Design Document

US Army Tactical Microgrid System Civilian Energy Storage System

ECE 445
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1 Introduction

1.1 Objective

The goal for our project is to develop an energy storage system for the Tactical Microgrid System (TMS), a decentralized power distribution system developed by the US Army Corps of Engineers (USACE). In Puerto Rico, solar energy is currently the main source of power for one of these microgrids, but due to its intermittent availability, an energy storage system must be developed to provide usability during all times of the day.

We will split this project into two connected segments. The first is the high level implementation of a battery management system, which will require us to calculate the required type and number of batteries, as well as the electrical components to enable a reversible flow of power.

The second is to develop a communication system with the TMS microgrid, which will be embedded on a PCB. This project is designed to integrate with the overall TMS project, so we are restricted by many of the TMS design guidelines. The most important protocol we will need to follow is the communication protocol, our system must be able to send and receive various predefined messages to and from the microgrid controller. The full list of commands we will need to support is in section 1.5.

1.2 Background

The Tactical Microgrid System (TMS) of the US Army Corps of Engineers is a decentralized power distribution system developed for seamless deployment in areas that have lost their means of producing electricity. It is currently deployed in multiple locations in United States military installations. Our client, the US Army Corps of Engineers, wants us to adapt this project for civilian use in Guayabota, Puerto Rico. The current system uses diesel generators to initially power the microgrid, but the USACE wants the ability to transition to renewable energies.

Across the globe there are still many places that do not have the infrastructure to deliver sustainable energy to its citizens, whether due to underdevelopment or destruction from natural disasters. The current tactical microgrid utilized by the military is not designed for civilian use; it requires a trained technician, unsustainable methods of power generation, and expensive equipment. The army wishes to fix these problems, starting with a civilian deployment in Guayabota, Puerto Rico. The city currently has access to a commercial power grid infrastructure. However, earthquakes in recent months have destroyed much of this infrastructure and is causing it to run at maximum capacity. Due to these reasons and the region's proximity to the continental US, the army has chosen this destination for deploying the microgrid solution.

One of the most critical demands for electricity in Guayabota is their water distribution system, which is currently being powered with solar energy. The US Army Corps of Engineers wants the ability to incorporate renewable energy sources to the tactical microgrid design, and in order to efficiently use solar energy the microgrid needs an energy storage system. The city also does not have any supply of batteries available from the solar farm for use on the microgrid. The local population of Guayabota is approximately 3000 people, and it is located in a rural, mountainous region. According to a survey by the United States Geological Survey agency, the groundwater that must be pumped to the surface for drinking is approximately 56.5 ft below the surface [5]. This will be critical when calculating the amount of energy required for the daily energy consumption of the water pumping system in Guayabota.

Our main focus is developing a system that integrates the solar energy and also follows the design protocols of the existing TMS technology. The TMS network architecture, also known as the TMS-DDS protocol, is a distributed UDP communication protocol actively used in other compliant microgrids around the world. The protocol identifies and controls components of the microgrid through the central Microgrid Controller module, which reads status messages from all components, calculates necessary changes, and redirects power appropriately. The other module types are Power Sources, Loads, Distribution Boxes, and Storage. In order to integrate our system, we must design it as a Storage module. Notably, Guayabota's Solar Farm does not follow the Power Sources communications protocol, so we must assume that the distribution system is able to monitor its status.

1.3 High Level Requirements

Communication System Requirements:

- The energy storage system is able to monitor and send its status to the Microgrid Controller through an ethernet connection through UDP
- The energy storage system supports all published and subscribed topics specified by the TMS-DDS STOR protocol (refer to section 1.5)
- The energy storage system has a physical user interface that toggles the energy output (on/off) and displays its current status

