Feasibility study, Dynamic modeling, Optimization, and Implementation of Low-cost communication systems for Remote DC microgrids in Nigeria

PhD Oral Defence

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Presentation Outline

- Introduction
- Literature Review
- Research Objectives
- Research Contributions
- Optimal Sizing and Analysis of a Small Hybrid Power System for Umuokpo Amumara in Eastern Nigeria
- Sizing , Dynamic Modelling and Simulation of a Standalone PV Based DC Microgrid with Battery Storage System for A Remote Community in Nigeria
- LoRa-based communication system for data transfer in microgrids.
- An Open Source LoRa Based, Low-Cost IoT Platform for Renewable Energy Generation Unit Monitoring and Supervisory Control.
- Conclusion
  - Summary, Contributions, Future work
- References

Introduction

- Most remote communities especially in developing countries lack electricity.
- Usually caused by lack of access to these areas causing a negative effect on the quality of life and economy of the communities.
- Most of these areas have abundant renewable energy resources such as wind, solar and hydro.
- These Renewable energy sources can be harnessed as a cost-effective and clean energy solution.
- A microgrid can be AC or DC based on the power being fed.
- Remote communities have very low energy requirements and as such a DC microgrid will meet energy needs.
- To achieve proper control and operation of a microgrid, each DG unit should be updated with information pertaining to the microgrid's operating mode.
- It is expected that soon, microgrid operations will be automated by employing sensors integration for data collections and actuators for controls.
- To achieve automation, a reliable communication system for data and command transfer at every control level within the microgrid is a fundamental requirement.
- Communication system can be wired or wireless.

Literature Review

- **DC Microgrid [1-7]**
  - The DC microgrid features easy integration with higher number of renewable energy sources thereby reducing the conversion stages and losses.
  - It delivers its energy to its load in Direct Current form.

- **DC Microgrid Advantages**
  - Seamless integration with renewable energy sources and storage
    - PV, small wind turbines, micro-hydro, biomass and most energy storage systems produce power in DC form.
  - DC load
    - Most consumer electronic products, home appliances and lighting fixtures run using DC power
  - Loss Reduction
    - A reduction is the amount of conversion stages in the DC system reduces the amount of system losses
  - Low Cost of Energy Distribution
    - Reduction in overall system cost due to reduction in energy distribution components
  - Low System Complexity
    - There is no need for reactive power control, frequency regulation and phase synchronization.
    - Operational complexity of a DC system will be reduced

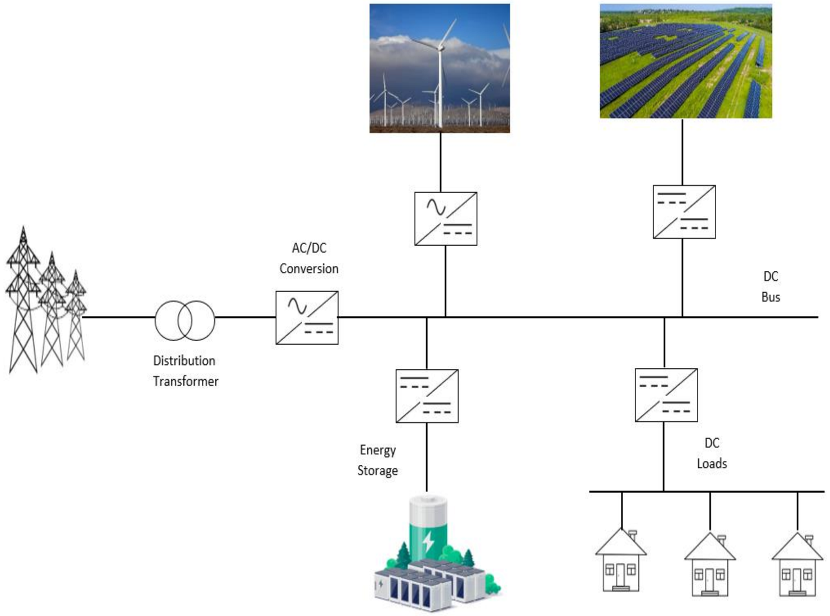


Fig. 1. Schematic diagram of a grid-connected DC microgrid

Literature Review – Contd.

- **Dc Microgrid Control Schemes**
  - The main control objectives of the DC microgrid include [8-12]
    - Efficient voltage and current control in all operating nodes.
    - Coordination among different DERs and Energy Storage Devices.
    - Smooth transition between various operation modes.
    - Power flow control within the DC microgrid.
    - Maximum utilization of DERs potentials.
  - DC microgrid control schemes can be mainly classified into two categories:
  - **Basic Control**
    - Normally achieved by employing centralized, decentralised or distributed control.
  - **Multilevel Control**
    - Usually achieved through different levels of control in the hierarchy.
    - In this scheme, each of the control levels then employs either or multiple basic control strategies.

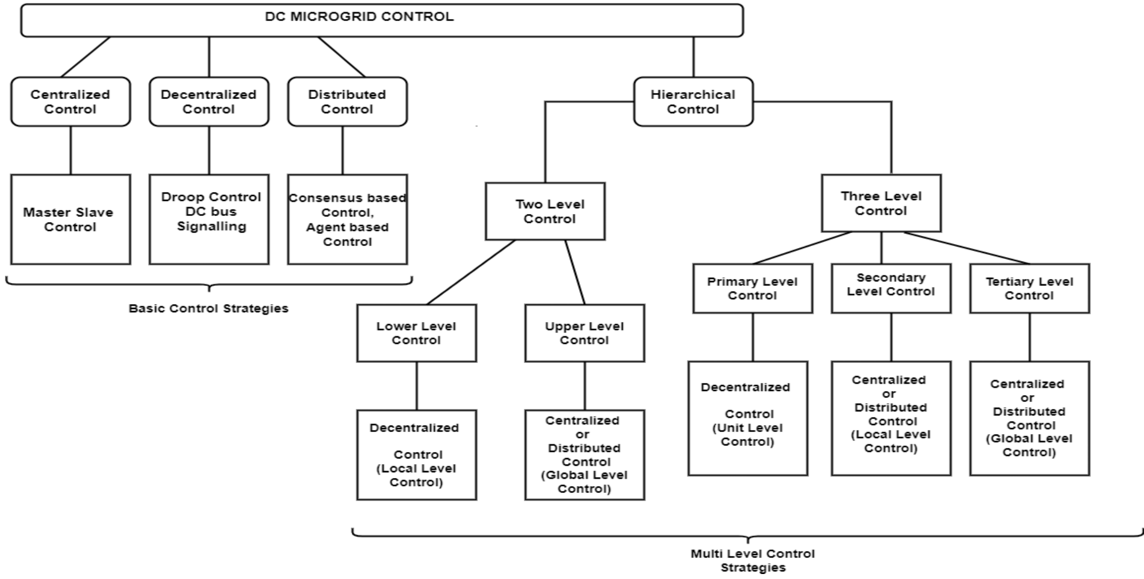


Fig. 2. A diagrammatic representation of the various control schemes .

- **Basic Control Strategies**
- *Centralised Control[13]*
  - This strategy employs a central controller to control the distributed units.
  - Data processing and control commands developments are initiated at the central controller.
  - This makes this control strategy highly communication dependent.
  - High level of system observability and controllability are the main advantages of this strategy.
  - Single point of failure and scalability are the main disadvantage of this strategy.

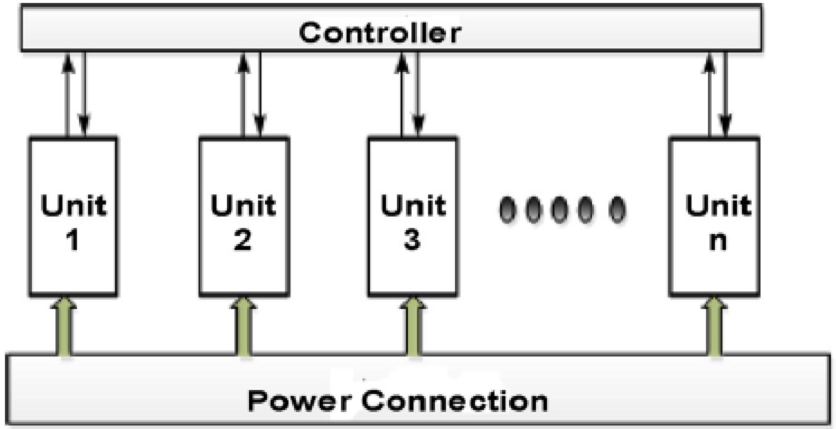


Fig. 3. Schematic Configuration of the Centralized control Strategy.

Literature Review – Contd.

- *Decentralised Control [14]*
    - This strategy does not depend on a communication system thereby eliminating single point of failure.
    - The distributed units are normally controlled by independent controllers using their local variables.
    - Normally considered the most reliable control strategy because it is not communication dependent.
    - Its main drawback is insufficient unit information as there are communication between neighbouring units
- *Distributed Control [15-20]*
    - This strategy employs the advantages of centralised and decentralized control.
    - In this strategy, the limited communication links are used for data transfer between neighbouring units to achieve control objectives such as voltage restoration and current sharing.
    - The main advantage of this strategy
        - Immunity to single point of failure
        - Communication between neighbouring units
    - Main disadvantage
        - Complexity
        - Power tracking error
        - Voltage deviation

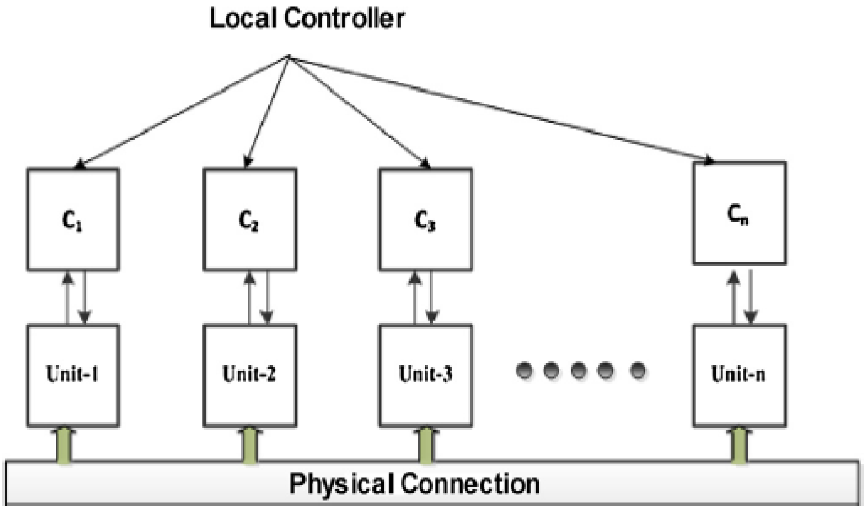


Fig. 4. Schematic diagram of the decentralized control Strategy

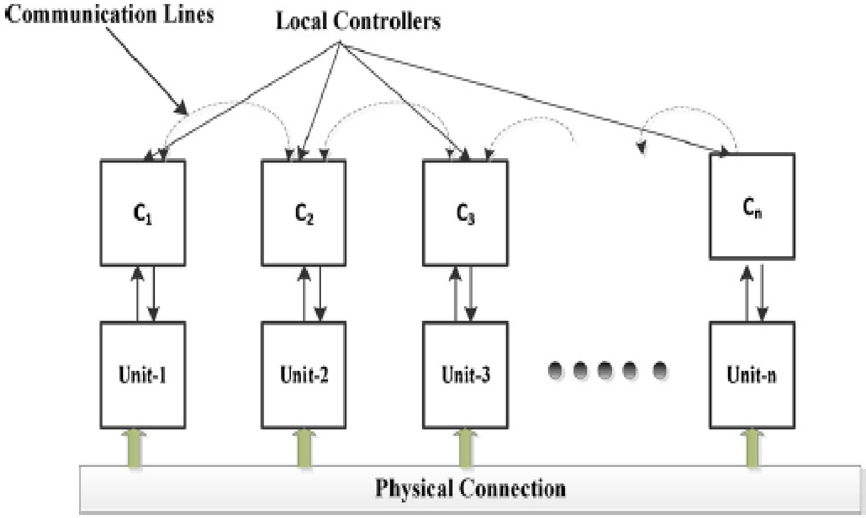


Figure 5. Diagrammatic representation of distributed control scheme

Literature Review – Contd.

- **Hierarchical (multi-level) Control Strategies** [21-27]
  - Control objectives such as voltage control, current control etc. alongside advanced controls such as power sharing between DGs and energy market participation cannot be achieved by single level controls.
  - Modern power systems such as the DC microgrid require these multilevel control for various control functions according to their levels of complexity and latency requirements.
  - This control strategy improves the overall system reliability as failures at any level do not affect other levels and as such system can still be operational while rectifying the problem.
- **Hierarchical Control levels**
- In the hierarchical control framework, there are three control levels:
  - Primary (local) Control Level [28-30]
  - Secondary Control Level [31-35]
  - Tertiary Control Level [36-39]

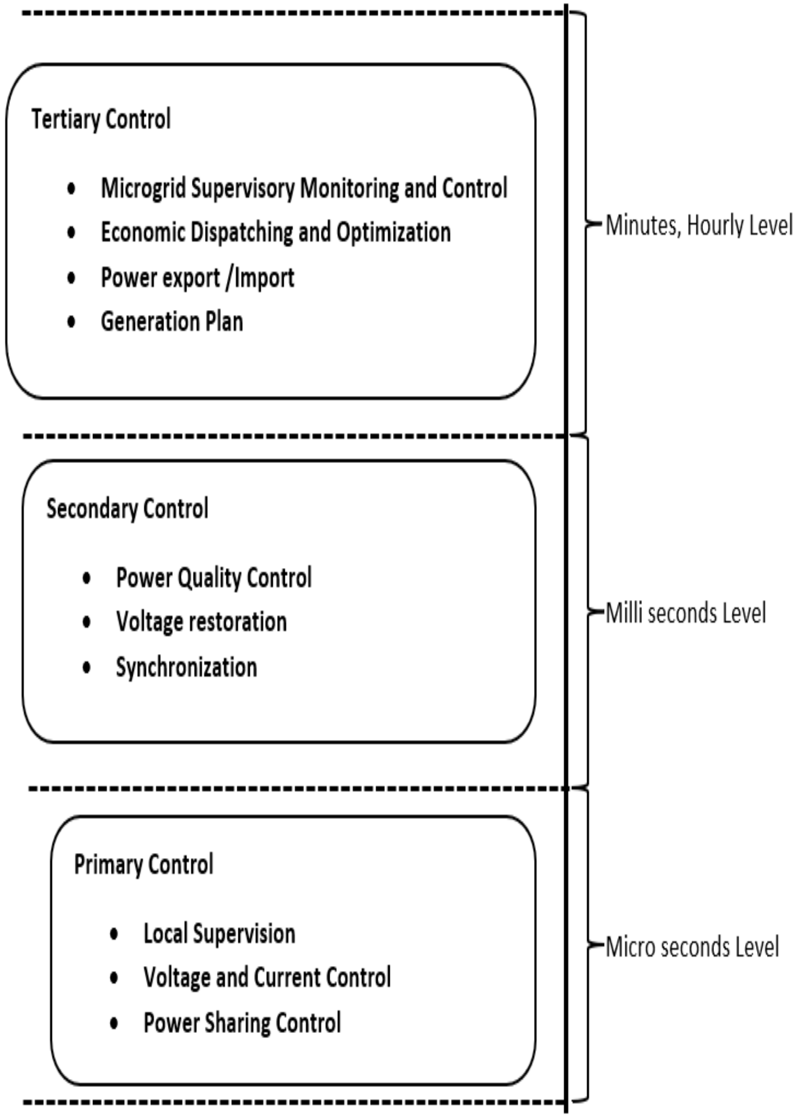
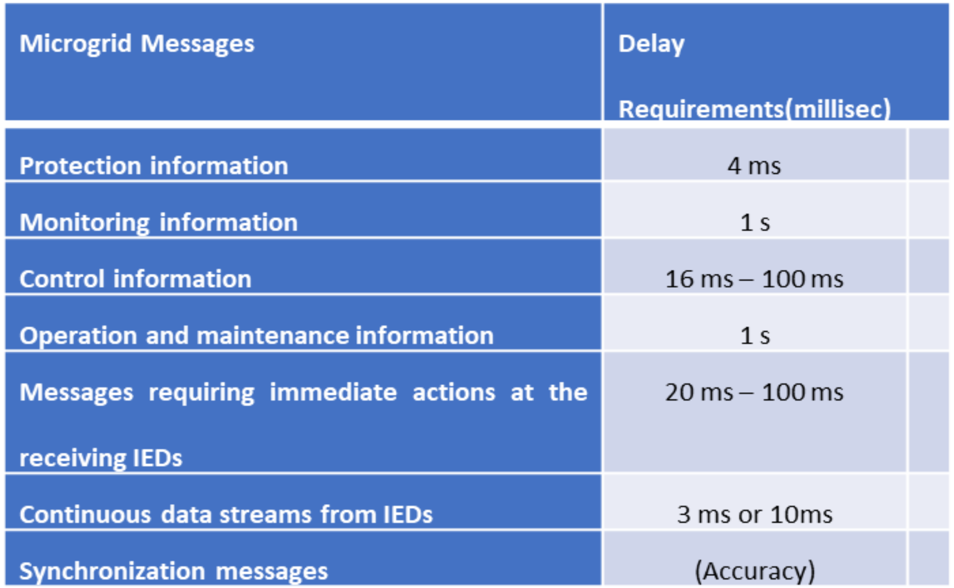


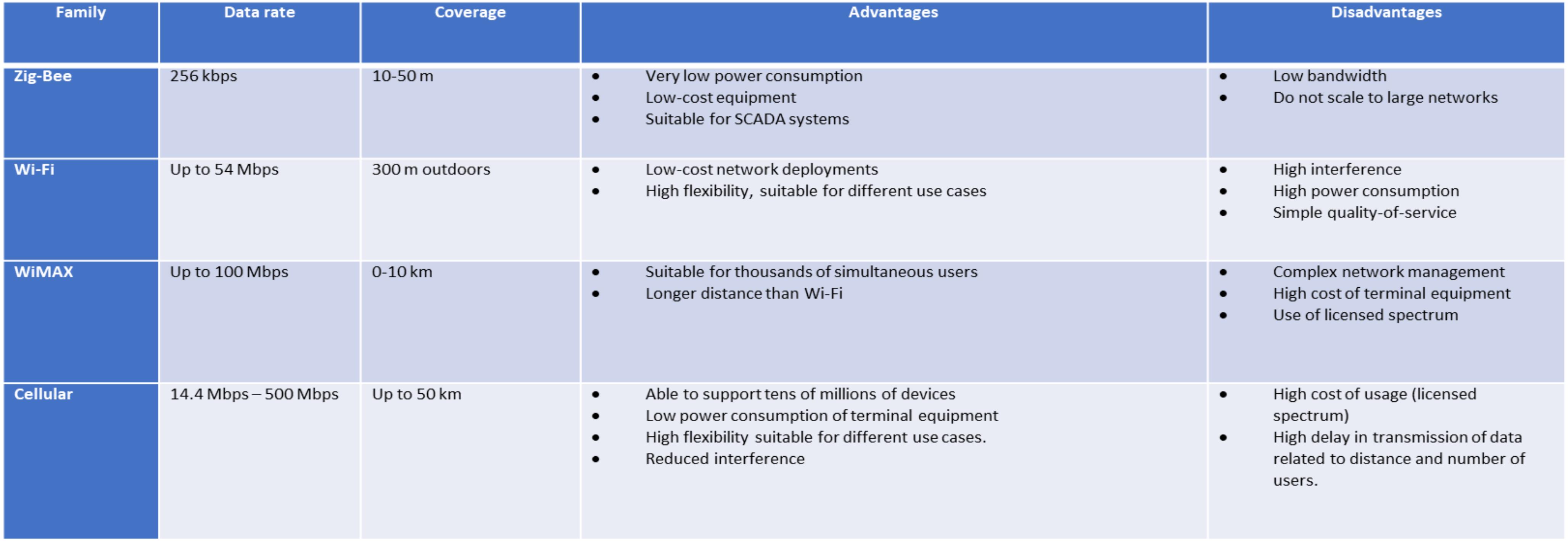
Fig. 6. Hierarchical Control: Functions and timeframe

Literature Review – Contd.

