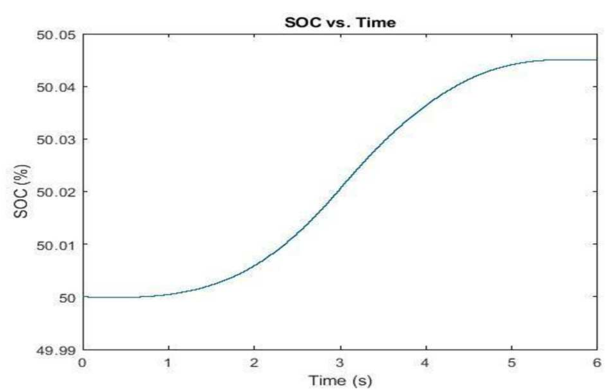

Figure 7. BESS SOC

Moreover, it can be observed that the UEs which connect to the gNB are labeled P_i, P_o, V_{pu}, SOC, and UE. Input power, Output power, voltage per unit, State-of-Charge, and user equipment are their full terms. These UEs are connected to the wireless node labeled control system by application connection which is determined by its solid purple line. The application connection is used to connect to the third-party application MATLAB and have the data sent from MATLAB to the NetSim.

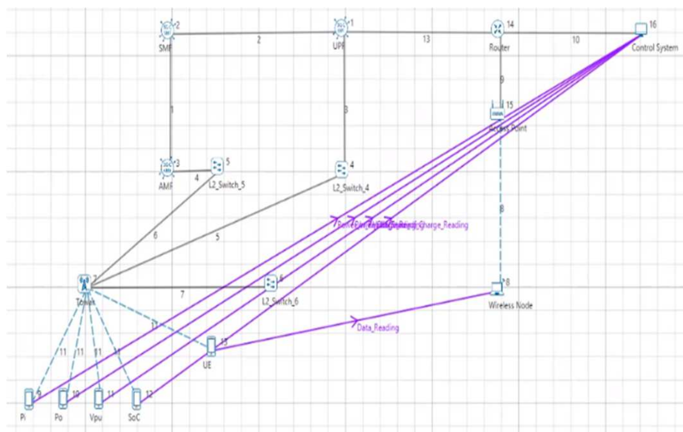

Figure 8. NetSim Model

Table I displays the metric results for our specified model in NetSim. The table shows the number of packets generated, packets received throughput, delay, and jitter for each application connection from NetSim. Packets are units of data that travel from one end of a computer network to another, and 65,535 is the maximum number of bytes that each packet can contain. Throughput is the amount of data that is passed through NetSim and is displayed in megabits per second. Delay is the time it takes for data to go from one end in a network to another and is taken in microseconds (μs). Jitter is the change in time from when data is transmitted and when it has been received over a network connection and is displayed in μs. In Table I, each application (app) connection has similar results to each other except for App ID 5. Data Reading is different from the others because it uses an app connection with a wireless node instead of a wired node. This results in the Data_Reading having jitter and a longer delay traveling the network.

C. *Throughput*

Tetcos, developers of Netsim, offer the throughput definition via NetSim's Help Centre library using (1) and (2). "This selection is carried out by the scheduler till all Physical Resource Blocks (PRBs) in slot t are allocated. In the above expression, $\mathcal{T}_j(t)$ is the past throughput performance perceived by the user j, and is defined as:

$$\mathcal{T}_j(t) = \left(1 - \frac{1}{\alpha}\right) \mathcal{T}_j(t-1) + \frac{1}{\alpha}\, \mathbb{T}_j(t) \tag{1}$$

Where α is the time constant (in units of slots) of the exponential moving average. NetSim uses $\alpha = 50$, and $\mathbb{T}_j(t)$ is the actual throughput achieved by the user j in the subframe t. If $\mathcal{B}_j(t)$ is the number of PRBs allocated to user j …" [9].

$$\mathbb{T}_j(t) = \frac{\ell\left(\mathcal{M}_j(t), \mathcal{B}_j(t)\right)}{\tau} \tag{2}$$

Table I. NetSim Application Metrics Results

App_metrics						
App ID	App Name	Packets Generated	Packets Received	Throughput (Mbps)	Delay (μs)	Jitter (μs)
1	P_i	5000	4906	0.58	6518.6	0
2	P_o	5000	4906	0.58	6394.9	0
3	V_{pu}	5000	4983	0.58	6271.2	0
4	SOC	5000	4985	0.58	6147.5	0
5	UE	5000	4984	0.58	7824.7	205.2

D. *Delays*

Tetcos describes the sequence of delays when a packet leaves a node via the NetSim Experiment Manual. The first delay that impacts a packet being sent is Transmission Delay, T_D. T_D is calculated in seconds as R bits/s with a packet size B bit using (3) [13].