1.4 Visual Aid

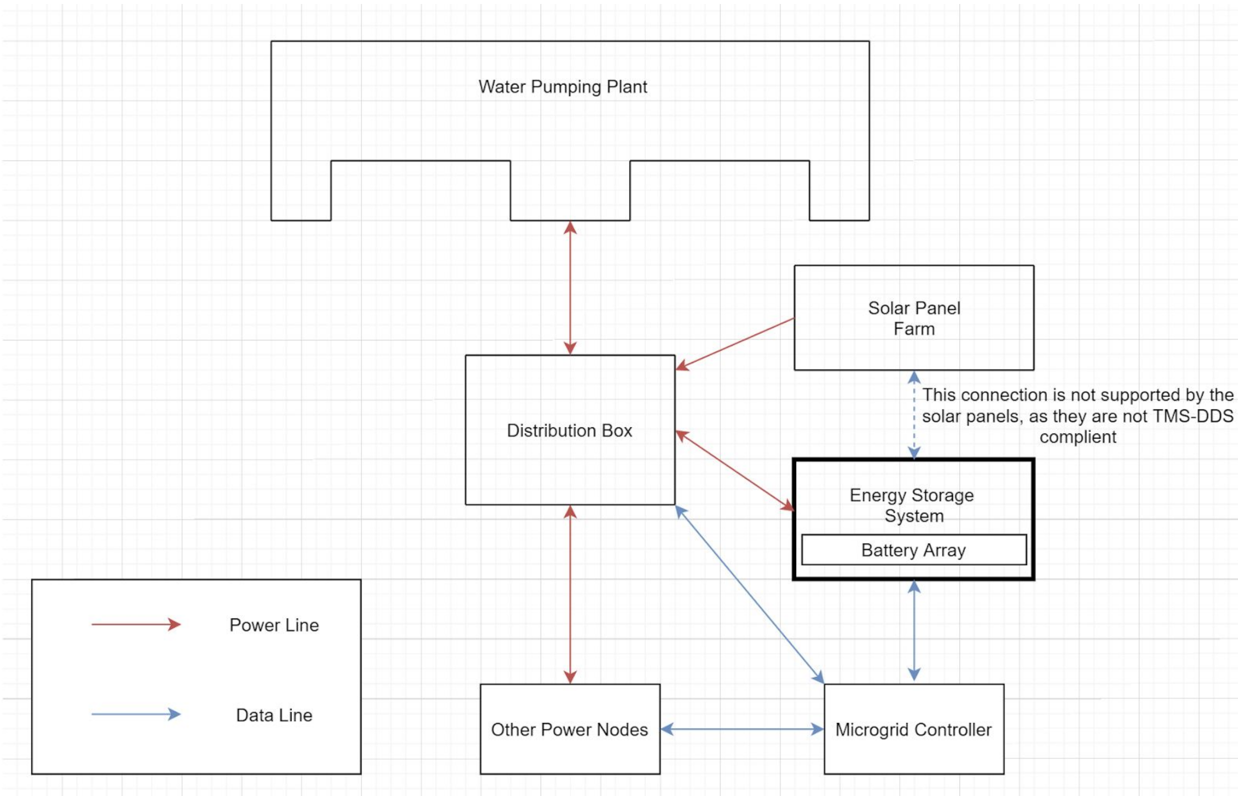

Figure 1: Overall layout of the microgrid system

1.5 Communication Protocol

The TMS-DDS architecture has documented requirements for the messages our storage system must be able to support. The order and frequency of how these messages are sent and received, but not the data inside each message nor how they are executed, are specified in the TMS OMG DDS Implementation Guide. These messages will be generated and read through the software running on our microprocessor, and sent and received through the ethernet adapter. We will assume that the LoadSharingRequest and SourceTransitionRequest controls the input and output of the battery.

Device Role	Pub/Sub	Topic Name
Storage / STOR	pub	ActiveDiagnostics
	pub	AuthorizationToEnergizeOutcome
	pub	AuthorizationToEnergizeRequest
	pub	ConfigReservationState
	pub	DeviceAnnouncement
	pub	DeviceClockStatus
	pub	DeviceParameterStatus
	pub	DevicePowerMeasurementList
	pub	DevicePowerPortList
	pub	DevicePowerStatusList
	pub	DiscoveredConnectionList
	pub	GetConfigDeviceParameterResponse
	pub	GetConfigLoadSharingResponse
	pub	GetConfigPowerSwitchResponse
	pub	GetConfigSourceTransitionResponse
	pub	LoadSharingStatus
	pub	RequestResponse
	pub	ReserveConfigReply
	pub	SourceTransitionState
	pub	StandardConfigMaster
	sub	AuthorizationToEnergizeResponse
	sub	CopyConfigRequest
	sub	DeviceAnnouncement
	sub	DeviceParameterRequest
	sub	GetConfigContentsRequest
	sub	LoadSharingRequest
	sub	ReleaseConfigRequest
	sub	ReserveConfigRequest
	sub	SourceTransitionRequest