- **Data Transfer In Microgrids [40]**
- Data transfer is very important to maintain optimum microgrid performance
- A reliable and consistent communication system is therefore very important.
- To achieve proper operation of the microgrid the following data requirements are important.
    - Data latency
    - Data Delivery Criticality (high, medium, non-critical)
    - Reliability
    - Time Synchronization



Microgrid Messages	Delay Requirements(millisec)
Protection information	4 ms
Monitoring information	1 s
Control information	16 ms – 100 ms
Operation and maintenance information	1 s
Messages requiring immediate actions at the receiving IEDs	20 ms – 100 ms
Continuous data streams from IEDs	3 ms or 10ms
Synchronization messages	(Accuracy)

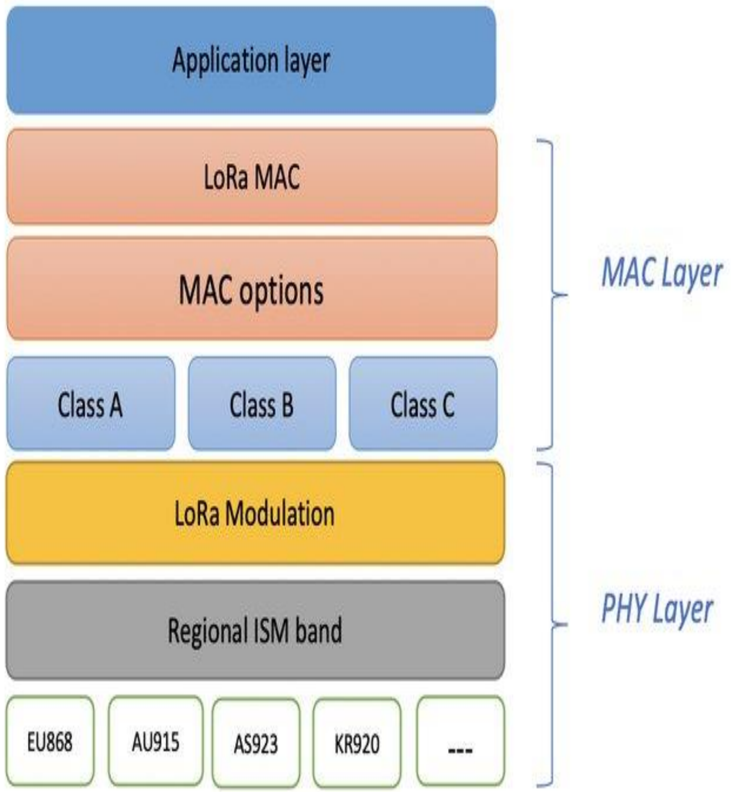


Family	Data rate	Coverage	Advantages	Disadvantages
Zig-Bee	256 kbps	10-50 m	• Very low power consumption • Low-cost equipment • Suitable for SCADA systems	• Low bandwidth • Do not scale to large networks
Wi-Fi	Up to 54 Mbps	300 m outdoors	• Low-cost network deployments • High flexibility, suitable for different use cases	• High interference • High power consumption • Simple quality-of-service
WiMAX	Up to 100 Mbps	0-10 km	• Suitable for thousands of simultaneous users • Longer distance than Wi-Fi	• Complex network management • High cost of terminal equipment • Use of licensed spectrum
Cellular	14.4 Mbps – 500 Mbps	Up to 50 km	• Able to support tens of millions of devices • Low power consumption of terminal equipment • High flexibility suitable for different use cases. • Reduced interference	• High cost of usage (licensed spectrum) • High delay in transmission of data related to distance and number of users.

Literature Review – Contd.

- **LoRa Communication Technology [40-42]**

- A low power wide area network technology developed by Semtech Corporation.
- LoRa employs a star topology.
- LoRa is the physical layer, or the wireless modulation used in creating a long-range communication link for LoRaWAN data transfer (5 km urban and 15km Rural).
- LoRa physical layer operates in the unlicensed Industrial, Scientific, and Medical (ISM) frequency band.
- **Chirp Spread Spectrum Modulation (CSS) technique**, to achieve both low power and long-range communication.
- LoRa achieves long data transfer ranges and high level of interference immunity.



Application layer

LoRa MAC

MAC options

Class A | Class B | Class C

LoRa Modulation

Regional ISM band

EU868 | AU915 | AS923 | KR920 | ---

MAC Layer

PHY Layer

Fig. 8. LoRa Protocol Stack

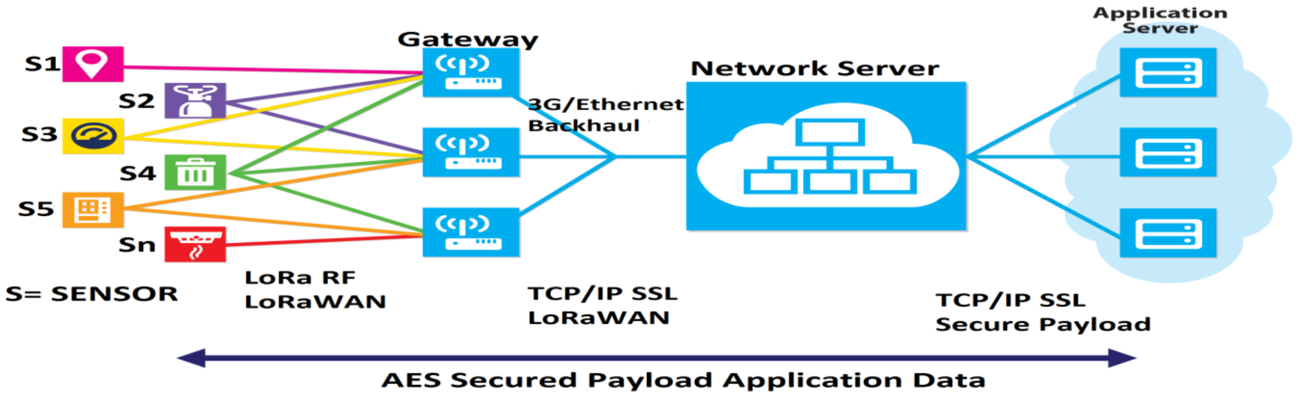


Fig. 7. LoRaWAN Architecture

Literature Review – Contd.

- **Supervisory Control and Data Acquisition(SCADA) [43-52]**
- A technology that allows for collection of data from one or various facilities for monitoring and control purposes.
- SCADA can be applied to any system (energy, generation, waste management etc.).
- SCADA has evolved in 4 generations since inception.
- SCADA system components.
    - Field Instrumentation devices: Devices directly connected to the plant (Sensors, actuators etc.)
    - Remote Terminal Units (RTUs): Generally small computerised units for data collection from FIDs.
    - Master Terminal Units (MTUs): In charge of data collection, processing and control command processing and transmission.
    - Communication Network: the mode through which data is transferred between the SCADA components.
- Features of SCADA (Desired features of a SCADA system include:
    - Low Power Consumption.
    - Reliability and availability.
    - Ease of installation and use.
    - Redundancy.
    - Scalability.
    - Security.
- Classes of SCADA Systems
    - Proprietary (traditional) SCADA
        - Mainly manufactured by one vendor: Allen Bradley, Schneider etc.
    - Open-Source SCADA
        - Allows for mix and match components.
        - Efficiency of the system is not the sole responsibility of one vendor.
        - Combination of various components to achieve better standards and cheaper.

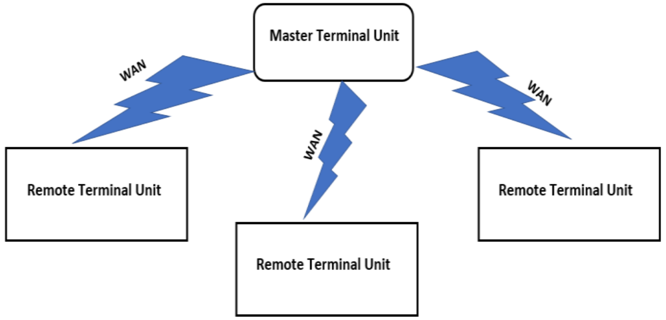


Fig. 9. Monolithic SCADA

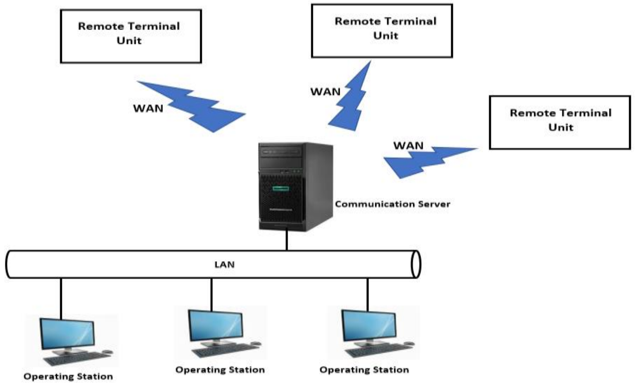


Fig. 10 Distributed SCADA

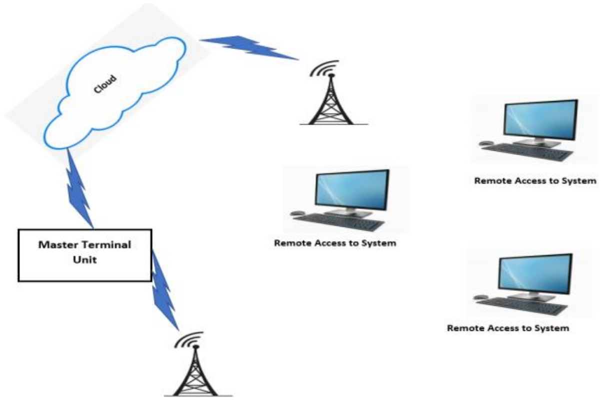


Fig. 12. Internet of Things (IoT) based SCADA architecture.

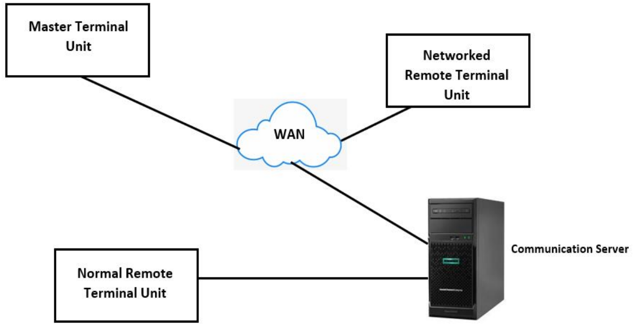


Fig. 11 Networked SCADA architecture.

Research Objectives

1. Techno-economic feasibility study of AC microgrids for power generation and supply in rural communities in West Africa.
2. Design, dynamic Modelling, and Simulation of a Standalone PV-based DC microgrid with a battery storage system for a remote community in Nigeria.
3. Development of a LoRa-based communication scheme for secondary control level data transfer in remote microgrids.
4. Design and development of a low-cost LoRa-Based SCADA system for monitoring small renewable energy generation systems.
5. Analysis of LoRa data transmission delay on the dynamic performance of the DC microgrid.

Optimal Sizing and Analysis of a Small Hybrid Power System for Umuokpo Amumara in Eastern Nigeria

- This study focuses on the techno-economic feasibility of developing a hybrid power system to meet the electrical power needs of remote communities.
- This analysis assumed each house consists of a living room, four bedrooms, a kitchen, a bathroom, and a balcony.
- Each house has a peak load of 1.42 kW, which amounts to 1.136 MW for 800 houses
- Public community installations were also considered in the analysis.
- **Community Peak load** = House Peak + Community Peak = 1,136 kW + 7.3 kW = 1,143 kW

Installation	Electrical features	Load rating(W)	Hours of operation	Energy (Wh/day)
Schools (2)	2*(10*60 W bulbs) + (2*80 W bulbs)	1360	6	8160
Churches (3)	3*(10*100 W bulbs)	3000	4	36000
Town hall	4*60 W bulbs	240	3	720
Small shops (20)	20*60 W bulbs	1200	12	14400
Village water Pumping system (1)	1500 W	1500	2	3000
Total		7,300		62,280

Installations	Number in Village
Houses	800
Schools	2
Churches	3
Town hall	1
Small Shops	20
Village Water Pumping System	1

Installation	Electrical features	Load rating (W)	Hours of operation	Energy (Wh/day)
4 bedrooms	4 * 100 W bulbs	400	6	2400
Sitting room	2* 100 W bulbs	200	6	1200
Kitchen	100 W bulb	100	6	600
Bathroom	100 W Bulb	100	6	600
Balcony	100 W bulb	100	6	600
Television	150 W	150	10	1500
Stereo	50 W	50	4	200
Ceiling Fan	120 W	120	5	600
Refrigerator	200 W	200	20	4000
Total		1,420		11,700

Optimal Sizing and Analysis of a Small Hybrid Power System for Umuokpo Amumara in Eastern Nigeria – Contd.

- In this community, the peak usage of power occurs in the evenings from 1600 -2200 hours.
- The village has a total energy consumption of 9.422 MWh/day.
- The village has an average solar irradiation of 4.71 kWh/m^2/d, which indicates a high potential of electricity generation from solar.
- Data obtained from NASA states that Umuokpo has an average wind speed of 2.70 m/s at an anemometer height of 50 m.

- The power-law wind speed model is used to calculate the wind speed at a higher height.

$$U_Z = U_{Zr}(\frac{Z}{Z_r})^{\alpha}$$

- Where,

Where, Z, Z_r are the proposed height above the ground and reference height, respectively; U_Z, U_{zr} are wind speed at the proposed height and known wind speed, respectively; and α is the wind shear coefficient (0.2).

- Wind speed of 3.0 m/s was achieved at 84 m height. This therefore entails that the wind resource in the community will not power a utility scale wind turbine for power production.

The proposed AC hybrid power system

- The considered hybrid system is consisted of PV arrays, a diesel generator serving as back up, and a battery storage.

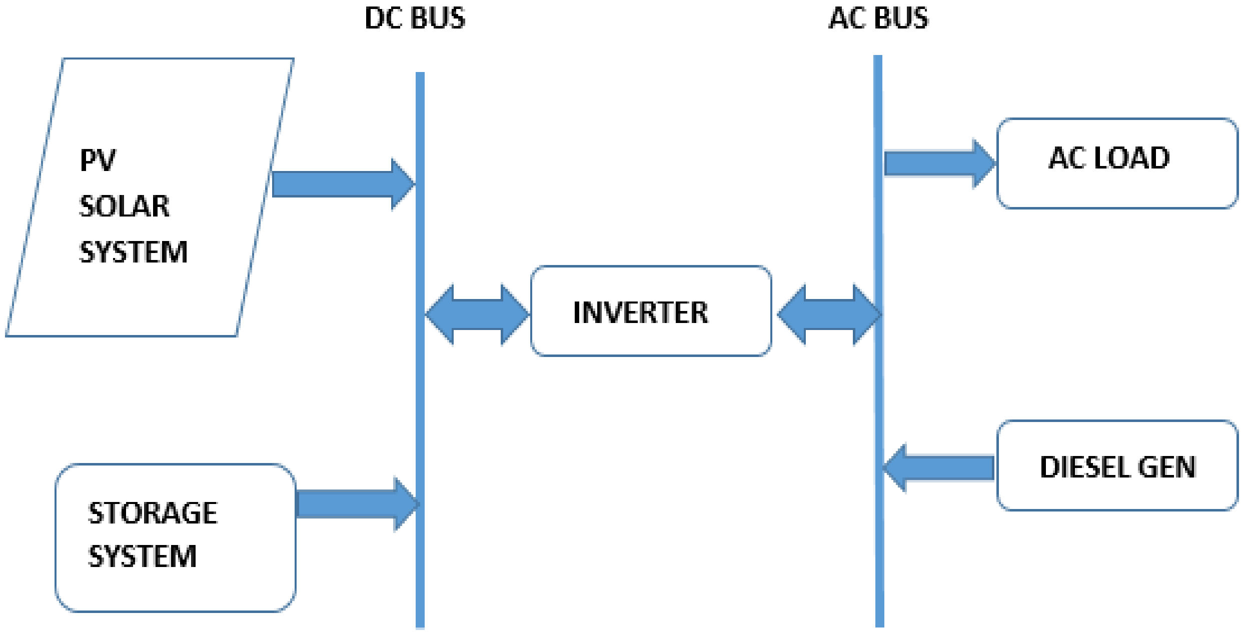


Fig. 13. The proposed hybrid system configuration.

Homer optimization of AC microgrid

- Simulations to identify the optimal system for the village electrification was carried out on HOMER.
- A total of 5,292 simulations were carried out on the software.
- The optimal system configuration based on both cost and capacity to serve the community electrical load consists of a 2,750 kW PV array, a 1,500-kW diesel generator as backup, and 15,000 units of battery system (12V, 200Ah) for energy storage.
- This optimal system achieved 79% renewable energy fraction with the generated power of 3.6 GWh/yr from the PV.
- The proposed system met the energy requirements of the community and charged the energy storage system

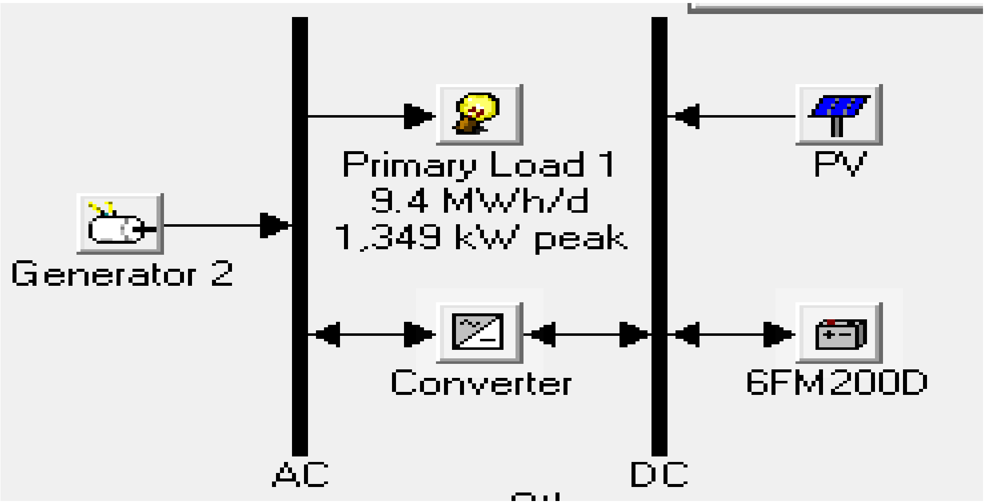


Fig. 14. Configuration of the optimal proposed system

Production	kWh/yr	% Production
PV array	3,635,785	79
Generator 2	959,000	21
Total	4,594,785	100
Consumption	kWh/yr	% Consumption
AC primary Load	3,439,031	100
Quantity	kWh/yr	%
Excess electricity	143,164	3.12
Unmet electric load	0.00237	0
Capacity shortage	42.2	0
Renewable Fraction		79

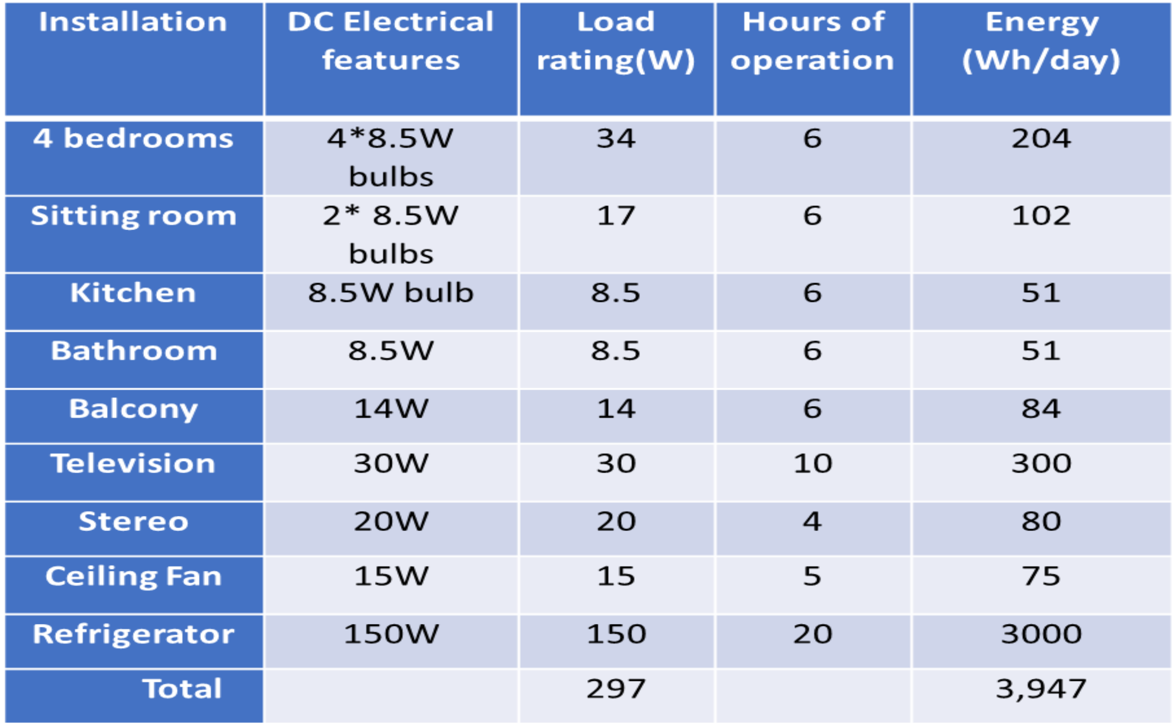
Battery	
Nominal Capacity	36,000 kWh
Usable Nominal Capacity	21,600 kWh
Autonomy	55 hrs
Lifetime throughput	13,755,000 kWh
String Size	50
Strings in parallel	300
Total number of battery units	15,000
Energy in	2,970,676 kWh/yr
Energy out	2,391,040 kWh/yr
Expected Life	5.15 yrs
SOLAR PV SYSTEM	
Rated Capacity	2,750kW
Mean Output	415 kW
Mean Output	9,916 kWh/d
Capacity Factor	15.1%
Maximum Output	2,649 kW
Annual Total Energy Production	3,635,785 kWh/yr
DIESEL GENERATOR	
Rated Capacity	1,500 kW
Mean Electrical Output	1,000 kW
Operational Life	15.6 yrs
Capacity Factor	10.9 %

Sizing And Dynamic Modelling and Simulation of a Standalone PV Based DC Microgrid with Battery Storage System for A Remote Community in Nigeria

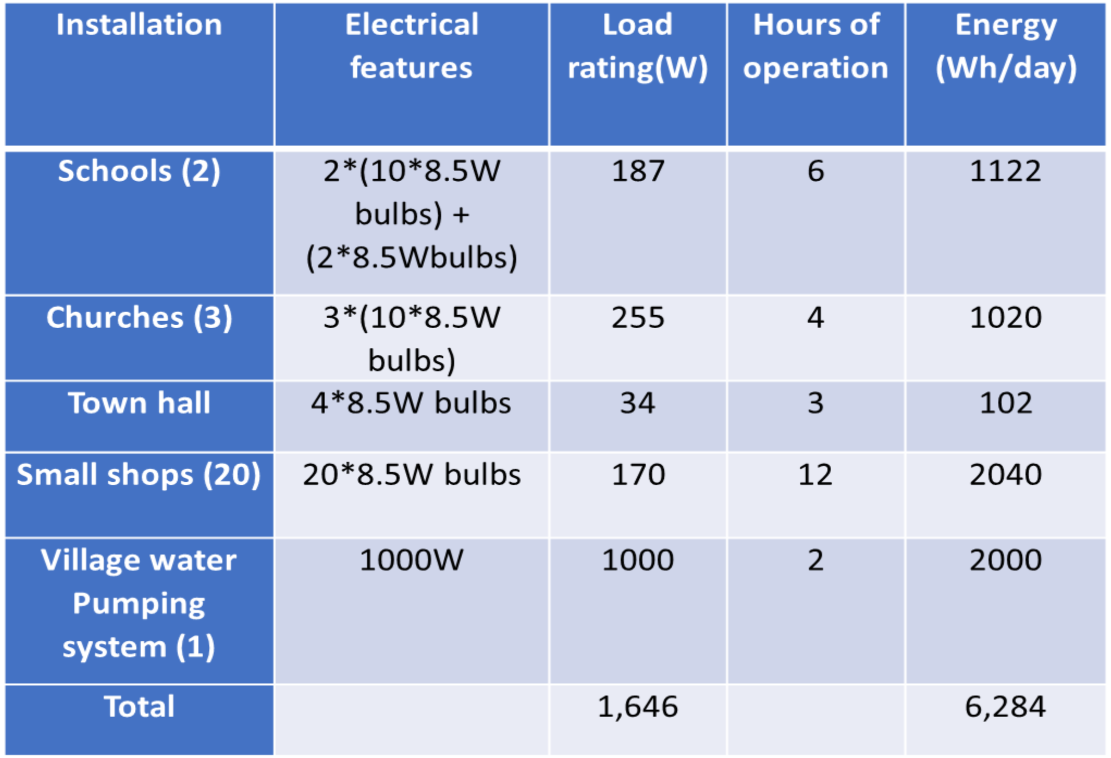
- The same community was used for this study.
- Since the study is focused on DC microgrid for the community, the electrical features that will be used for the design will be DC installations.