$$T_D = \frac{B}{R} \tag{3}$$

Tetcos introduces the second delay as Propagation Delay, T_P. T_P is included since, "…bits have to propagate at the speed of waves in the transmission medium to reach the other end" [13]. The second delay is largely dependent on the length of the wire and its negative impacts increase as the distance between links increases [13]. T_P is calculated using (4).

$$T_P = \frac{d}{s} \tag{4}$$

The variable d is the distance traveled by the wave and s represents the speed of the medium [13]. Processing Delay is initiated once the packet begins to be processed by the switch or the router [13]. Tetcos states that the negative effects are not detrimental given today's technological advancements [13]. For Queueing Delays, T_Q, packets are received at the rate of L bits/s and with the link rate of R bits/s [13]. Per Tetcos, there is no T_Q when, in terms of rates, L bits/s is less than R [13]. Tetcos establishes that the delay may still be large since the rates are often received in an erratic fashion. This includes if the result, using (5), is true.

$$T_Q = \frac{L}{R} < 0.1 \tag{5}$$

It is noted that T_Q increases in severity as it gets closer to 1 [13]. T_Q is stated to be the most unpredictable since it involves traffic sent by other nodes. The optimal ratio for T_Q is desired to be under 1.

Little's Law may be used when, "the average number of packets in the network is equal to the average arrival rate of packets into the network multiplied by the average end-to-end delay in the network" [13]. The average packets in the network may be obtained using (6).

$$Avg. Packets = (avg. arrival\ rate) * (avg. end\ to\ end\ delay) \quad (6)$$

Tetcos states that the average queuing delay, avg_Q, is found using (7), thanks to Little's Law [13].

$$avg_Q = (avg. arrival\ rate\ in\ queue) * (avg. delay\ in\ queue) \quad (7)$$

A low packet loss means more data is being transferred successfully. Listed below are the outcomes of packet loss for Power_In_Reading, Power_Out_Reading, Voltage_Reading, State_of_Charge_Reading, and Data_ Reading. Packet Loss was determined using (8). The number of packets generated does not change for all five experiments. Packet losses for the five experiments are given below.

$$Packet\ Loss = \frac{(Packet\ generated - Packet\ received)}{Packet\ generated} \quad (8)$$

$$Packet\ Loss_{P_i} = \frac{(5000 - 4986)}{5000} = 0.0028$$

$$Packet\ Loss_{P_o} = \frac{(5000 - 4986)}{5000} = 0.0028$$

$$Packet\ Loss_{V_{pu}} = \frac{(5000 - 4983)}{5000} = 0.0034$$

$$Packet\ Loss_{SOC} = \frac{(5000 - 4985)}{5000} = 0.0030$$

$$Packet\ Loss_{UE} = \frac{(5000 - 4984)}{5000} = 0.0032$$

This demonstrates the success of transmitting and receiving packets from the simulation with very low packet losses, and in the ideal case would have 0 packet losses.

Table II, shown below, lists all the links used in NetSim and numbers them in sequential order from the time it was placed on the grid. In Table II, on the third column, packets transmitted, we see the data and control packets that each link has transmitted. The next column, packets errored, shows the number of data and control packets that may have something wrong with them, such as a transmission error or a formatting error. The last column, packets collided, shows the number of data and control packets where two or more links have simultaneously collided and could have a possible loss of data.

VI. Conclusion

This work focused on establishing a 5G communication protocol between the SCADA system and the solar micro-inverter of the solar power system. To illustrate that, a 5G Communication Architecture was built, and NetSim was able to simulate the transmission of data over 5G during the execution, and the results were gathered for the generated packets and received packets. The simulation results demonstrate that the designed architecture is working properly. The implementation of the design is collecting data from the Solar Power System. It is sending data to the SCADA system via 5G Communication Architecture which is simulated in NetSim.

For future recommendations, the focus should be designing the model that was simulated in MATLAB Simulink using hardware to generate real data and using the NetSim emulator to interface with the hardware-based model of the Solar Power and SCADA Systems to verify the results shown in this paper.

Table II. NetSim Link Metrics Results

Link_metrics						
Link ID	Packets Transmitted		Packets Errored		Packets Collided	
	Data	Control	Data	Control	Data	Control
All	129759	5034	31	0	0	0
1	0	10	0	0	0	0
2	0	10	0	0	0	0
3	24955	0	0	0	0	0
4	0	15	0	0	0	0
5	24955	0	0	0	0	0
6	0	15	0	0	0	0
7	0	0	0	0	0	0
8	4984	4984	0	0	0	0
9	4991	0	7	0	0	0
10	19964	0	24	0	0	0
11	24955	0	0	0	0	0
12	24955	0	0	0	0	0

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