Figure 2. TMS-DDS Storage Communication Protocol

2 Design

2.1 Block Diagram

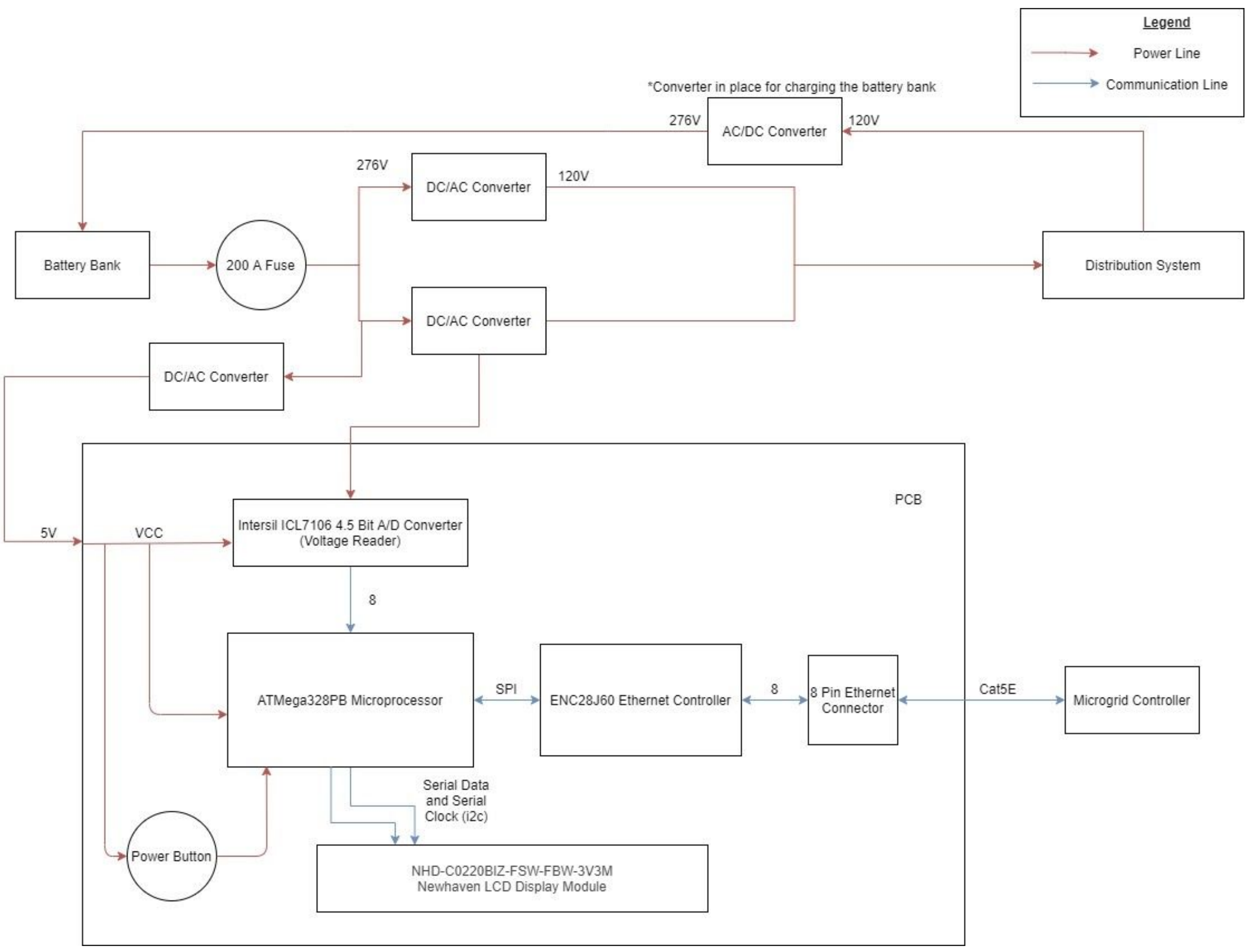

Figure 3: Functional Block Diagram

2.2 Functional Overview

2.2.1: Battery Bank

The batteries will be charged when the input power generators, whether it is solar energy or diesel generators, are providing the necessary power to meet all of the load requirements. When the load requirements are not being met, that is when the batteries will have to be used. In order to solve for the energy consumption there are several assumptions that must be made. First, the National Environmental Education Foundation estimates that Puerto Rico residents require 62 gallons of water per day [6]. Next, one acre-foot of water is equivalent to 325,851 gallons of water. Finally, the energy consumption to pump one acre-foot of water one foot is 1.71 kWh, operating at 60% efficiency [7]. Combining information with the depth of groundwater and the population of Guayabota, the energy consumption result is shown in Equation 1.

$$\frac{62\ gal/person{-}day * 3000\ people}{325851\ gal} * 1.71kWh * 56.5ft = 55.15\ kWh/day$$

Equation 1: Equation to solve estimated energy consumption of a water pumping plant.