Community Peak Load = Houses Peak + Community Installation Peak

238kW + 1.64kW= 239.7kW



Installation	DC Electrical features	Load rating(W)	Hours of operation	Energy (Wh/day)
4 bedrooms	4*8.5W bulbs	34	6	204
Sitting room	2* 8.5W bulbs	17	6	102
Kitchen	8.5W bulb	8.5	6	51
Bathroom	8.5W	8.5	6	51
Balcony	14W	14	6	84
Television	30W	30	10	300
Stereo	20W	20	4	80
Ceiling Fan	15W	15	5	75
Refrigerator	150W	150	20	3000
Total		297		3,947



Installation	Electrical features	Load rating(W)	Hours of operation	Energy (Wh/day)
Schools (2)	2*(10*8.5W bulbs) + (2*8.5Wbulbs)	187	6	1122
Churches (3)	3*(10*8.5W bulbs)	255	4	1020
Town hall	4*8.5W bulbs	34	3	102
Small shops (20)	20*8.5W bulbs	170	12	2040
Village water Pumping system (1)	1000W	1000	2	2000
Total		1,646		6,284

Homer optimization of DC microgrid

- The simulations to select the optimal DC system for the village electrification was carried out on HOMER.
- The optimal system was chosen based on the Net Present Cost analysis.
- The system consists of a 1,000kW PV array, a 630kW, Diesel generator as backup and 4,680 units of battery system for energy storage.
- The optimized proposed system achieved 88.6% renewable energy fraction with electrical production of 1.38GWh/yr from the PV array.
- The optimized DC system met the energy requirements of the community completely.

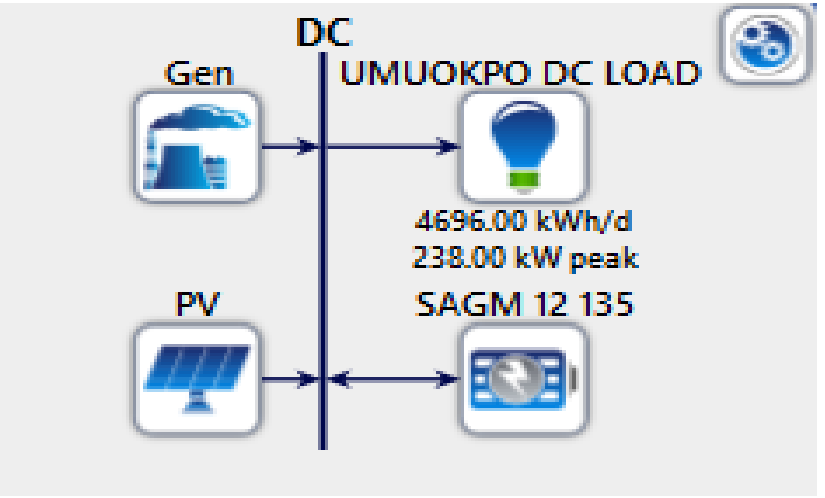


Fig. 15. Homer Configuration of the proposed DC microgrid.

Production	kWh/yr	% Production
PV array	1,384,263	91.3
Diesel Generator	131,371	8.67
Total	1,515,634	100
Consumption	kWh/yr	% Consumption
DC primary Load	1,153,400	100
Quantity	kWh/yr	%
Excess electricity	241,547	15.9
Unmet electric load	0	0
Capacity shortage	0	0
Renewable Fraction		88.6

Battery	
Nominal Capacity	7,857 kWh
Usable Nominal Capacity	3,929 kWh
Autonomy	29.8 hrs
Lifetime throughput	6,835,608 kWh
String Size	30
Strings in parallel	156
Total number of battery units	4,680
Energy in	824,522 kWh/yr
Energy out	703,835 kWh/yr
Expected Life	8.95 yrs
SOLAR PV SYSTEM	
Rated Capacity	1,000 kW
Mean Output	158 kW
Mean Output	3,793 kWh/d
Capacity Factor	15.8%
Maximum Output	973 kW
Annual Total Energy Production	1,384,263 kWh/yr
DIESEL GENERATOR	
Rated Capacity	630 kW
Mean Electrical Output	213 kW
Operational Life	24.4 yrs
Capacity Factor	2.38%

Cost Summary and Energy Comparison of AC and DC systems

- The cost requirements, energy requirements of the community and energy generation of each type of the microgrids are the basis for the comparison.
- Results obtained showed that the DC microgrid was more suitable for power generation and supply to rural areas due to the following advantages over the AC power systems:
- **Low – Cost**
  - There is a 73.7% reduction in capital cost for the development of the DC microgrid to that of the AC microgrid.
  - The annual operation and maintenance cost of the DC microgrid reduced by almost 80% from that of the AC microgrid.
- **Lower Energy Requirements**
  - The daily energy requirement of the community reduced from about 9.22MWh/day to 3.6MWh/day.
  - This represents an energy requirement reduction of about 60%.
  - This had a reducing effect on the energy generation system that was developed and as a result on the cost of the whole system.

	AC Microgrid	DC Microgrid
Capital ($)	12,576,464	3,310,400
Replacement ($)	10,450,994	1,424,360
Operation & Maintenance ($)	29,821,416	370,534
System Total ($)	52,848,874	5,105,294
Energy Production (kWh/yr)	4,594,785	1,515,634
Community Energy Requirement (kWh/yr)	3,439,031	1,153,400

Dynamic Modelling and Simulation of the DC Microgrid

- A dynamic simulation of the optimal system was carried out in MATLAB Simulink.
- 360VDC bus voltage, 24 VDC residential and 48VDC for community water pumping system.
- The Incremental Conductance MPPT algorithm is employed.
- A voltage mode controller was also employed to maintain the voltages in the system so as not to be affected by the system variations.

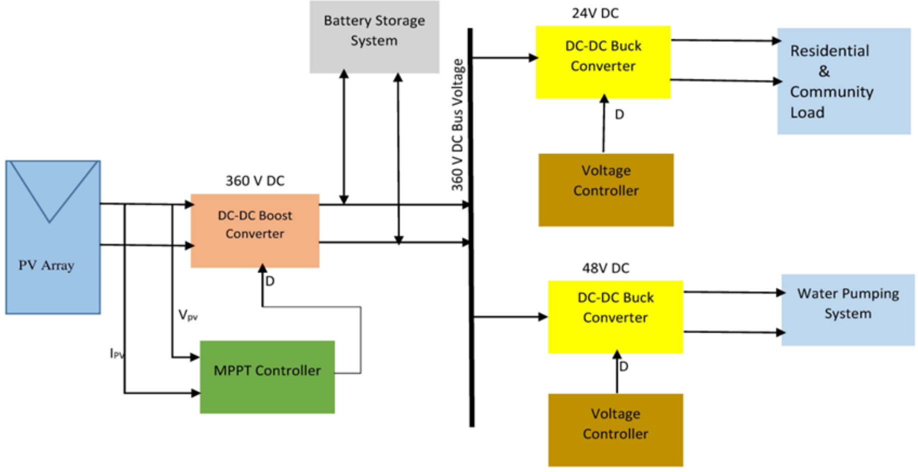


Fig. 16. Block Diagram of the proposed DC microgrid

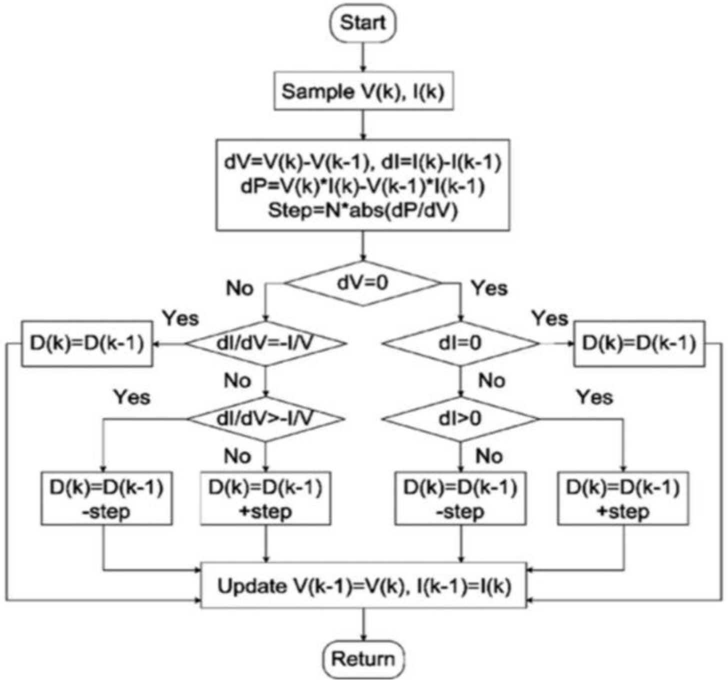


Fig. 17. Incremental Conductance MPPT Flow Chat

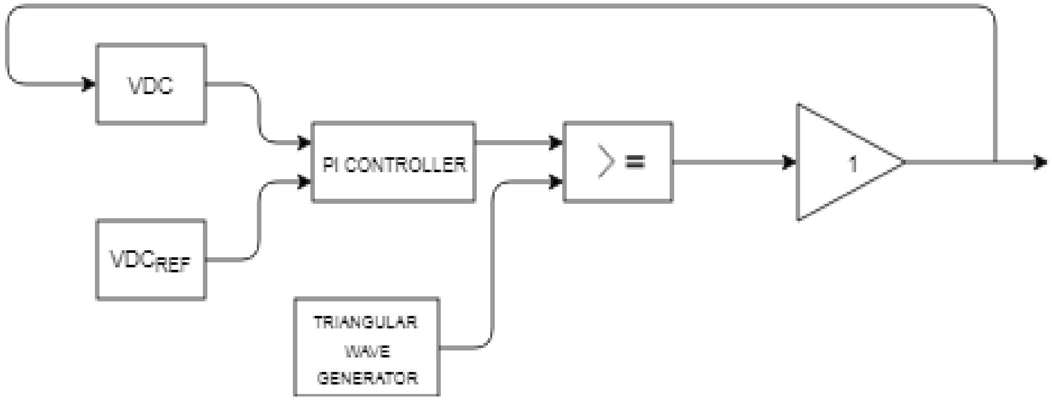


Fig. 18. The Voltage Control Block

Dynamic Modelling and Simulation of the DC Microgrid-Contd.

- Results from the dynamic simulation of the DC microgrid are as shown.

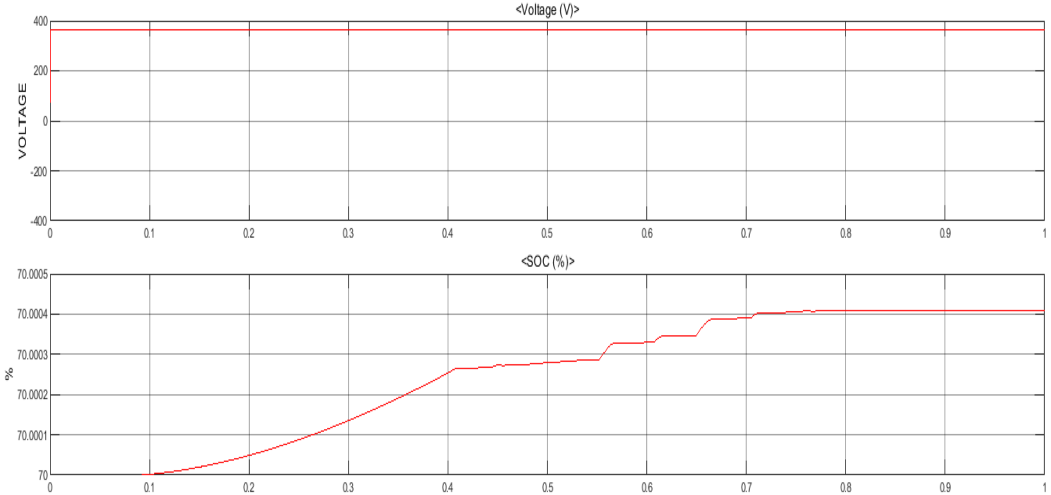


Fig. 19. Battery Voltage and State of Charge

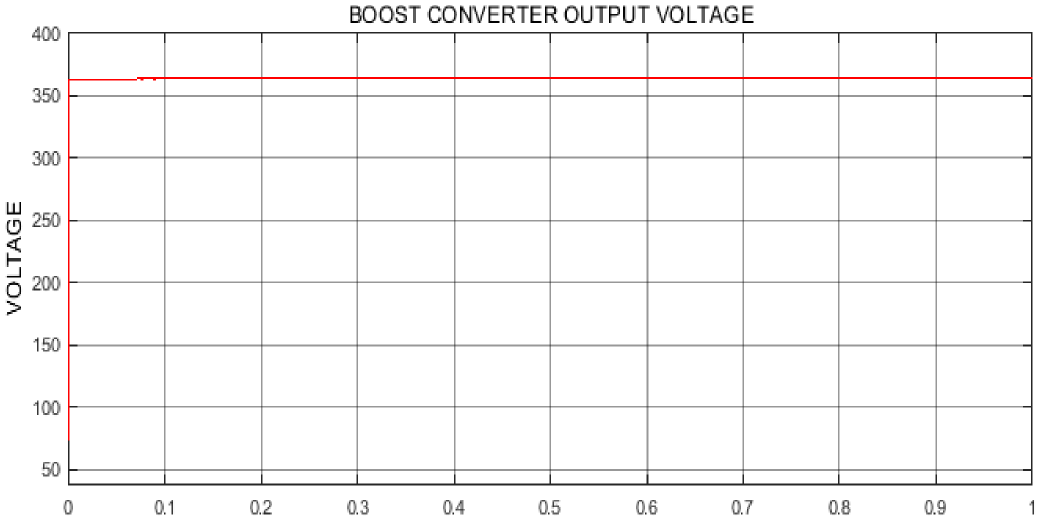


Fig. 20. DC-DC Boost Converter Output Voltage

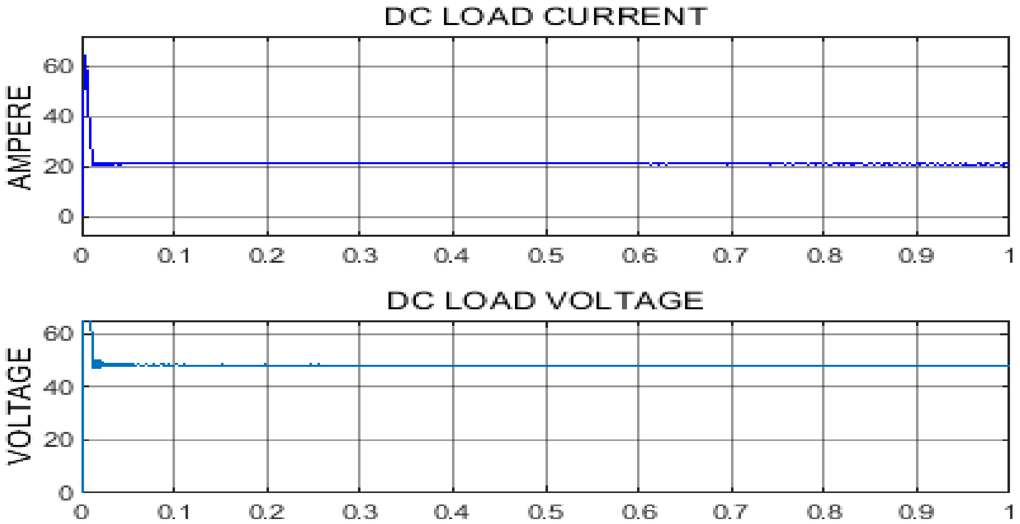


Fig. 21. The Voltage and Current Output for Water pumping facility

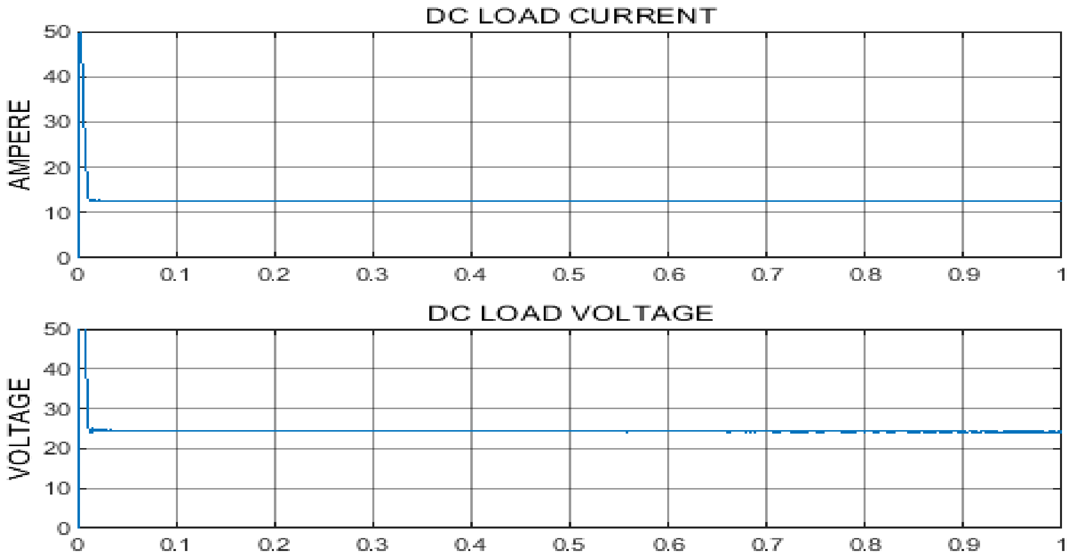


Fig. 22. Voltage and Current output for Residential house

LoRa for Microgrid Secondary Control and Data Transfer

Communication Schemes and Layers in Microgrids

- Predominantly, two types of data communication schemes :
  - Centralized (also known as hierarchical),
  - Distributed.
- Centralized scheme,
  - Advantage of easy implementation and maintenance.
  - Drawback is single point of failure.
- Distributed scheme,
  - Offers more flexibility and is more robust from communication failure
  - Drawback is it requires a complex algorithm.
    high processing time, less precision .
    and a higher possibility of data collision.
- This work focuses on the Centralized communication scheme.