The size of the battery bank is dependent on many factors. The first factor is that we will assume that the batteries will have enough storage to power the water pumping station for a single day. The reason for this choice is that the solar panel farm will be the long term solution for power, but the batteries will have to work at night, and if there is a prolonged period of bad weather or lack of sun for the solar panels, the diesel generators are there for backup. We will assume that our battery storage is large enough to last 12 hours, that way we balance the cost of the battery bank and the availability of the diesel generators.

The next factor is the type of battery that is used for the battery bank. The options that are available are Lithium Ion batteries or lead acid batteries. Lead acid batteries are a proven technology that cost less, but have a shorter lifespan. Lithium Ion batteries are more efficient and last longer, but have a higher cost. Given the remote location that the microgrid will be sent to we will use Lithium Ion batteries for our application. Lithium Ion batteries are able to discharge approximately 2000 times before it reaches the end of their lifetime in hot climates such as Puerto Rico. Lead Acid batteries are only able to go through 500 cycles in similar climates. Figure 4 shows a plot of the lifetime of Lithium Ion batteries versus Lead Acid batteries at different discharge percentages.

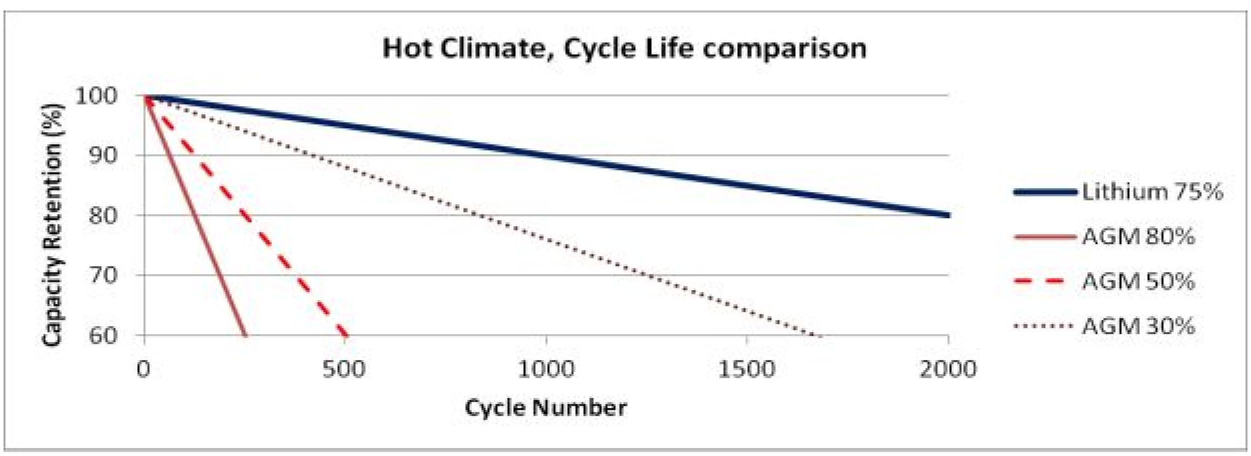

Figure 4: Battery Lifetime Comparison[9]