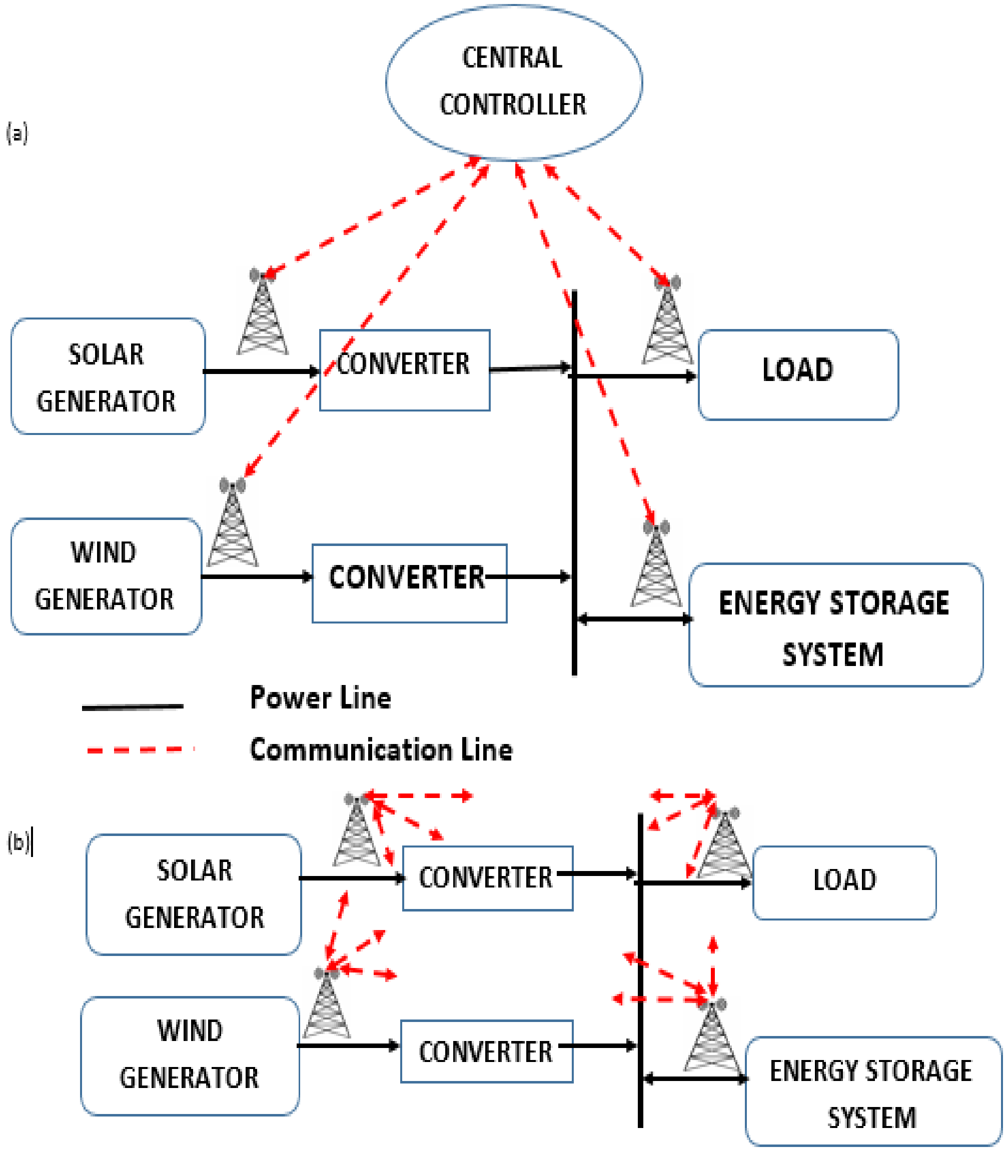


Fig. 23. Data communication schemes in microgrids: (a) centralized, and (b) distributed

Communication Schemes and Layers in Microgrids – Contd.

- A hierarchical control system for microgrid operation is consisted of three control levels:
- **The Local Controller:**
  - Lowest Control Block in the microgrid
  - Allows connection to sensors and actuators for data measurement and system control
  - Applies small data sampling time to acquire data from the DG units.
- **Microgrid Central Controller:**
  - Makes control decisions using sensor data obtained from local controllers and create operating points.
- **Tertiary Controller:**
  - Ensures general control of the power network.
  - Allows communication between neighboring microgrids and overall system stability.
- For proper functioning and stability of the microgrid, the three control layers described above will have to be in constant and reliable communication.
- Hence reliable communication system is important.

Communication Layers in Microgrids – Contd.

- Primary level communication allows communication between the sensors and local controller.
- Data obtained at the first level is transmitted to the central microgrid for processing using the secondary communication level.
- The second (secondary) level involves the communication between various local controllers situated in the DG units and the microgrid central controller.
- The secondary level allows for bidirectional data transfer to achieve monitoring and control activities to maintain performance of the microgrid.
- The secondary level allows for low bandwidth communication because it is normally employed for referencing.

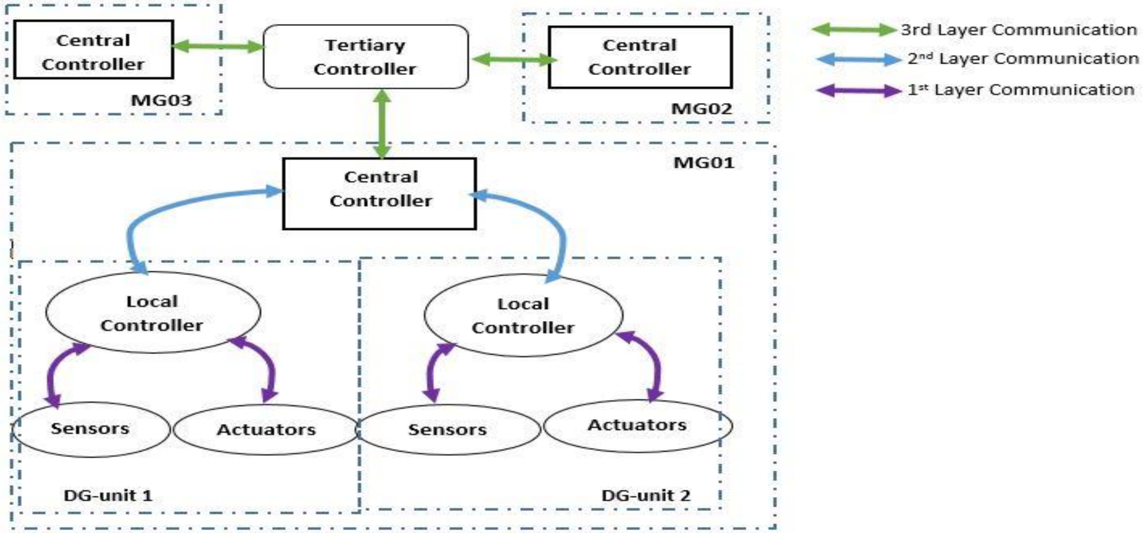


Fig. 24. Communication levels in a microgrid

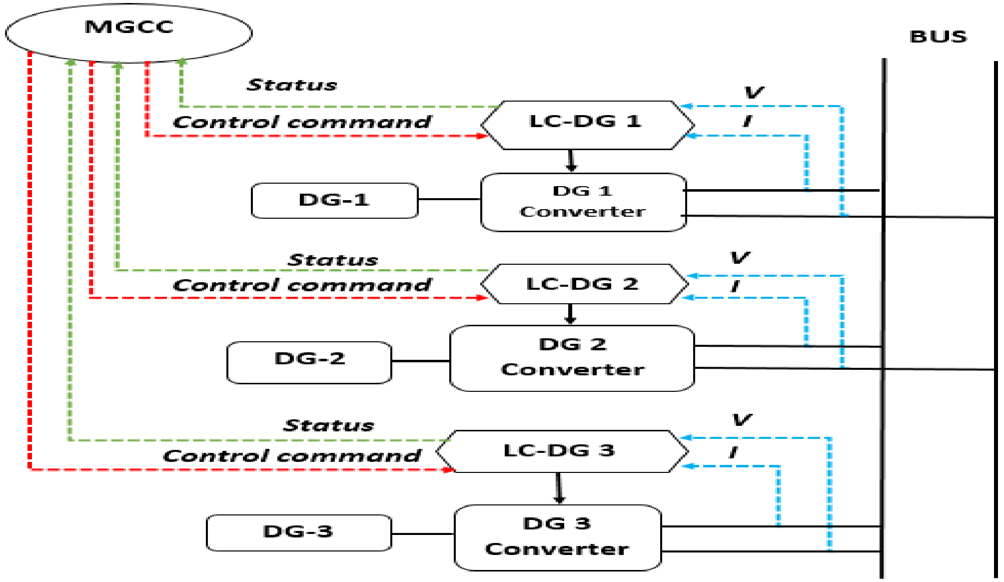


Fig. 25. Typical Description of the secondary communication layer of a microgrid

LoRa Communication in Microgrids

- LoRa is a fast-rising wireless communication technology.

- In LoRa communication, there are two classes of devices, with different communication capabilities.

- **LoRa Node:**

  - Capabilities for sensor and actuator connection through controllers or microcontrollers.

  - Allows data bidirectional data transfer with one device on same transmission frequency.

  - In the microgrid, it is connected for sensor data transfer from the DG local controller.

- **LoRa Gateway:**

  - Capabilities to communicate simultaneously with higher number of devices.

  - In the microgrid, it is connected to the central microgrid for communication with local controllers

Specification	LoRa	ZigBee	WiMAX	Bluetooth	Cellular	Wi-Fi
Low cost of system components	X	X		X		
High interference immunity	X					
Long distance coverage	X					
Low power consumption	X	X		X		
Multipoint connection	X	X	X		X	X
High security	X	X	X			X
Sensor direct connectivity	X	X		X		
Expansion capability	X	X		X		X

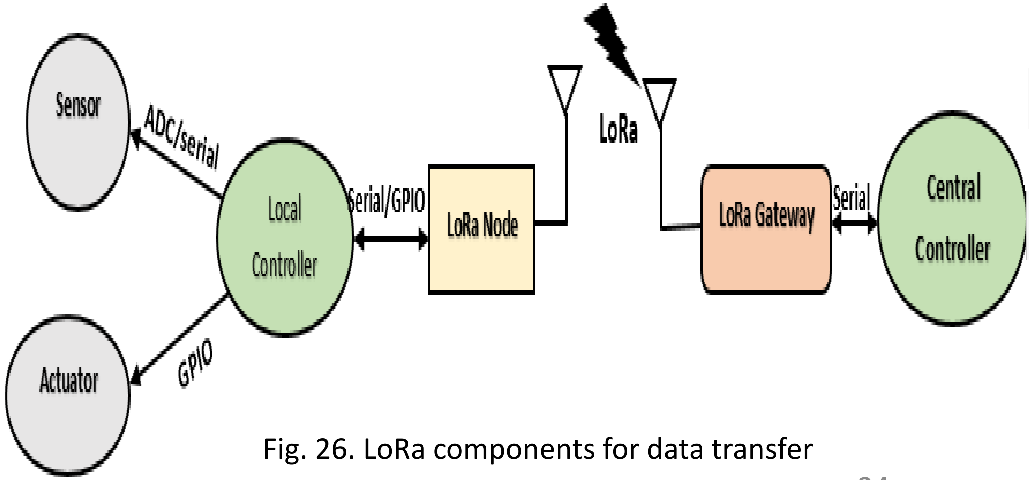


Fig. 26. LoRa components for data transfer

LoRa Range Test

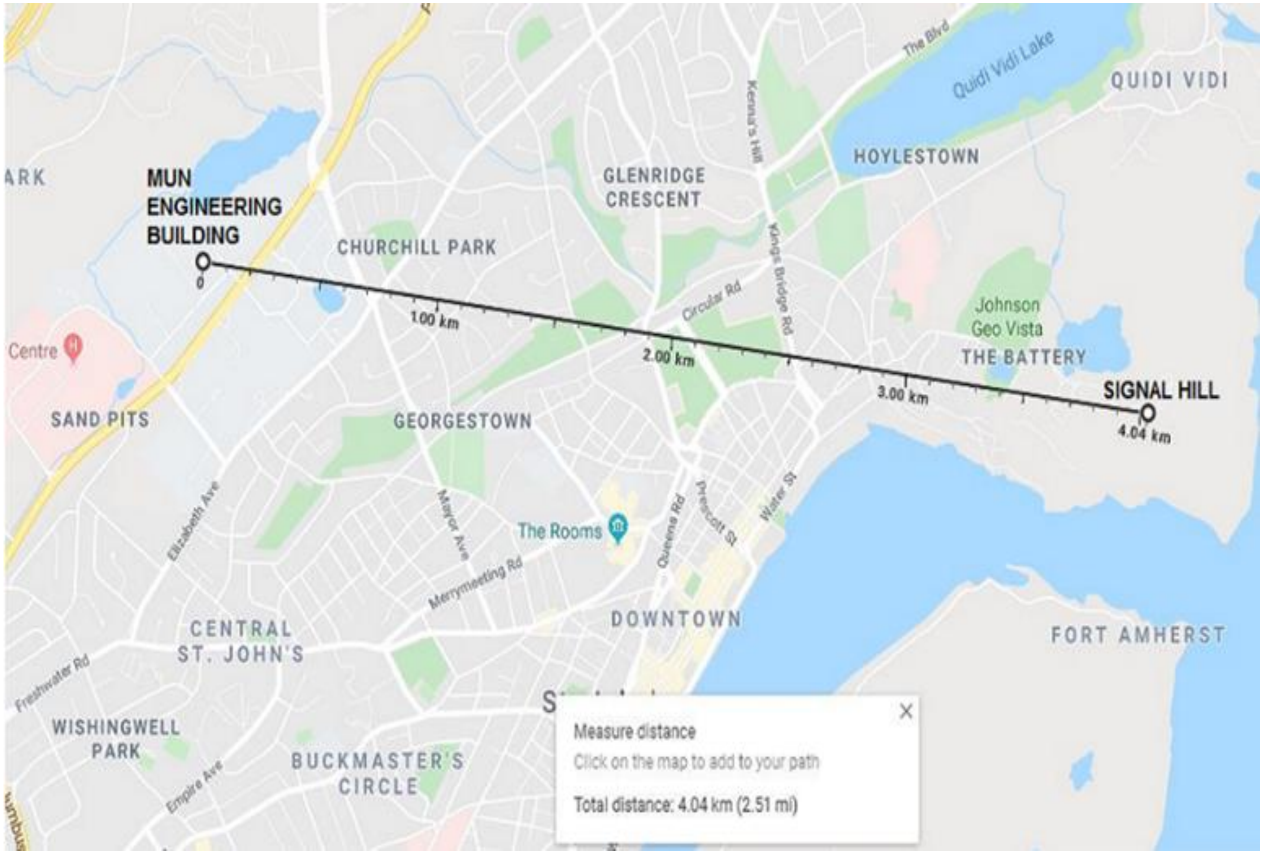
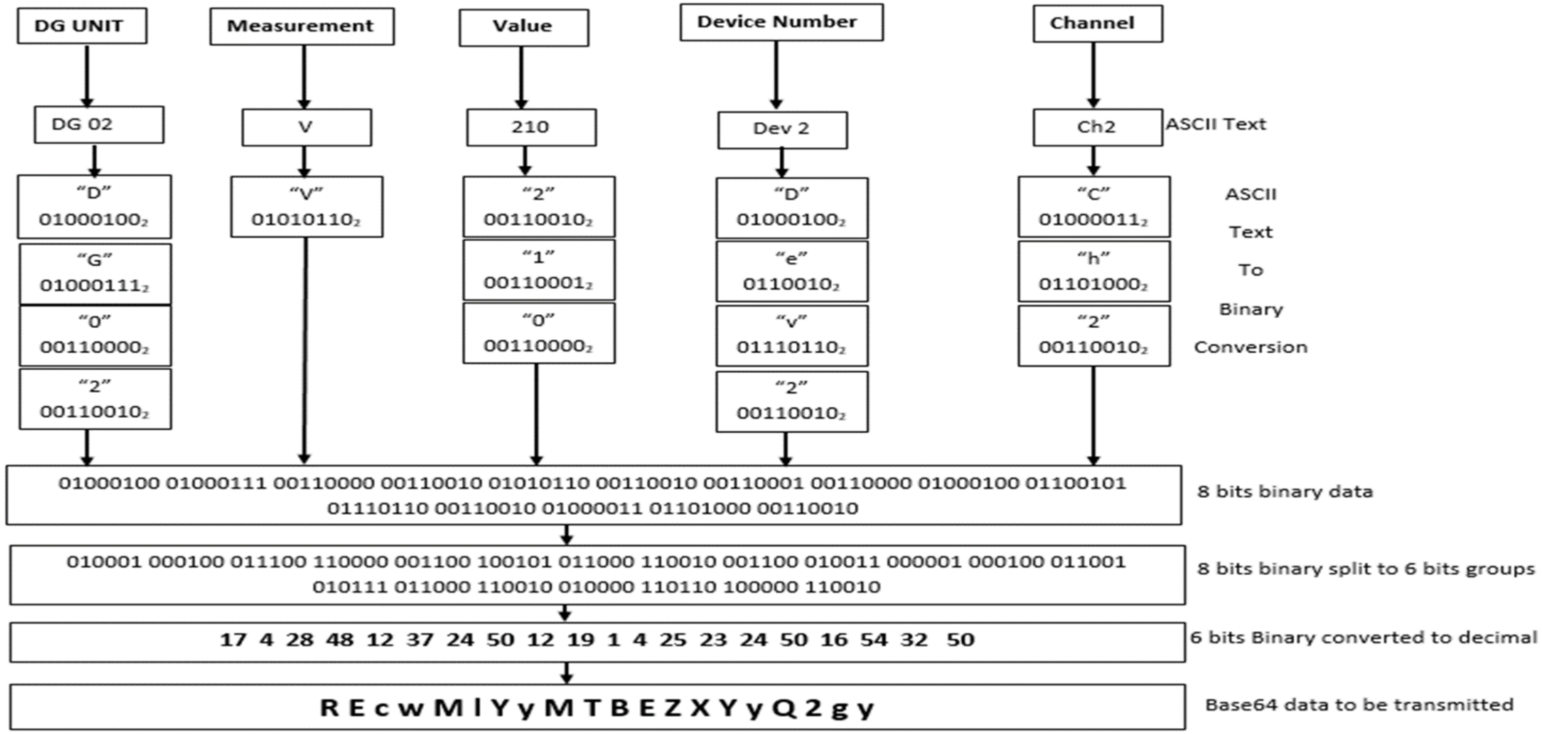


Figure 4. 15. Range test Distances in St. John’s, NL, Canada

Distance (km)	Number of Packets Transmitted	Packets Received	Packet Delivery Ratio (PDR)%
1	100	100	100%
2	100	100	100%
2.5	100	98	98%
3.48	100	93	93%
4	100	90	90%

LoRa Data Transmission Format

- The data being transmitted must be processed into the LoRa acceptable format before transmission conforming to the required length and data size for appropriate transmission.
- LoRa data rate has maximum limit of 50Kbps.
- The rate and size of data transferred in the microgrid has to be to ensure effective bandwidth usage.



DG UNIT
DG 02
"D" 01000100_2
"G" 01000111_2
"0" 00110000_2
"2" 00110010_2

Measurement
V
"V" 01010110_2

Value
210
"2" 00110010_2
"1" 00110001_2
"0" 00110000_2

Device Number
Dev 2
"D" 01000100_2
"e" 0110010_2
"v" 01110110_2
"2" 00110010_2

Channel
Ch2
"C" 01000011_2
"h" 01101000_2
"2" 00110010_2

ASCII Text

ASCII Text To Binary Conversion

01000100 01000111 00110000 00110010 01010110 00110010 00110001 00110000 01000100 01100101 01110110 00110010 01000011 01101000 00110010

8 bits binary data

010001 000100 011100 110000 001100 100101 011000 110010 001100 010011 000001 000100 011001 010111 011000 110010 010000 110110 100000 110010

8 bits binary split to 6 bits groups

17 4 28 48 12 37 24 50 12 19 1 4 25 23 24 50 16 54 32 50

6 bits Binary converted to decimal

R E c w M l Y y M T B E Z X Y y Q 2 g y

Base64 data to be transmitted

Fig. 27. Steps involved in encoding sensor value from a specific device in the microgrid.

Data Transmission Delay Analysis

- The time to transfer each chip by a LoRa device depends on the bandwidth. This time is calculated as:

$$\boldsymbol{T_{chip} = \frac{1}{Bandwidth}} \qquad (1)$$

- In LoRa, there are three statutory bandwidths through which data can be transmitted. They are 125 KHz, 250 KHz, and 500 KHz. The bandwidth can also be defined as the chip rate which is the number of vibrations or wave cycles per second. Hence,

$$\boldsymbol{BW = R_C = Chip\ Rate} \qquad (2)$$

- For a bandwidth of 125 KHz, the chip rate is 125000 chips/sec. Therefore,

$$\boldsymbol{T_{chip} = \frac{1}{125{,}000} = 8\mu sec} \qquad (3)$$

- T_{chip} for the 125 KHz, 250 KHz and 500 KHz are 8μs, 4μs and 2μs respectively. This depicts that with increased bandwidth there is a reduction in transmission time.

- The transmission time for a LoRa symbol T_{symbol} is calculated as:

$$\boldsymbol{T_{symbol} = \frac{2^{SF}}{BW}} \qquad (4)$$

Where, SF is the spreading factor and BW is the bandwidth.

Data Transmission Delay Analysis-Contd.

- Symbol transmission time for the various bandwidth at the spreading factors

SF	Tsymbol (µs) @ BW = 125 KHz	Tsymbol (µs) @ BW = 250 KHz	Tsymbol (µs) @ BW = 500 KHz
7	1,024	512	256
8	2,048	1,024	512
9	4,096	2,048	1024
10	8,192	4,096	2048
11	16,384	8,192	4096
12	32,768	16,384	8,192

- An increase in bandwidth has a decreasing effect on the data transmission time.
- An increase in the spreading factor increases the transmission time.
- The transmission time doubles with a one-step increase in the spreading factor (SF).

Data Transmission Delay Analysis-Contd

- The expressions for calculating the data transmission time for a LoRa frame is given by:

$$T_{frame} = T_{preamble} + T_{payload} \quad (5)$$

$$T_{payload} = n_{payload} + T_{symbol} \quad (6)$$

$$n_{payload} = 8 + \max(ceil\left[\frac{8PL-4SF+28+16CRC-20IH}{4(SF-2DE)}\right](CR+4), 0) \quad (7)$$

$$T_{preamble} = (n_{preamble} + 4.25)T_{symbol} \quad (8)$$

- Normally, $n_{preamble}$ = 8 for LoRa
- Where;
- PL = number of bytes.
- IH = Implicit header.
- (If Header is enabled, IH =0, if Header is disabled, IH = 1).
- DE = low data optimization
- (DE = 1, enabled, 0 = disabled)
- CR = Coding rate (default = 1)
- CRC = 1 if enabled, 0 if disabled (default is 1)

Data Transmission Delay Analysis-Microgrid Case Study

- The DC microgrid studied consists of a 1000 kW photovoltaic ,Battery system, and a 630 kW diesel generator.
- The microgrid bus voltage is 360 V DC.
- The microgrid operates in three modes:
  - Photovoltaic (PV) mode
  - Battery mode
  - Generator mode

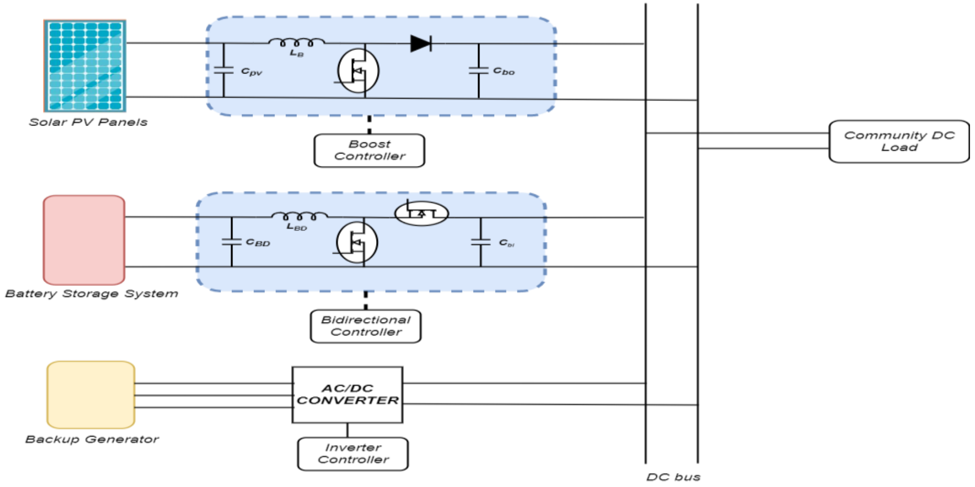


Fig. 29. Block Diagram of Studied DC microgrid

Unit	Component	Value
Bidirectional Converter	Inductor	13.38e-6 H
	Capacitor	38.5e-6F
Boost Converter	Inductor	7.5e-6 H
	Capacitor	1200e-6 F

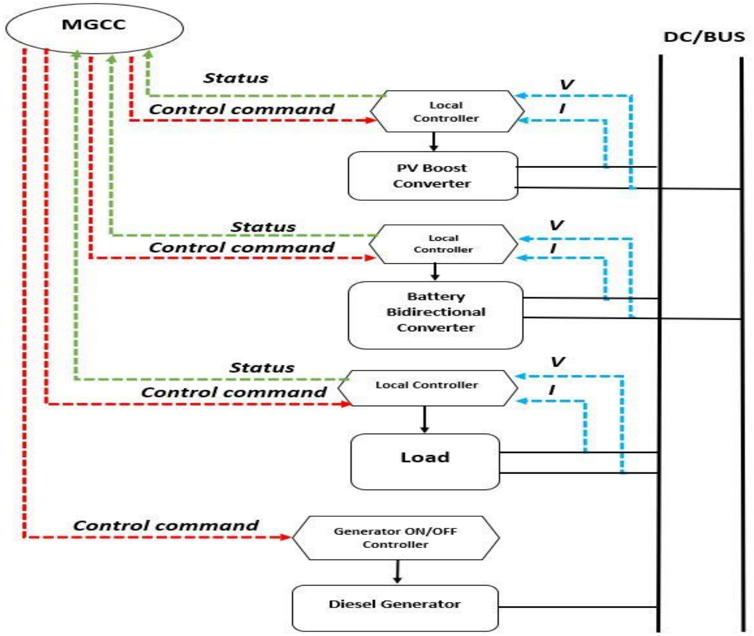


Fig. 30. Communication topology of DC microgrid

Data Transmission Delay Analysis-Microgrid Case Study

- The LoRa transmission delay as calculated for the transmitted data is introduced into the communication between the bidirectional local controller and the MGCC.
- The effect on the dynamic performance of the microgrid are analysed during transitions between the operational modes.

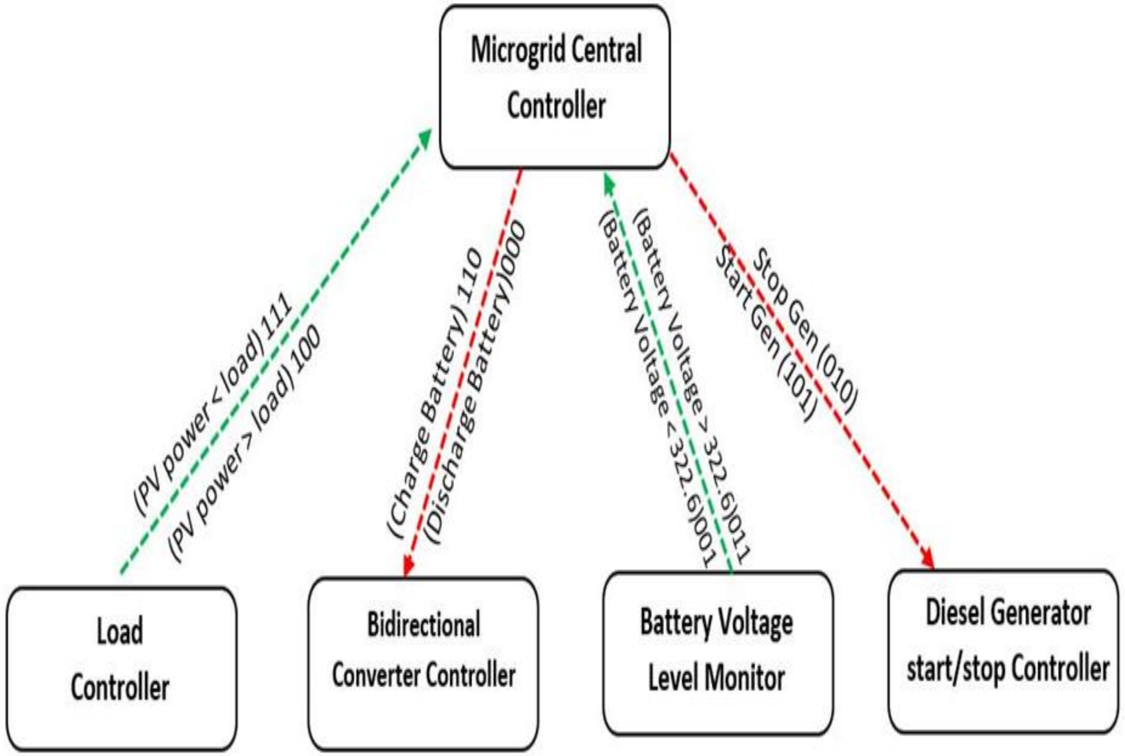


Fig. 31. Microgrid Control Scheme

Simulation Results

- **Microgrid normal operation (no transmission delay)**

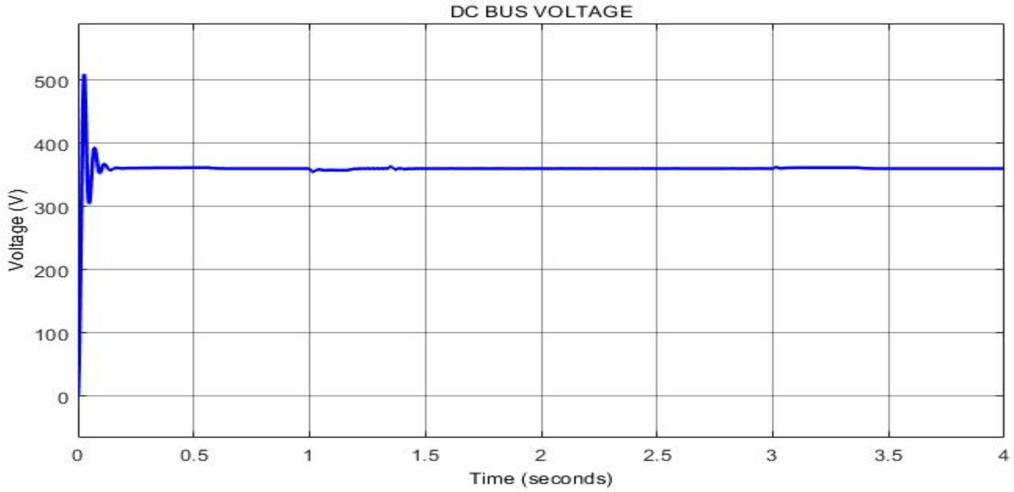


Fig. 32. Microgrid DC voltage for simulation without LoRa delay

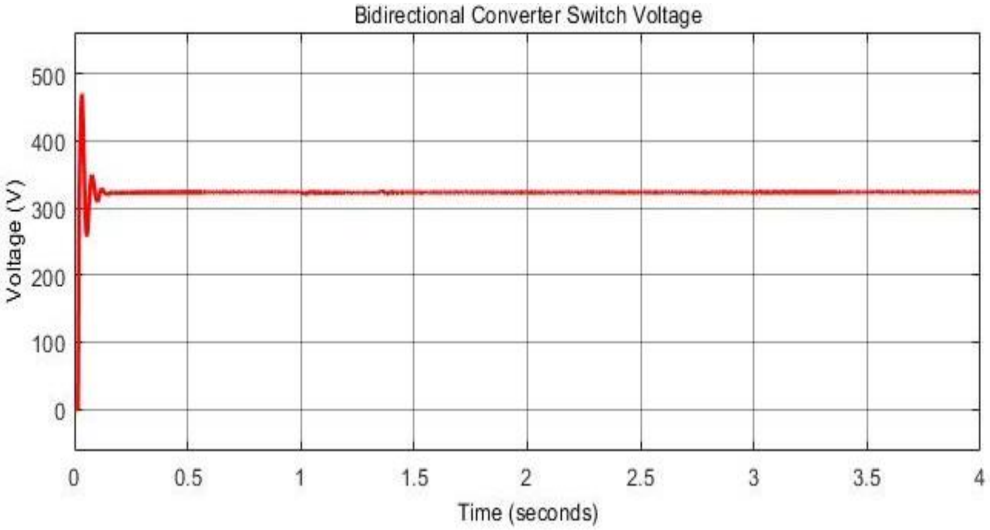


Fig. 33. Bidirectional converter switch voltage

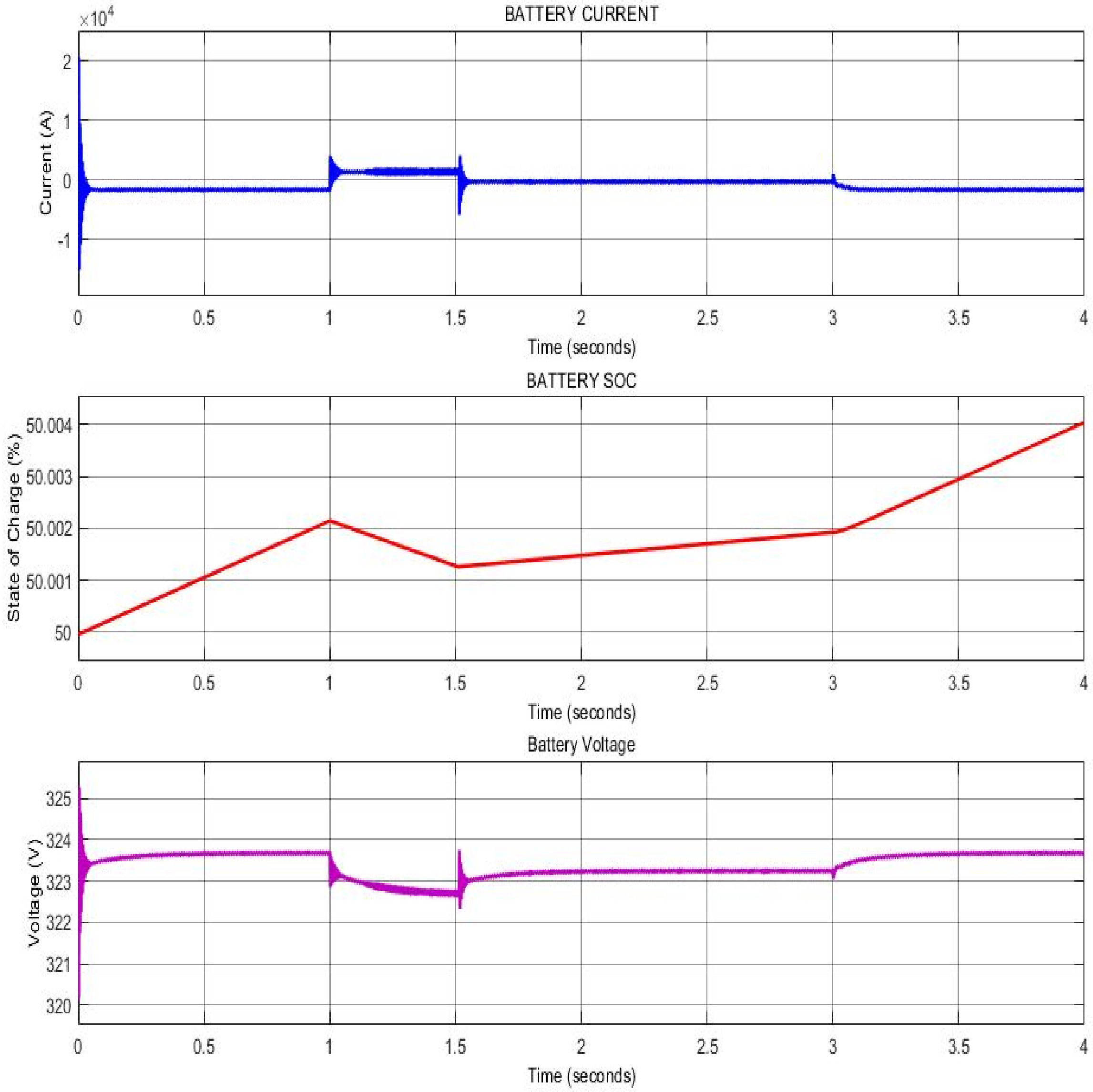


Fig. 34. DC microgrid battery parameters

Simulation Results

- **Microgrid operation with LoRa data transmission delay**

- The LoRa transmission delays were calculated.
- The LoRa bandwidth of 500 KHz was employed to achieve lower the transmission delay.
- Delay calculation was carried out for bidirectional data transfer between the local controller and the MGCC.
- Total transmission delay of 21.76 ms per data transfer.
- The transmission delay was introduced to the DC microgrid as a transport delay in Simulink

Signal	Base64 Format	Transmission time (milliseconds)
100	MTAw	10.88
110	MTEw	10.88
111	MTEx	10.88
000	MDAw	10.88
001	MDAx	10.88
011	MDEx	10.88

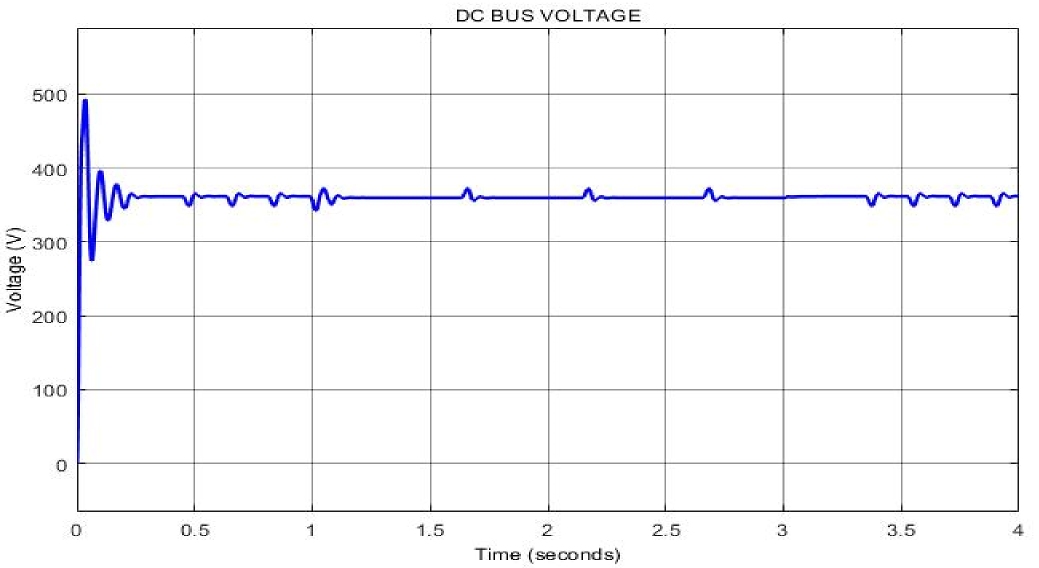


Fig. 35. Microgrid DC voltage for simulation with LoRa transmission delay

Fig. 36. Bidirectional converter switch voltage with delay

Mitigating the effects of LoRa transmission delay on DC bus voltage

- **Bidirectional Converter LC Component Recalculation**

- To compensate for the effect of the transmission delay, the LC components of the microgrid were recalculated as shown in the table and reapplied to the system.

Unit	Component	Value
Bidirectional Converter	Inductor	13.38e-6 H
	Capacitor	45.8e-6 F
Boost Converter	Inductor	7.5e-6 H
	Capacitor	1200e-6 F

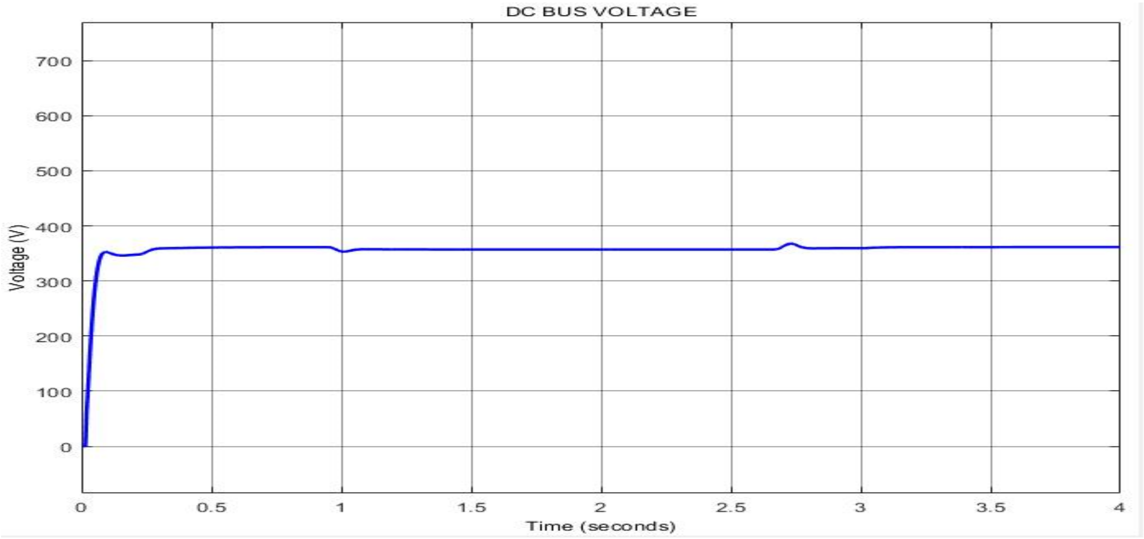


Fig. 37. DC bus voltage for redesigned microgrid with LoRa transmission delay

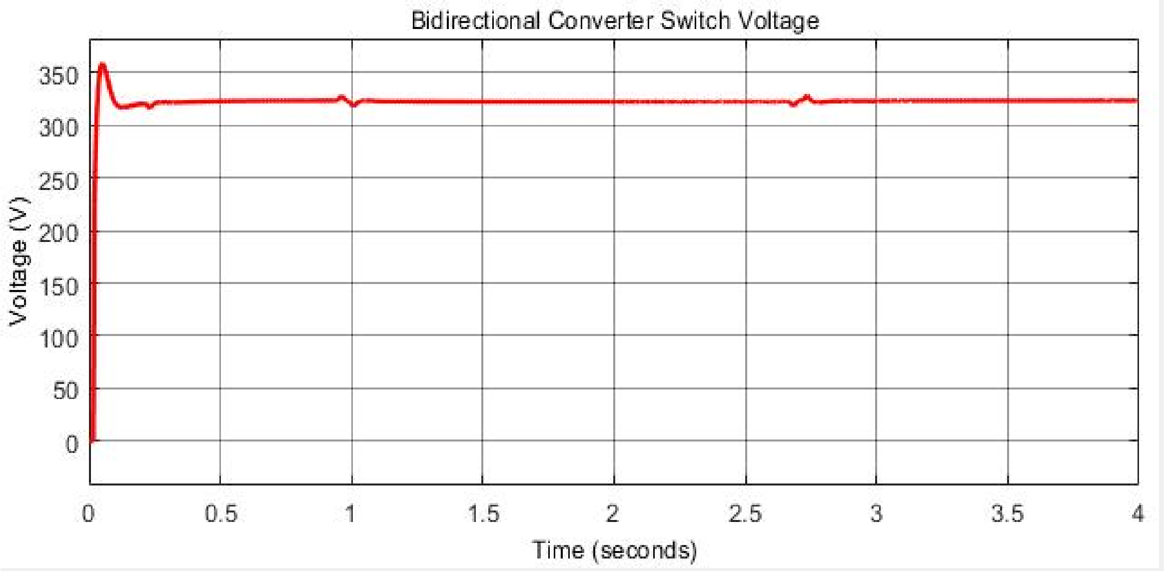


Fig. 38. Bidirectional converter switch voltage with modified parameters

Mitigating the effects of LoRa transmission delay on DC bus voltage

- **Modification of the PI Controller for Better System Robustness**

- In studied literature, PI controllers have been used to address time delay effects such as Dc voltage variations [54 - 57].