Finally, the battery voltage multiplied by the discharge rate represents the 50% depth of discharge, so a factor of two must be included to make sure the battery bank's energy storage will not be used up before the batteries need to be recharged.

$$\frac{2*kWh * \# \ of \ days}{Battery\ Voltage*Battery\ Discharge\ Rate} * 1000 = \# \ of\ Batteries$$

$$\frac{2*55.15kWh*0.5\ days}{12V\ *\ 100AH} * 1000 = 46\ Batteries$$

Equation 2: Calculation for the size of the battery bank.

Requirement	Verification
1. Battery Bank outputs 276 V. 2. Current does not exceed 200 A to comply with the distribution box current limit.	1. Connect a wattmeter in between the battery bank and 200 A fuse and measure the battery bank's output.

2.2.2: Power Conversion

Solar panels produce DC electricity, however the microgrid needs to transmit AC electricity because that is what the water plant runs on. This means that DC/AC converters will be needed. Based on the calculations in 2.2.1 (Battery Storage) and the fact that the civilian microgrid distribution boxes are rated for 200 A, we know that our power converters need to be rated for 55.15 KWh and 200 A. The battery bank will output to one bus, which we can call the battery bus. This battery bus will be connected to a 200 A rated fuse and a switch. After the switch there will be two power converters. The reason there would be two power converters is in case the primary power converter is damaged for whatever reason. If this happens, the switch will then direct power flow through the secondary power converter. This extra precaution is necessary in order to ensure that the battery bank can always discharge to the microgrid.

The power converters themselves will be DC/AC converters. The parameters of the converter will be that the input voltage is 276 V, the output voltage will be 120 V, and output load is 55.2 kWh (The parameters are calculated in the tolerance analysis).

Requirement	Verification
1. Power converters step down the battery bank voltage to 120V AC to the distribution box. 2. Output 5V DC to the Communication System PCB to power the on-board IC chips.	1. Connect wattmeters before and after the converter to check for power losses, as well as an oscilloscope probe after the DC/AC converter to make sure the output is 120V AC at 60Hz.

2.2.3: Microprocessor

The microprocessor is used to evaluate and control the status of the energy management system. It is also responsible for reporting the status of the device to the microgrid controller, as well as interpreting commands from the controller to adjust the power flow. It is the central interface for all data processing and evaluation. We chose to use the ATMega chip as it has enough pins, and supports both i2C and UART communication protocols.

The connection to the A/D converter is a multi-line connection that reads the voltage output of the AC/DC converters. This value is stored internally, displayed on the display module, and also sent to the microgrid controller.

The connection to the display module is a i2C connection. This enables us to display more information than a standard 7-segment display, but requires more computation power.

The connection to the ethernet controller is a bidirectional SPI connection that can both read and send packets. Since ethernet communications run at a higher frequency than what the chip is able to support, SPI is fast enough to transmit data that is then condensed even more by the ethernet controller.

Requirement	Verification
1. Is able to read UDP data packets received from the Ethernet Controller, through a SPI interface 2. Is able to send UDP data packets to the Microgrid Controller through the Ethernet Controller, through a SPI interface. 3. Is able to interface with the Display Module to display simple 16-character text messages, through a i2c Interface. 4. Is able to be powered on and off with a manual power switch 5. Is able to interpret data from the voltage reader though 8 single-line connections	1. Using a desktop software for interpreting SPI data (many examples on github using C), simulated inbound data is able to be interpreted by the microcontroller and information is displayed via GPIO lines 2. Using the same software, the microprocessor/network adaptor pair sends readable data following the TMS-DDS protocol to the desktop application 3. The Display Module displays the intended message, and toggles power saving mode when requested 4. The current drain from the power source is zero or negligible 5. Additional GPIO lines are able to mirror the voltage (High/Low) of each data line

2.2.4: A/D Converter (Voltage Reader)

The voltage reader will be necessary to read the output of the battery bank after the power is converted through the DC/AC converters. The A/D converter is similar to what is used in multimeters, and supports voltages up to 19999 volts (4.5 digit). This information will be used by the microcontroller to determine the charge level of the battery bank, since the voltage will slowly drop as the batteries are discharged. This measurement will give an indication to the battery management system that the batteries are in need of recharging, or if they have become fully charged and all of the energy can be used to power the water pumping system.