- This method presents the redesigning of the PI controller towards achieving a robust controller system.

- For this simulation, a Fuzzy-PI dual-mode controller was employed [57].

- This controller features speedy response, low overshoot, good robustness and strong anti-interference.

- These variations are minimal and demonstrate that the system still maintains a high level of stability even with the communication delay.

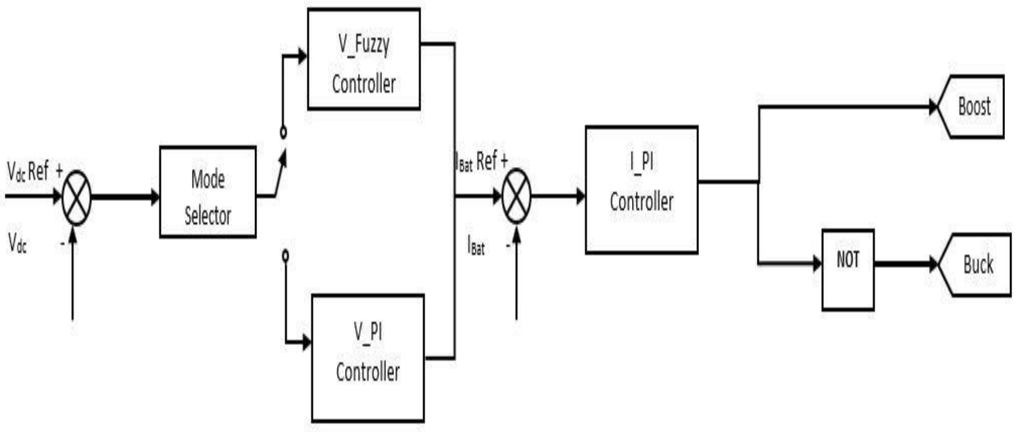


Fig. 39. Schematic of modified PI controller in MGCC

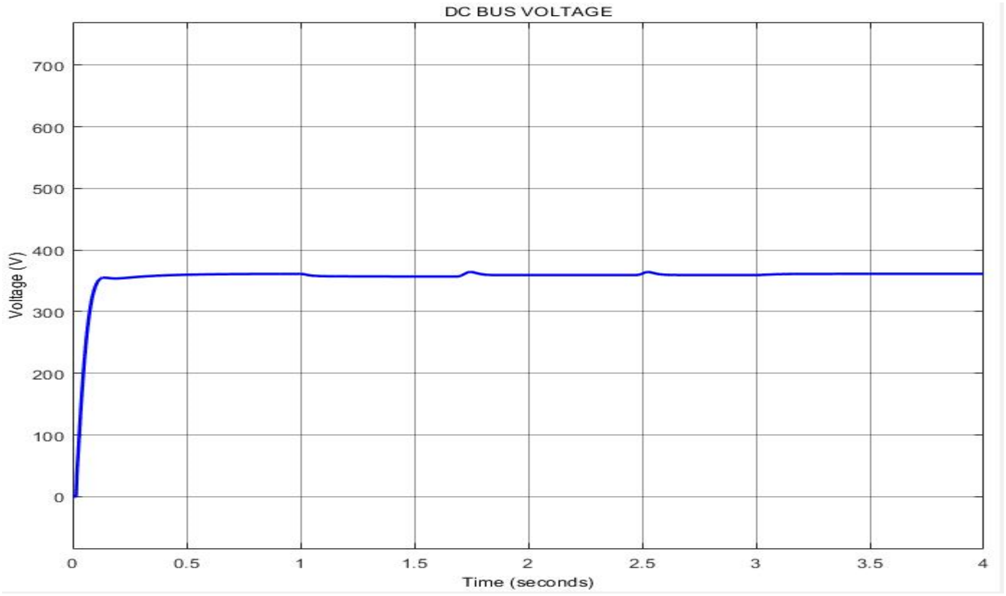


Fig. 40. DC microgrid DC bus voltage with modified controller

An Open Source LoRa Based, Low-Cost IoT Platform for Renewable Energy Generation Unit Monitoring and Supervisory Control.

Introduction

- SCADA systems have been the core of industrial automation and control over the years.
- A SCADA system is typically made up of
  - sensors and actuators that make up the Field Instrumentation
  - Remote Terminal Unit
  - Communication Channel
  - Master Terminal Unit
- The continuous increase in the sizes of the systems have also caused an increase in complexity hence a requirement for a more robust control system.
- One of the very promising paradigm shifts in the automation industry is the Internet of Things (IoT).
- IoT as a solution for industrial monitoring can be applied to distributed units of a renewable energy generation system.
- Due to the increased installed power capacity from renewable energy sources, there is an increasing need for more components

Fig. 41. Industrial automation Pyramid

Proprietary (traditional) SCADA Systems

- The large industrial companies employ the traditional SCADA systems for data transfer and monitoring.

- Till date, proprietary SCADA systems have been employed. The face some challenges:
  - High cost
  - Interoperability
  - Scalability
  - High security requirements

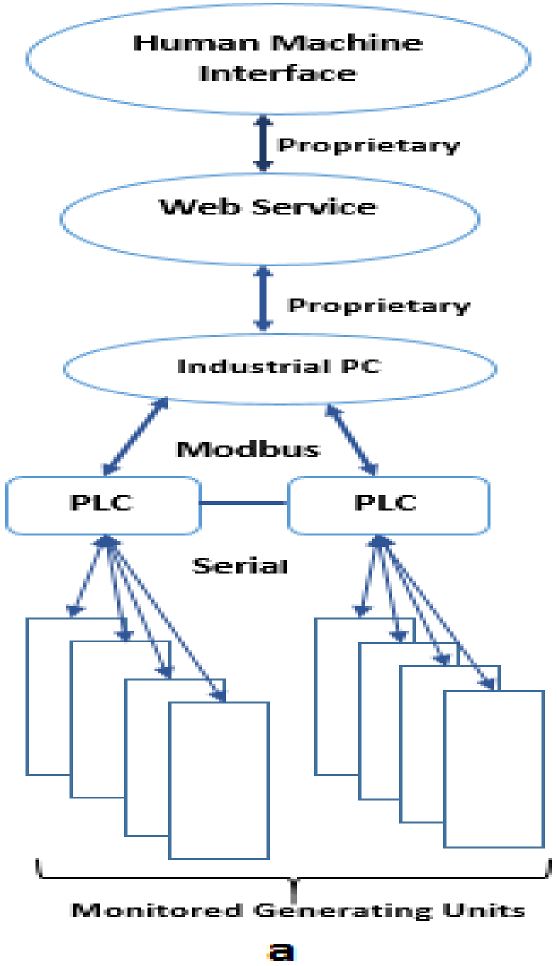


Fig. 42. Traditional SCADA architecture

IoT Application for Industrial Systems Monitoring

- IoT has harnessed extended improvement in the SCADA industry with better system monitoring and control
- Although IoT solutions differ at their various functions, attributes and target industry, IoT solutions shares the following core characteristics.
- **Data access:**
  - This Characteristic deals with extraction of data from a particular monitored system.
- **Data transfer:**
  - The data must be transferred from the point of extraction to where it will be analyzed.
- **Data management:**
  - This deals with the conversion of the extracted data to useful information for analytic or control use.
- **Data visualization:**
  - Data display for control actions.

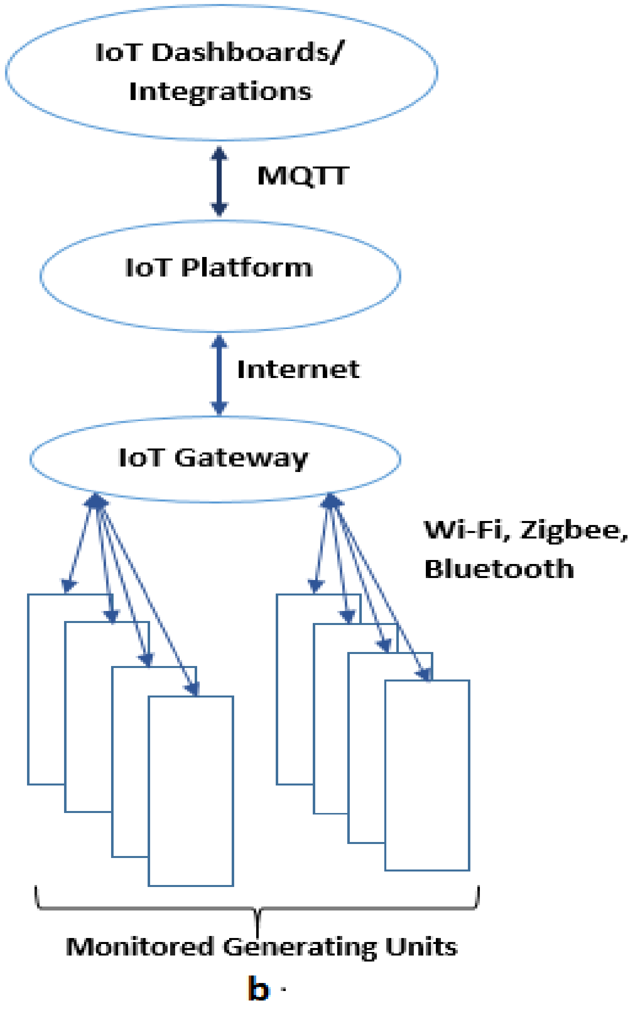


Fig. 43. IoT Solution architecture

IoT Application for Industrial Systems Monitoring- Contd.

- SCADA and IoT share the same manner of data extraction systems and communication channels.
- Programmable Logic controllers and the Human-Machine interfaces in the traditional SCADA systems are replaced with the IoT gateways and IoT platforms.
- This reduces number of components, hence less expensive, less power consuming while achieving same results as the traditional SCADA system.
- The two replacement components in the IoT architecture that has facilitated the shift are explained.

- **IoT Gateway**
  - A solution that enables the communication of various IoT components for data transfer.
  - The Important features of an IoT gateway include;
    - Data management and handling, Event management, Real-Time response, Reliability and robustness, Security
- **IoT platform**
  - A middleware and infrastructure that allows interaction between end users and the edge devices
  - With the increase in the diversity of the IoT devices, the IoT platform has become of high necessity for data retrieval and further processing.
  - Important features
    - Monitoring capability, Software management, Data centralization, Data processing, Security

Proposed IoT SCADA System Implementation

- The proposed low-cost, open-source SCADA system is based on the IoT infrastructure.
- The system is proposed to meet all the criteria of the proprietary SCADA systems with more features that mitigate the challenges of the traditional SCADA system.
- The architecture shows depicts the IoT integrations are installed on a single host machine.
- This eliminates the cloud hosted IoT platform in previous works and therefore internet is not required for data transfer.
- The proposed system is an independent and autonomous system and can be deployed to remote communities with no internet infrastructure.

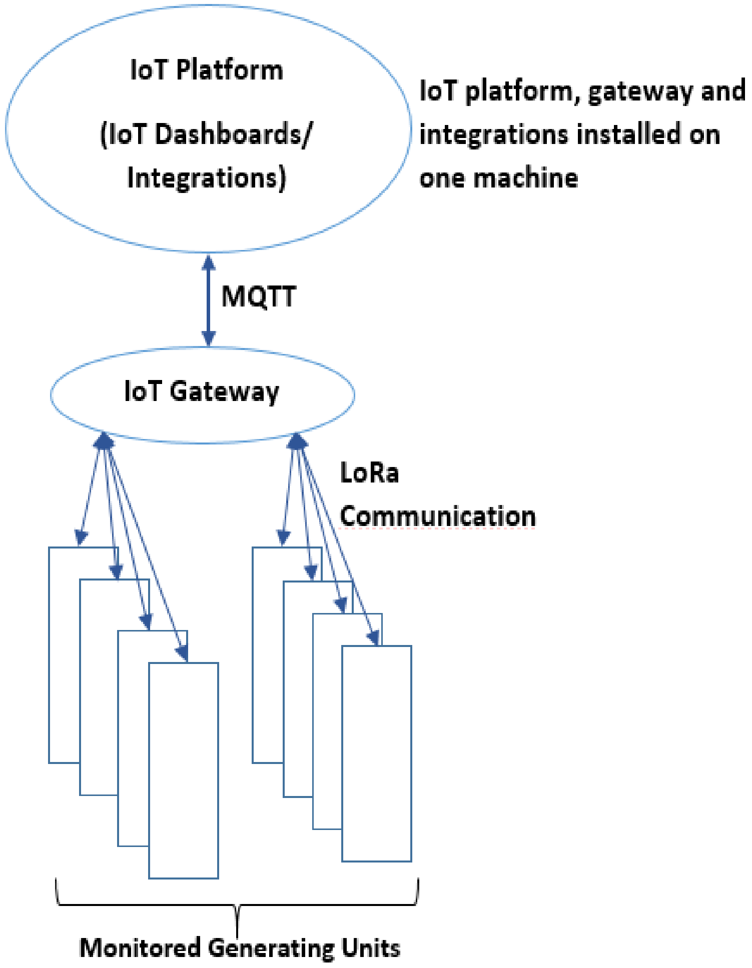


Fig. 44. Proposed IoT SCADA solution architecture

Proposed IoT SCADA System Implementation

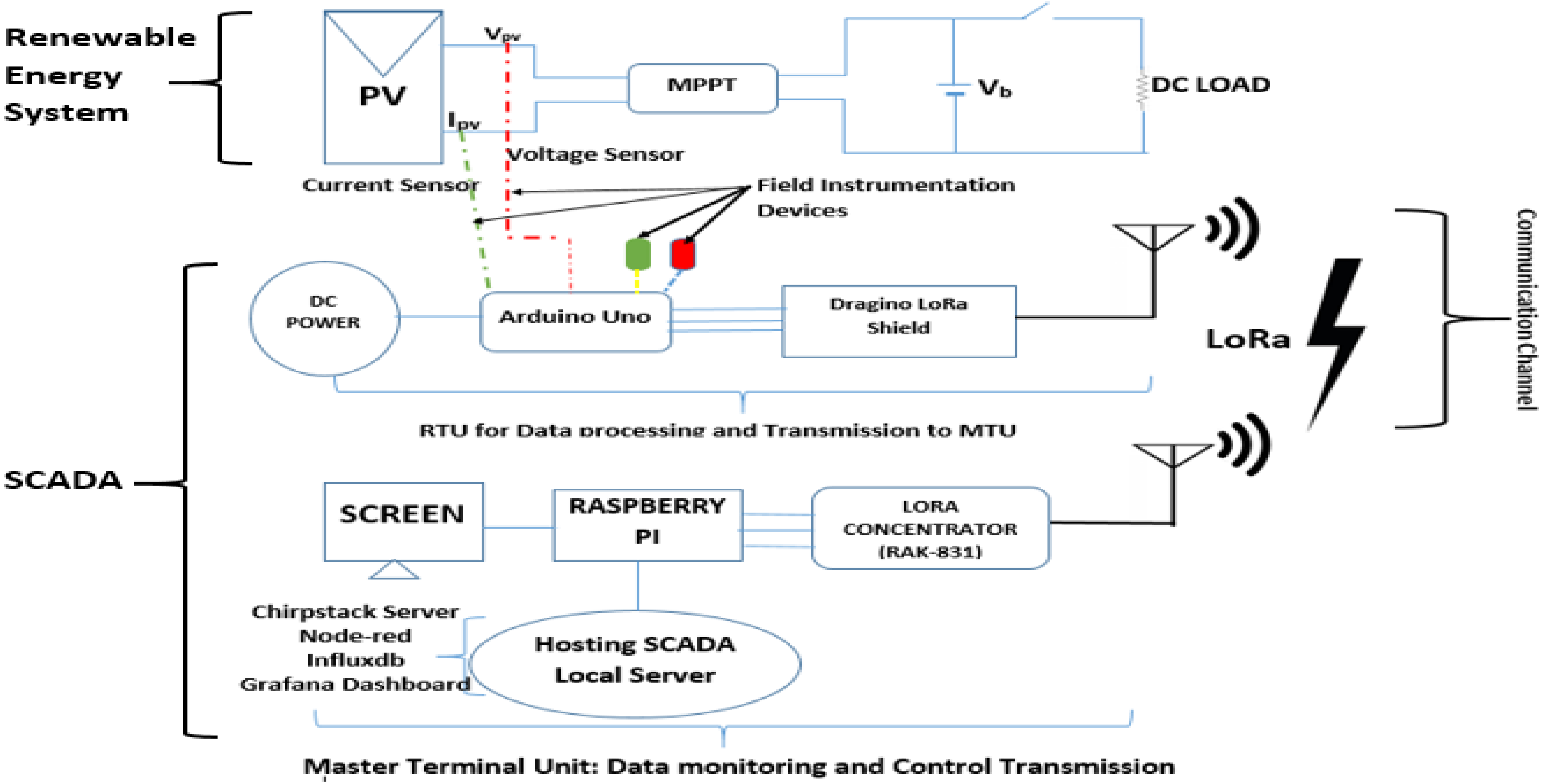


Fig. 45. Schematic configuration of the proposed SCADA system

Proposed System Prototype Components, Implementation Methodology and Prototype Design

- A prototype of the proposed system was designed and set up for testing and validation.
- The software employed in this prototype include: Chirpstack IoT platform, Node-Red programming tool, InfluxDB database and Grafana IoT dashboard for data display.
- The hardware employed include voltage (voltage divider), current sensors, Arduino Uno microcontroller (RTU) and the Raspberry pi model 3B+ (MTU).

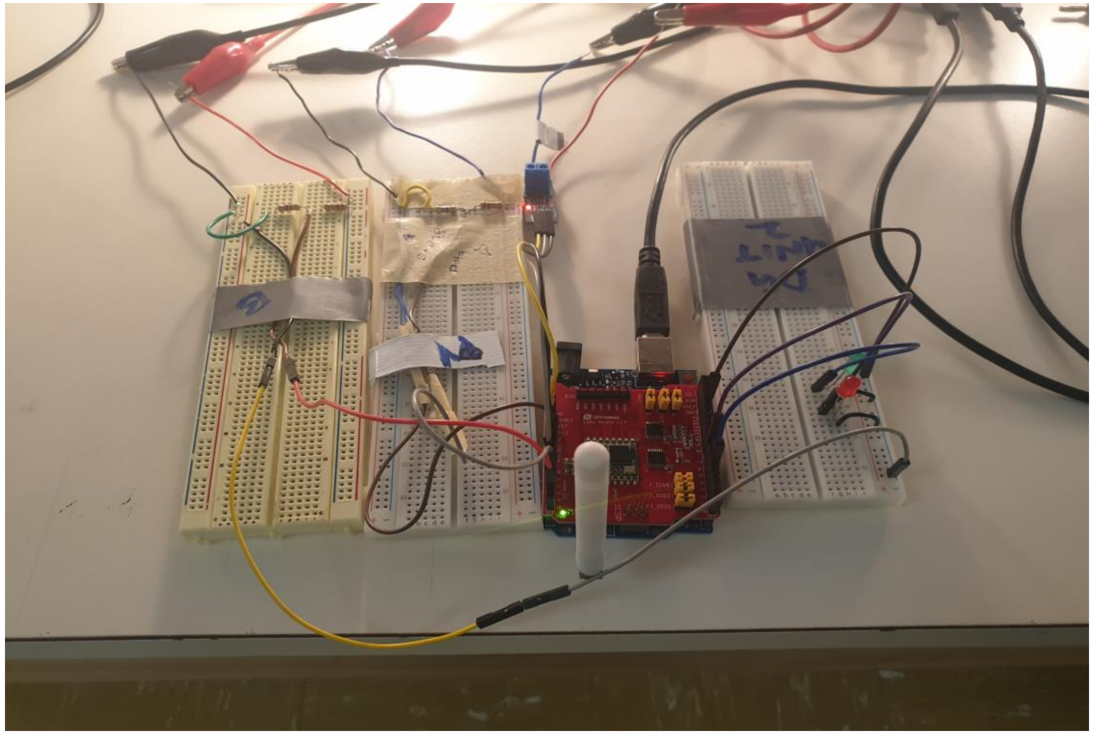


Fig. 46. Hardware implementation of the RTU

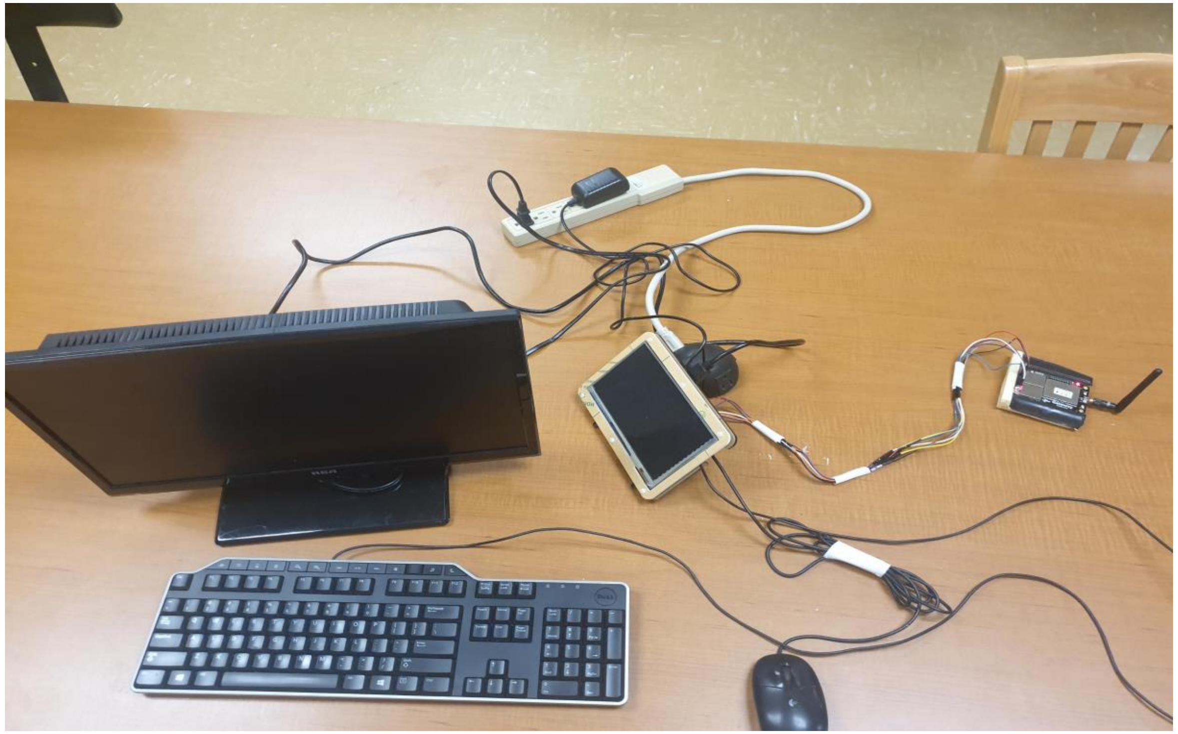


Fig. 47. Hardware implementation of the MTU

Experimental Setup and Results

- Testing of the designed prototype is carried out by connecting the implemented hardware to the solar photovoltaic system at the Memorial University Electrical Engineering Laboratory.
- Three units of the system are monitored using three RTUs, which acquire and transmit data to the MTU.
- On each RTU, there are two voltage sensors and a current sensor that collect the PV voltage, battery voltage and PV current, respectively.
- The sensor data are acquired by the Arduino Uno through cable connection to the analog pins of the microcontroller.
- The data acquired is processed and transmitted to the MTU through the LoRa transceivers that are connected to the Arduino Uno microcontrollers