Requirement	Verification
1. The voltage reported by the A/D converter compared to the battery voltage measured are within a range of 1%. 2. Source current kept below 10µA to keep power consumption low.	1. Use voltmeter to measure the battery voltage at the output of the power converters, and compare to the digital reading sent to the microprocessor. 2. Use a digital multimeter to measure the current drawn to power the A/D converter.

2.2.5: Ethernet Controller

Information in the Tactical Microgrid System is transferred to and received from the main microcontroller via ethernet. To ensure proper utilization of the batteries in the energy storage system, we will have to communicate with the microgrid controller, as our system cannot make decisions without knowledge of the entire microgrid's status. The ethernet controller will read the data from the battery management microprocessor about the current state of the battery bank, including voltage and capacity. This will then be sent to the microgrid controller so that it can redirect power from the solar panel farm, or activate the backup diesel generators in order to meet the load requirements at any given time of operation.

Requirement	Verification
1. Must be able to receive data from our microprocessor and send to the outbound microgrid controller, via SPI protocols. 2. Must be able to send data to the microprocessor interpreted from data packets from the microgrid controller, via SPI protocols	1. Using the TMS-DDS Desktop Packet Sending/Receive Simulation software, the microprocessor/network adaptor pair is able to interpret read packets 2. Using the same software, the microprocessor/network adaptor pair sends readable data to the desktop application

3. Must be able to interpret data quickly enough such that no data is loss due to buffer overflow	3. The ERXRDPT Register (forbidden receive buffer pointer) does not equal the ERXST Register (next write location).

2.2.6: Display Module

The display module is a 16x2 character screen with preset message formats for displaying characters. The i2C connection to the microcontroller writes data to certain buffers, which are then displayed upon an activation signal.

The component already supports numerous alpha-numeric characters, including spanish. We will aim to have support for english and spanish, in testing we will display english but for demonstration we will use spanish mode. These modes will be pre-programmed, and not configurable in production.

Requirement	Verification
1. Displays i2c messages received from the microcontroller. 2. Powers off display upon receiving an idle signal from the microcontroller.	1. Message is displayed at the correct locations on the screen with < 10ms latency. 2. Display is powered off upon receiving the message.

2.2.7: Ethernet Connector

Verification of this component is negligible, it is a female connector for CAT5e ethernet cables that exposes the pins for each wire.

Requirement	Verification
1. Is able to connect an ethernet cable to our design. 2. Each pin correctly transfers its voltage state to the corresponding pin on the other end of the connection	1. Connection to the ethernet cable is secure and reliably transmits data to the microcontroller with 100% accuracy and no delay. 2. On a breadboard, setting the voltage hi or low on each pin results in the same value on the respective pin in the ethernet connection port

2.3 Physical Design

Figure 5: Draft of the battery bank storage case

The physical design of our energy storage system will need to have connections to various other components. Our client has requested our product to be durable in extreme conditions and with a very minimalistic interface, so that untrained technicians are able to operate it. We imagine a rugged metal box with a single display, a power button, and the required connections to other components of the microgrid, including a power line between the battery array, a power line to the distribution box, and a communication line between the microgrid controller.

2.4 Risk Analysis

The microprocessor's ability to manage the power drawn from the battery storage system will be the most significant factor of success. In the event that the batteries are undercharged, this will lead to the water pumping plant being left without power. No power would severely harm the water supply for the people of Guayabota that depend on the plant for clean water. If the batteries were to be overcharged that would cause the microgrid to operate inefficiently. In extreme circumstances, it could lead to the batteries exploding. The majority of rural cities in Puerto Rico have struggled to maintain their power grid infrastructure, so it will be key to utilizing the energy storage system in tandem with the solar farm setup in the city of Guayabota. Without the microcontroller to control how the batteries are being used, the city will continue to struggle having consistent power performance.