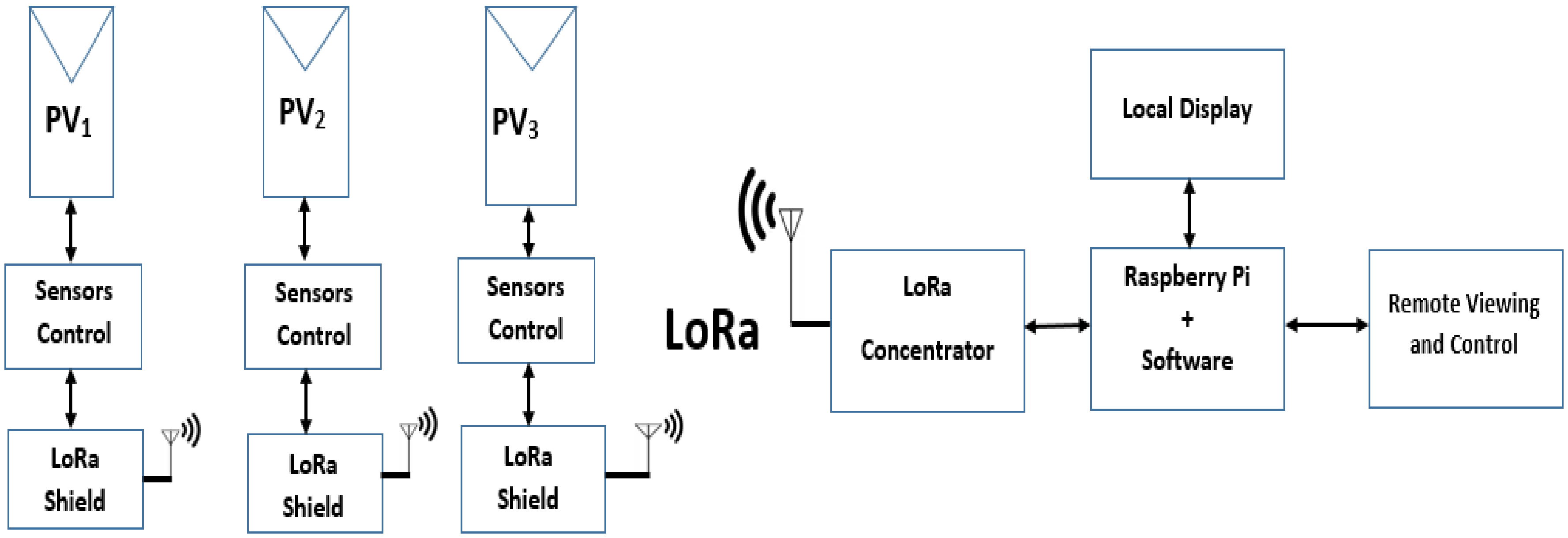


Fig. 48. The system prototype block diagram

Experimental Setup and Results

- The following flowcharts represents the process of data acquisition at the RTUs and the data processing as it is performed at the MTU .

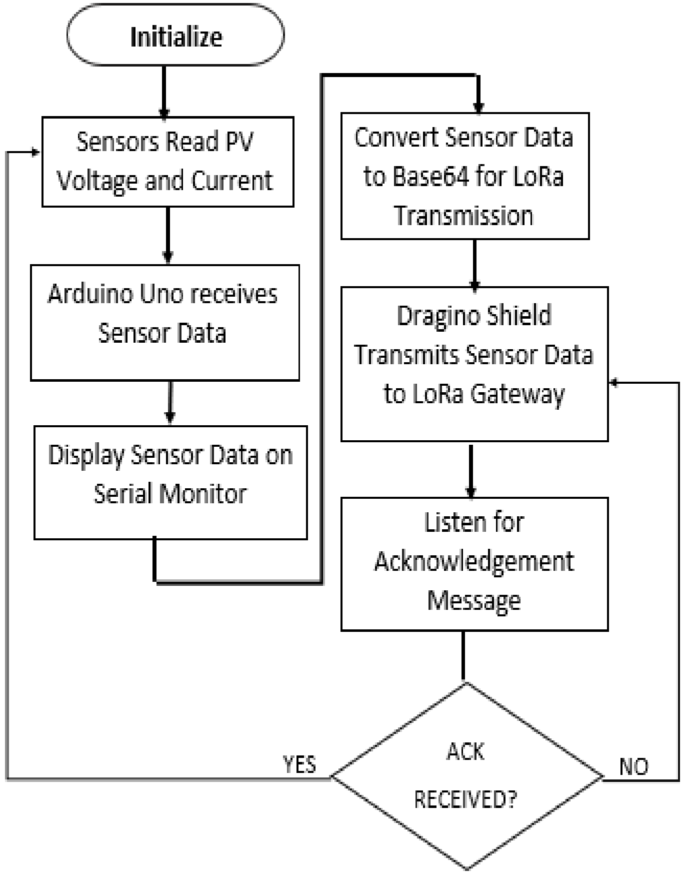


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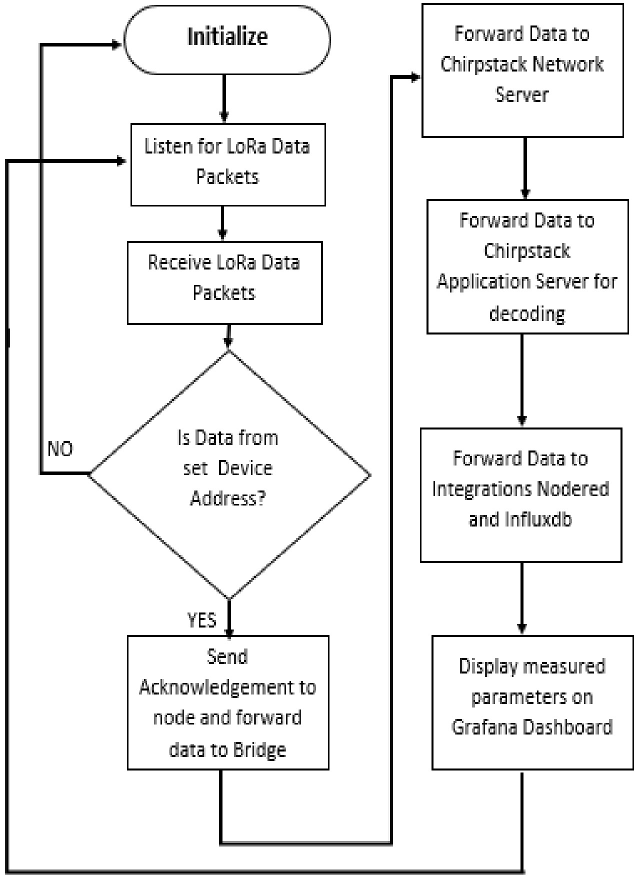
Fig. 50. RTU Flowchart



b

Fig. 51. MTU Flowchart.

Experimental Setup and Results

- The was tested for a period of 3 weeks.
- During the test, a load connected to system to ensure current flow
- multimeter readings matched parameters on system dashboards.
- System has a 1sec sampling time depicting a very high and reliable data transfer speed.
- The LEDs connected to the RTUs were used to represent various forms of actuators for control.

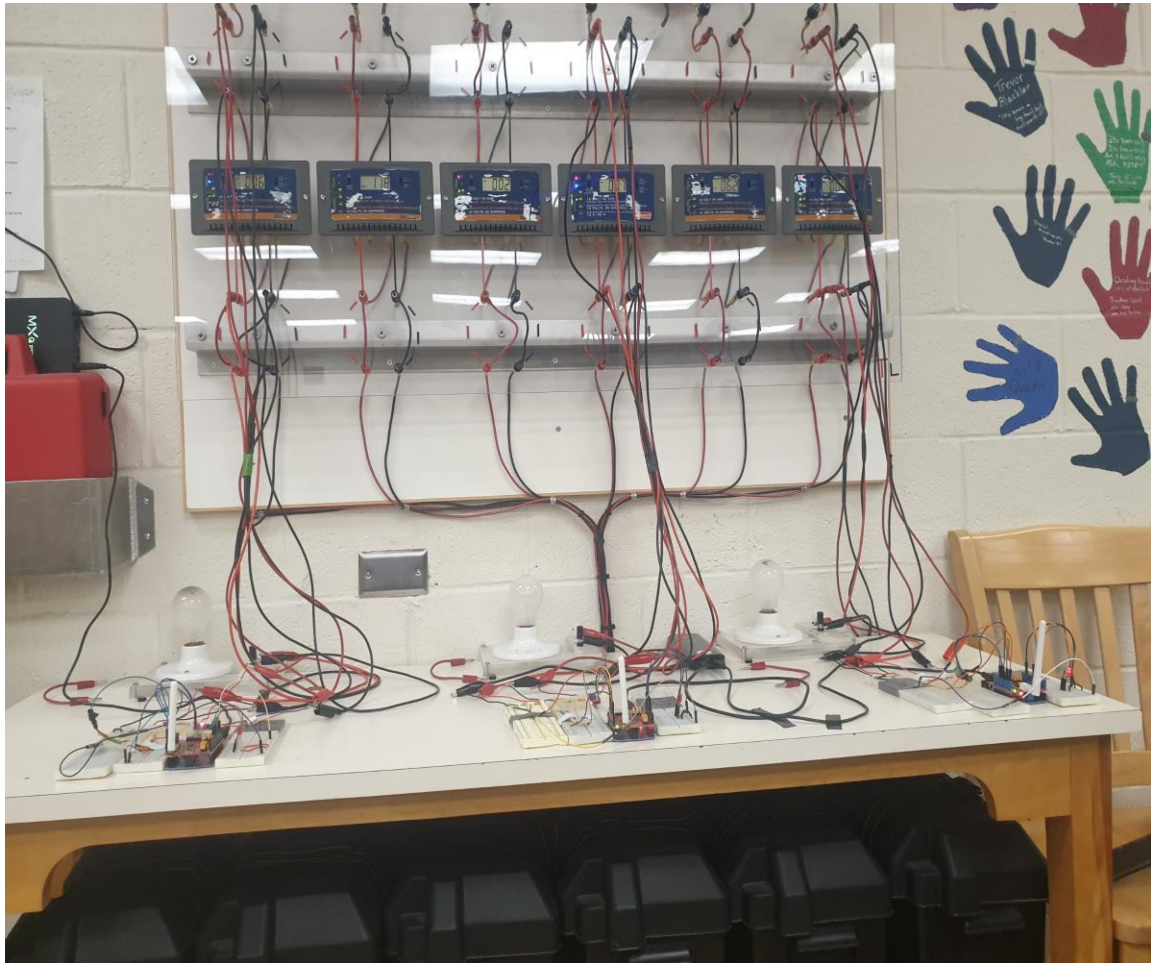
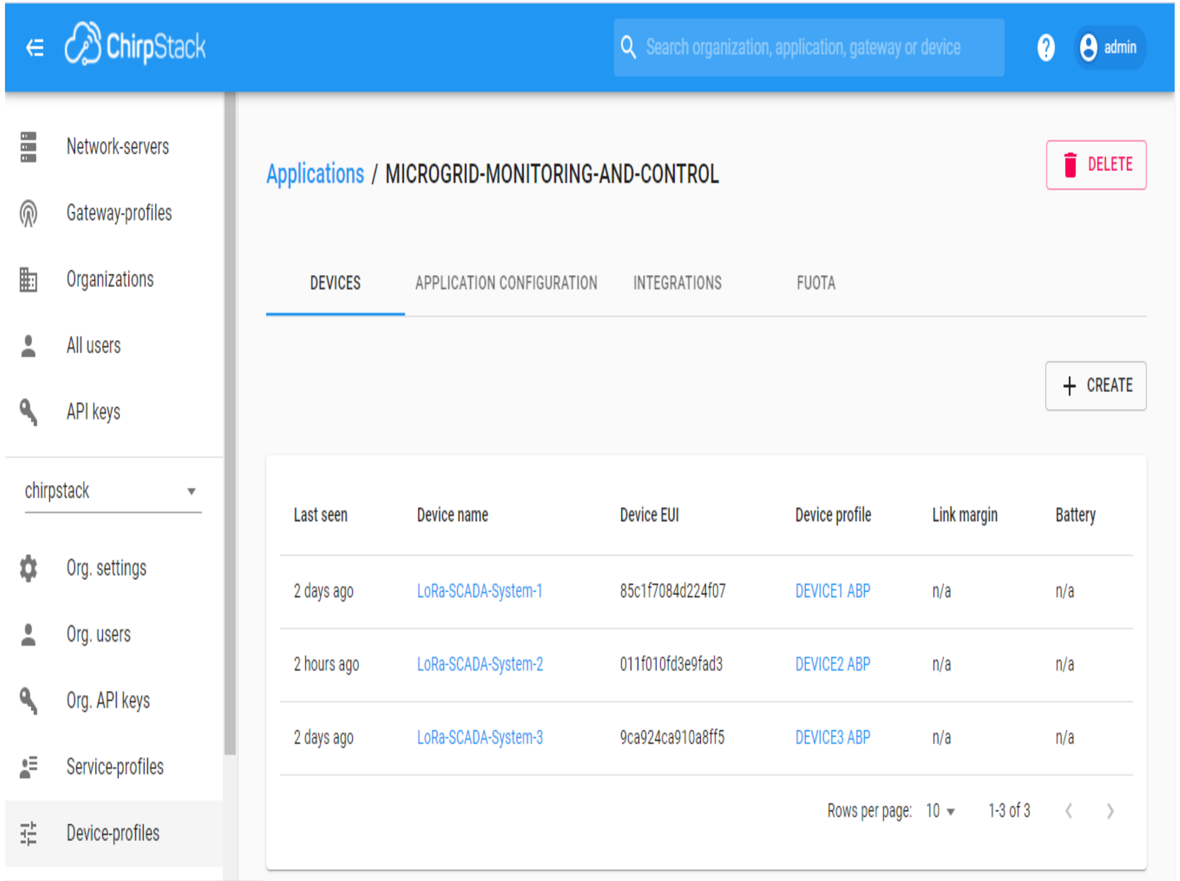


Fig. 49. Experimental setup of the proposed SCADA system including RTUs connected to PV system.

Experimental Setup and Results



Applications / MICROGRID-MONITORING-AND-CONTROL

Last seen	Device name	Device EUI	Device profile	Link margin	Battery
2 days ago	LoRa-SCADA-System-1	85c1f7084d224f07	DEVICE1 ABP	n/a	n/a
2 hours ago	LoRa-SCADA-System-2	011f010fd3e9fad3	DEVICE2 ABP	n/a	n/a
2 days ago	LoRa-SCADA-System-3	9ca924ca910a8ff5	DEVICE3 ABP	n/a	n/a

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Fig. 52. The device profiles shown on the Chirpstack application server console.

Fig. 53. Real-time data measurement displayed on Grafana dashboard.

MEMORIAL UNIVERSITY

Experimental Setup and Results

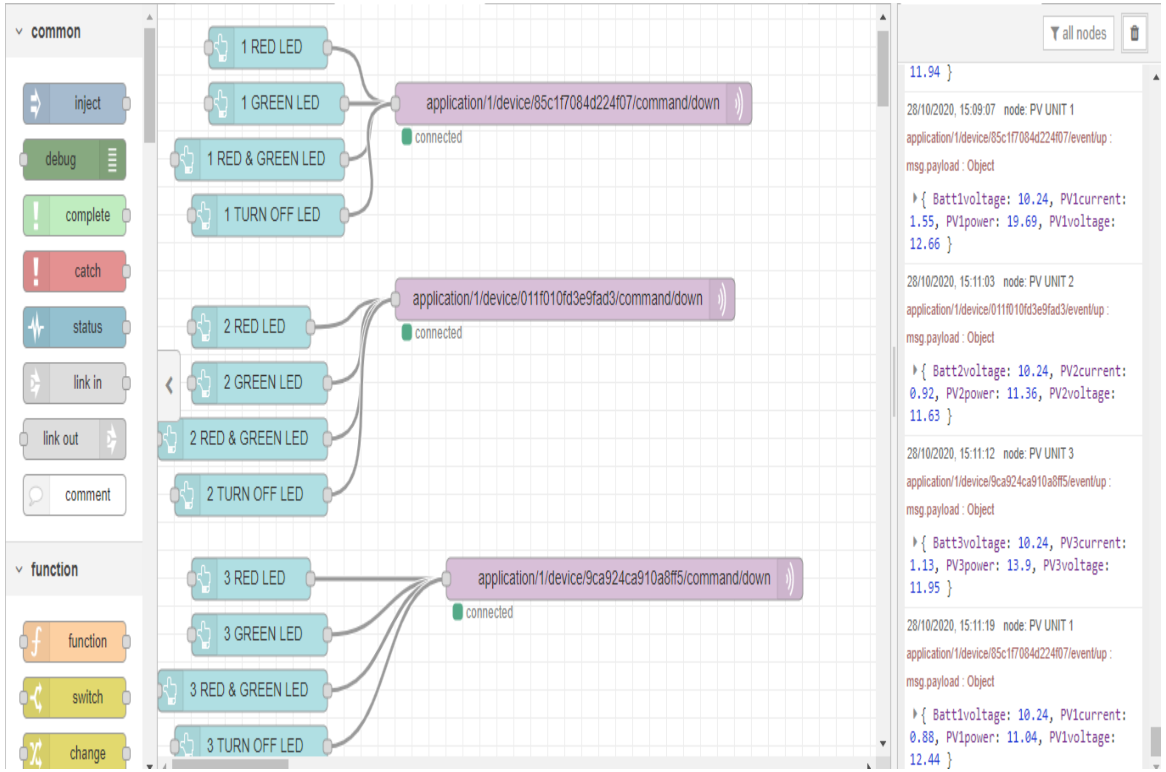
- Two supervisory control scenarios were considered with the proposed SCADA solution.

- Firstly, a manual scenario is presented.

- In this scenario, the commands carry out one or two of the functions: Turn ON the RED LED, Turn ON the GREEN LED, Turn ON both LEDs and Turn OFF both LEDs.

- The second scenario presented an automatic system.

- The LEDs were turned ON and OFF automatically with various parameter thresholds.

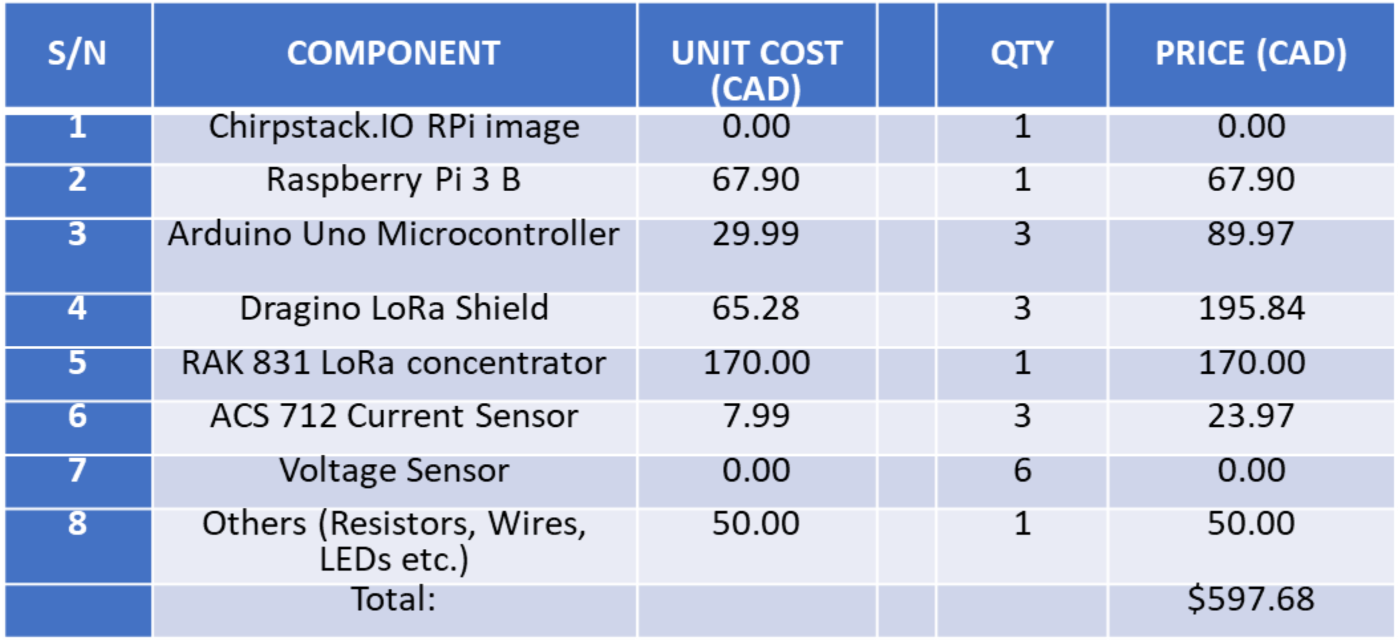


```
11.94 }
28/10/2020, 15:09:07   node: PV UNIT 1
application/1/device/85c1f7084d224f07/event/up :
msg.payload : Object
▸{ Batt1voltage: 10.24, PV1current:
1.55, PV1power: 19.69, PV1voltage:
12.66 }
28/10/2020, 15:11:03   node: PV UNIT 2
application/1/device/011f010fd3e9fad3/event/up :
msg.payload : Object
▸{ Batt2voltage: 10.24, PV2current:
0.92, PV2power: 11.36, PV2voltage:
11.63 }
28/10/2020, 15:11:12   node: PV UNIT 3
application/1/device/9ca924ca910a8ff5/event/up :
msg.payload : Object
▸{ Batt3voltage: 10.24, PV3current:
1.13, PV3power: 13.9, PV3voltage:
11.95 }
28/10/2020, 15:11:19   node: PV UNIT 1
application/1/device/85c1f7084d224f07/event/up :
msg.payload : Object
▸{ Batt1voltage: 10.24, PV1current:
0.88, PV1power: 11.04, PV1voltage:
12.44 }
```

Fig. 54. Node-red flow for the supervisory control of the LEDs connected to the RTUs.

Discussion

- Some of the key features of the proposed IoT SCADA solution are enumerated below:
    - Low-Cost
    - Open Source and Interoperability
    - System scalability
    - Robustness for remote area deployment
    - User friendliness
    - Feasibility of deployment to large generation systems (with proper upgrades)



S/N	COMPONENT	UNIT COST (CAD)		QTY	PRICE (CAD)
1	Chirpstack.IO RPi image	0.00		1	0.00
2	Raspberry Pi 3 B	67.90		1	67.90
3	Arduino Uno Microcontroller	29.99		3	89.97
4	Dragino LoRa Shield	65.28		3	195.84
5	RAK 831 LoRa concentrator	170.00		1	170.00
6	ACS 712 Current Sensor	7.99		3	23.97
7	Voltage Sensor	0.00		6	0.00
8	Others (Resistors, Wires, LEDs etc.)	50.00		1	50.00
	Total:				$597.68

Conclusion

- Summary:

- An AC microgrid was sized, designed and simulated for a remote community in Nigeria.
- A DC microgrid was sized, designed and simulated for same community to compare cost and energy generation.
- DC microgrid turns out to be the best energy system for remote communities with reduced energy requirements.
- The designed DC microgrid was simulated in MATLAB SIMULINK to observe the dynamic performance.
- LoRa communication technology was proposed for data transfer at the secondary control level of the DC microgrid.
- The LoRa transmission delay for data and command transfer were simulated to observe the effect on the dynamic performance of the DC microgrid.
- System enhancement were carried out on the DC microgrid to accommodate the transmission delay.
- A low cost LoRa based SCADA system was proposed, developed and a protype designed for monitoring of renewable energy systems.

Research Contributions

1. Sizing, Design and development of AC and DC microgrids for a remote community. The designs depicted the relevance of DC microgrids for remote communities.
2. Design and development of a Low-cost LoRa-based SCADA system for monitoring of small renewable energy generating systems.
3. Investigating the employment of LoRa physical level communication for data and control transfer at the secondary control level of hierarchical DC microgrids.

Publications

- **Journal Papers:**

1. C. Ndukwe, T. Iqbal, X. Liang and J. Khan, "Optimal Sizing and Analysis of a Small Hybrid Power System for Umuokpo Amumara in Eastern Nigeria", *International Journal of Photoenergy*, vol. 2019, pp. 1-8, 2019. Available: 10.1155/2019/6960191.

2. C. Ndukwe and T. Iqbal, "Sizing and dynamic modelling and simulation of a standalone PV based DC microgrid with battery storage system for a remote community in Nigeria", *Journal of Energy Systems*, pp. 67-85, 2019. Available: 10.30521/jes.544710.

3. C. Ndukwe, M. Tariq Iqbal, X. Liang, J. Khan and L. Aghenta, "LoRa-based communication system for data transfer in microgrids", *AIMS Electronics and Electrical Engineering*, vol. 4, no. 3, pp. 303-325, 2020. Available: 10.3934/electreng.2020.3.303.

4. C. Ndukwe, M. Iqbal and J. Khan, "An Open Source LoRa Based, Low-Cost IoT Platform for Renewable Energy Generation Unit Monitoring and Supervisory Control", *Journal of Energy and Power Technology*, vol. 4, no. 1, pp. 1-1, 2021. Available: 10.21926/jept.2201007.

5. C. Ndukwe, M. Iqbal, J. Khan and M. Jamil, "Analysis of LoRa Transmission Delay on Dynamic Performance of Standalone DC Microgrids", *Journal of Energy and Power Technology*, vol. 4, no. 2, pp. 1-1, 2022. Available: 10.21926/jept.2202022.

- **Conference Papers:**

1. C. Ndukwe, M. T. Iqbal and J. Khan, "Development of a Low-cost LoRa based SCADA system for Monitoring and Supervisory Control of Small Renewable Energy Generation Systems," 2020 11th IEEE Annual Information Technology, Electronics and Mobile Communication Conference (IEMCON), 2020, pp. 0479-0484, doi: 10.1109/IEMCON51383.2020.9284933.

Future Work

- Since LoRa has proven to be very capable from research to be employed for data transfer and can achieve results like the other communication systems. research into how to extend the data coverage distance to allow for employment in larger renewable energy generation systems will be very important.

- Increased security in the designed SCADA system solution can be achieved through the development of reliable data encryption Algorithms on the LoRa communication channel for safety and integrity of the transferred data.

References

[1] L. Shaver, "Implementation of a DC Microgrid", Master's Degree, UNIVERSITY OF WISCONSIN-MADISON, 2017.

[2] A. Elsayed, A. Mohamed and O. Mohammed, "DC microgrids and distribution systems: An overview", *Electric Power Systems Research*, vol. 119, pp. 407-417, 2015.

[3] S. Ryu, J. Ahn, K. Cho and B. Lee, "Single-Switch ZVZCS Quasi-Resonant CLL Isolated DC-DC Converter for 32" LCD TV", *Journal of Electrical Engineering and Technology*, vol. 10, no. 4, pp. 1646-1654, 2015.

[4] B. Thomas, "Edison revisited: impact of DC distribution on the cost of LED lighting and distribution generation", *27th Annual IEEE Applied Power Electronics Conference and Exposition (APEC),*, pp. 588–593, 2010.

[5] K. Vijayaragavan, "Feasibility of DC Microgrids for Rural Electrification", Master's Degree, European Solar Engineering School, 2017.

[6] D. Kumar, F. Zare and A. Ghosh, "DC Microgrid Technology: System Architectures, AC Grid Interfaces, Grounding Schemes, Power Quality, Communication Networks, Applications, and Standardizations Aspects", *IEEE Access*, vol. 5, pp. 12230-12256, 2017.

[7] Planas E, Andreu J, Gárate JI, et al. (2015) AC and DC technology inmicrogrids: A review. *Renew Sustain Energy Rev* 43: 726–749

[8] L. Herrera, W. Zhang and J. Wang, "Stability Analysis and Controller Design of DC Microgrids With Constant Power Loads," in *IEEE Transactions on Smart Grid*, vol. 8, no. 2, pp. 881-888, March 2017, doi: 10.1109/TSG.2015.2457909.

[9] L. Meng et al., "Review on Control of DC Microgrids and Multiple Microgrid Clusters," in IEEE Journal of Emerging and Selected Topics in Power Electronics, vol. 5, no. 3, pp. 928-948, Sept. 2017, doi: 10.1109/JESTPE.2017.2690219.

[10] A. Gupta, S. Doolla and K. Chatterjee, "Hybrid AC–DC Microgrid: Systematic Evaluation of Control Strategies," in *IEEE Transactions on Smart Grid*, vol. 9, no. 4, pp. 3830-3843, July 2018, doi: 10.1109/TSG.2017.2727344.

References

[11] Sen, S. and Kumar, V., 2018. Microgrid control: A comprehensive survey. *Annual Reviews in Control*, 45, pp.118-151.

[12] Z. Shuai, J. Fang, F. Ning and Z. Shen, "Hierarchical structure and bus voltage control of DC microgrid", *Renewable and Sustainable Energy Reviews*, vol. 82, pp. 3670-3682, 2018. Available: 10.1016/j.rser.2017.10.096.

[13] Z. Shuai, J. Fang, F. Ning and Z. Shen, "Hierarchical structure and bus voltage control of DC microgrid", *Renewable and Sustainable Energy Reviews*, vol. 82, pp. 3670-3682, 2018. Available: 10.1016/j.rser.2017.10.096.

[14] R. A. F. Ferreira, H. A. C. Braga, A. A. Ferreira and P. G. Barbosa, "Analysis of voltage droop control method for dc microgrids with Simulink: Modelling and simulation," *2012 10th IEEE/IAS International Conference on Industry Applications*, 2012, pp. 1-6, doi: 10.1109/INDUSCON.2012.6452563.

[15] S. Anand, B. G. Fernandes and J. Guerrero, "Distributed Control to Ensure Proportional Load Sharing and Improve Voltage Regulation in Low-Voltage DC Microgrids," in *IEEE Transactions on Power Electronics*, vol. 28, no. 4, pp. 1900-1913, April 2013, doi: 10.1109/TPEL.2012.2215055.

[16] K. Sun, L. Zhang, Y. Xing and J. M. Guerrero, "A Distributed Control Strategy Based on DC Bus Signaling for Modular Photovoltaic Generation Systems with Battery Energy Storage," in *IEEE Transactions on Power Electronics*, vol. 26, no. 10, pp. 3032-3045, Oct. 2011, doi: 10.1109/TPEL.2011.2127488.

[17] M. Yazdanian and A. Mehrizi-Sani, "Distributed Control Techniques in Microgrids," in *IEEE Transactions on Smart Grid*, vol. 5, no. 6, pp. 2901-2909, Nov. 2014.

[18] D. Dam and H. Lee, "A Power Distributed Control Method for Proportional Load Power Sharing and Bus Voltage Restoration in a DC Microgrid," in *IEEE Transactions on Industry Applications*, vol. 54, no. 4, pp. 3616-3625, July-Aug. 2018.

[19] C. D. Persis, E. R. A. Weitenberg and F. Dorfler, “A power consensus algorithm for DC microgrids”, Elsevier, Automatica, Vol. 89, pp -364-375, March 2018.

[20] D. D. Sharma, S. N. Singh, J. Lin and E. Foruzan, "Agent-Based Distributed Control Schemes for

References

[21] J. Kumar, A. Agarwal and V. Agarwal, "A review on overall control of DC microgrids", *Journal of Energy Storage*, vol. 21, pp. 113-138, 2019. Available: 10.1016/j.est.2018.11.013.

[22] T. R. Oliveira, W. W. A. Gonçalves Silva and P. F. Donoso-Garcia, "Distributed Secondary Level Control for Energy Storage Management in DC Microgrids," in *IEEE Transactions on Smart Grid*, vol. 8, no. 6, pp. 2597-2607, Nov. 2017.

[23] L. Meng, T. Dragicevic, J. C. Vasquez and J. M. Guerrero, "Tertiary and Secondary Control Levels for Efficiency Optimization and System Damping in Droop Controlled DC–DC Converters," in *IEEE Transactions on Smart Grid*, vol. 6, no. 6, pp. 2615-2626, Nov. 2015.

[24] A. Bidram and A. Davoudi, "Hierarchical Structure of Microgrids Control System," in *IEEE Transactions on Smart Grid*, vol. 3, no. 4, pp. 1963-1976, Dec. 2012.

[25] J. Hu, J. Duan, H. Ma and M. -Y. Chow, "Distributed Adaptive Droop Control for Optimal Power Dispatch in DC Microgrid," in *IEEE Transactions on Industrial Electronics*, vol. 65, no. 1, pp. 778-789, Jan. 2018.

[26] C. Jin, P. Wang, J. Xiao, Y. Tang and F. H. Choo, "Implementation of Hierarchical Control in DC Microgrids," in *IEEE Transactions on Industrial Electronics*, vol. 61, no. 8, pp. 4032-4042, Aug. 2014.

[27] Q. Shafiee, T. Dragičević, J. C. Vasquez and J. M. Guerrero, "Hierarchical Control for Multiple DC-Microgrids Clusters," in *IEEE Transactions on Energy Conversion*, vol. 29, no. 4, pp. 922-933, Dec. 2014.

[28] V. Mortezapour and H. Lesani, "Adaptive primary droop control for islanded operation of hybrid AC–DC MGs", *IET Generation, Transmission & Distribution*, vol. 12, no. 10, pp. 2388-2396, 2018.

[29] G. Xu, D. Sha and X. Liao, "Decentralized Inverse-Droop Control for Input-Series–Output-Parallel DC–DC Converters," in *IEEE Transactions on Power Electronics*, vol. 30, no. 9, pp. 4621-4625, Sept. 2015.

[30] F. Chen, R. Burgos, D. Boroyevich and W. Zhang, "A nonlinear droop method to improve voltage regulation and load sharing in DC systems," *2015 IEEE First International Conference on DC Microgrids (ICDCM)*, 2015, pp. 45-50.

References

[31] P. Pinceti, M. Vanti, C. Brocca, M. Carnesecchi and G. Macera, "Design criteria for a power management system for microgrids with renewable sources", *Electric Power Systems Research*, vol. 122, pp. 168-179, 2015.

[32] A. Kwasinski, "Quantitative Evaluation of DC Microgrids Availability: Effects of System Architecture and Converter Topology Design Choices," in IEEE Transactions on Power Electronics, vol. 26, no. 3, pp. 835-851, March 2011.

[33] J. Shen and A. Khaligh, "A Supervisory Energy Management Control Strategy in a Battery/Ultracapacitor Hybrid Energy Storage System," in IEEE Transactions on Transportation Electrification, vol. 1, no. 3, pp. 223-231, Oct. 2015.

[34] U. Manandhar, A. Ukil and T. K. Kiat Jonathan, "Efficiency comparison of DC and AC microgrid," 2015 IEEE Innovative Smart Grid Technologies - Asia (ISGT ASIA), 2015, pp. 1-6.

[35] P. C. Loh, F. Blaabjerg, S. Peyghami-Akhuleh and H. Mokhtari, "Distributed secondary control in DC microgrids with low-bandwidth communication link," 2016 7th Power Electronics and Drive Systems Technologies Conference (PEDSTC), 2016, pp. 641-645.

[36] P. Prabhakaran, Y. Goyal and V. Agarwal, "A Novel Communication-Based Average Voltage Regulation Scheme for a Droop Controlled DC Microgrid," in IEEE Transactions on Smart Grid, vol. 10, no. 2, pp. 1250-1258, March 2019.

[37] M. Zaery, E. M. Ahmed and M. Orabi, "Consensus algorithm based distributed control for economic operation of islanded DC microgrids," 2016 Eighteenth International Middle East Power Systems Conference (MEPCON), 2016, pp. 854-859.

[38] L. Che and M. Shahidehpour, "DC Microgrids: Economic Operation and Enhancement of Resilience by Hierarchical Control," in IEEE Transactions on Smart Grid, vol. 5, no. 5, pp. 2517-2526, Sept. 2014.

[39] X. Li et al., "Flexible Interlinking and Coordinated Power Control of Multiple DC Microgrids Clusters," in IEEE Transactions on Sustainable Energy, vol. 9, no. 2, pp. 904-915, April 2018.

[40] M. Ertürk, M. Aydın, M. Büyükakkaşlar and H. Evirgen, "A Survey on LoRaWAN Architecture, Protocol and Technologies", *Future Internet*, vol. 11, no. 10, p. 216, 2019.

References

[41] Haxhibeqiri, E. De Poorter, I. Moerman and J. Hoebeke, "A Survey of LoRaWAN for IoT: From Technology to Application", *Sensors*, vol. 18, no. 11, p. 3995, 2018.

[42] T. T. Nguyen, H. H. Nguyen, R. Barton and P. Grossetete, "Efficient Design of Chirp Spread Spectrum Modulation for Low-Power Wide-Area Networks," in IEEE Internet of Things Journal, vol. 6, no. 6, pp. 9503-9515, Dec. 2019.

[43] K. Stouffer, J. Falco and K. Kent, “Guide to Supervisory Control and Data Acquisition (SCADA) and Industrial Control Systems Security—Recommendations of the National Institute of Standards and Technology,” Special Publication 800-82, Initial Public Draft, Sept. 2006.

[44] White paper on SCADA Systems Overview, "Telemetry & Remote SCADA Solutions." Available Online: www.schneider-electric.com. Document Number TBUL00001-31, March 2012.

[45] A. Sajid, H. Abbas and K. Saleem, "Cloud-Assisted IoT-Based SCADA Systems Security: A Review of the State of the Art and Future Challenges,". IEEE Access, vol. 4, pp. 1375-1384, 2016.

[46] L. Abbey, "Telemetry / SCADA Open Systems vs Proprietary Systems," Available Online: https://www.abbey.co.nz/telemetry–scada-open-vs-proprietarysystems-2003.html.

[47] IDC Technologies, "Fundamentals of Instrumentation, Process Control, PLCs and SCADA for Plant Operators and Other Non-Instrument Personnel," Available Online:https://books.idc-online.com/book-categories/instrumentation/

[48] Mader Electric, "Automation & Controls,". Available Online:https://www.maderelectricinc.com/automation-electrical-controls.

[49] A. M. Grilo, J. Chen, M. Díaz, D. Garrido and A. Casaca, "An Integrated WSAN and SCADA System for Monitoring a Critical Infrastructure," in IEEE Transactions on Industrial Informatics, vol. 10, no. 3, pp. 1755-1764, Aug. 2014.

[50] A. G. Bruce, "Reliability analysis of electric utility SCADA systems," IEEE Transactions on Power Systems, vol. 13, no. 3, pp. 844-849, Aug. 1998.

References

[51] H. Guozhen, C. Tao, C. Changsong and D. Shanxu, "Solutions for SCADA system communication reliability in photovoltaic power plants," 2009 IEEE 6th International Power Electronics and Motion Control Conference, Wuhan, 2009, pp. 2482-2485.

[52] B. Chae, "The evolution of the Internet of Things (IoT): A computational text analysis", *Telecommunications Policy*, vol. 43, no. 10, p. 101848, 2019.

[53] P. de Arquer Fernández, M. Fernández Fernández, J. Carús Candás and P. Arboleya Arboleya, "An IoT open source platform for photovoltaic plants supervision", *International Journal of Electrical Power & Energy Systems*, vol. 125, p. 106540, 2021.

[54] W. Zhang, Y. Fang, R. Ye and Z. Wang, "Analysis and Design of a Double Fuzzy PI Controller of a Voltage Outer Loop in a Reversible Three-Phase PWM Converter", *Energies*, vol. 13, no. 15, p. 3778, 2020.

[55] A. Elnady, "PI Controller Based Operational Scheme to Stabilize Voltage in Microgrid," *2019 Advances in Science and Engineering Technology International Conferences (ASET)*, 2019, pp. 1-6.

[56] R. A. Barbosa, D. de Almeida Souza and A. P. da Nóbrega Tahim, "Adaptive Control of DC Microgrid Using PI Controller and Fuzzy Inference," *2019 IEEE PES Innovative Smart Grid Technologies Conference - Latin America (ISGT Latin America)*, 2019, pp. 1-6.

[57] Y. Zhang, S. Wei, J. Wang and L. Zhang, "Bus Voltage Stabilization Control of Photovoltaic DC Microgrid Based on Fuzzy-PI Dual-Mode Controller", *Journal of Electrical and Computer Engineering*, vol. 2020, pp. 1-10, 2020.

THANK YOU

Questions!!!!