2.5 Tolerance Analysis

The purpose of the battery bank is to ensure that there is enough battery storage available to back up the solar panels during times where they are not outputting enough energy. Since the distribution boxes that the USACE wants to use are rated for 200 A, the battery bank should be set up with 2 rows in parallel, with each row having 23 batteries in series. This limits the amount of current that can be discharged at once to 200 A, matching the rating of the distribution boxes. The power output of the battery bank is calculated below in equation 3.

$$Battery\ Discharge\ Rate\ *\ \#\ of\ rows\ in\ parallel\ =\ current\ output$$
$$100\ AH * 2\ = 200\ AH$$

$$Battery\ Voltage\ *\ \#\ of\ batteries\ in\ series\ =\ voltage\ output$$
$$12\ V\ *\ 23\ =\ 276\ V$$

$$current\ output\ *\ voltage\ output\ =\ power\ output$$
$$200\ AH\ *\ 276\ V\ = 55.2\ kWh$$

Equation 3: Battery bank power output calculation

3 Project Differences

The current design of the Tactical Microgrid System does not utilize renewable energy sources or any energy storage system. There are other solar panel battery management systems that exist and are available for purchase. One example is from a company called Iron Edison, and they offer a complete solar panel, battery bank, and management system for $10,407.30 [8]. However, there are some major issues with implementing this example with the TMS design. The system that is sold only offers 4.3 kWh of energy, whereas the water pumping system in Guayabota requires approximately 55.15 kWh of energy. This means that the size of the battery bank would have to be significantly increased, and the power inverters that are being utilized would have to be rated at a higher voltage in order to meet the power requirements of the water pump. The most important area that differs between a purchased solution and our design is that we need to make sure our design is compatible with the DDS communication protocol that defines the TMS design.

The location that our system will be used in already has a solar farm available, and the TMS distribution box and main microgrid controller provide the basis for the overall microgrid solution. The missing components are the actual battery bank storage system and a communication module. The TMS-DDS architecture is capable of commanding the distribution boxes to redirect power flow to meet the load power requirements. That means it has the ability to use the solar panels to power the water pump, or charge the batteries as the load demands vary over time, and the main microgrid controller is responsible for making those decisions. Our design will monitor the status of the batteries and transmit that information to the microgrid controller via ethernet, following the TMS-DDS protocol, that way the microgrid can constantly react to the load requirements and what energy sources are available to power the loads.

4 Cost and Schedule

4.1 Cost Analysis

Labor: We will assume that our contacts in the USACE will not be receiving wages for this project.
5 Students * 10 hours/week * 10 weeks * 50$/hour = $25,000

Battery Cost: The cost of the Lithium Ion batteries is higher than the cost of Lead Acid batteries. The price of the batteries vary between the supplier as well. The following table compares the price of each type of battery from large suppliers.

Battery Type	Supplier	Cost
Lithium Ion	Tesla	$449.99
Lead Acid	Duralast	$157.99

The cost of resupplying the batteries in Guayabota, Puerto Rico would be extremely high since it is in a remote location on the island. That is why we deemed the longer lifetime of the lithium ion batteries would be a more cost efficient choice since the technicians working on the microgrid would not have to worry about resupplying the batteries in the battery bank as frequently. The lifetime of Lithium Ion batteries is typically about four times longer than the lifetime of Lead Acid [9]. Given the cost from these two suppliers is approximately three times greater for the Lithium Ion batteries, this increased cost would be recovered overtime.

Battery Bank Management System: The products listed below will encompass the proposed battery storage solution that we will be utilizing for the microgrid system. The price will also include the components required to build the communication module that will send the status of the batteries to the main microgrid controller.

Item	Quantity	Price
ATMega Microprocessor	2	$3
Ethernet Connectors	4	$4
Female USB Port	2	$2
Ethernet Controller	2	$3
Push Button	2	$2
LCD Display Module	2	$12
Power Switch	2	$2
Intersil ICL7106 Digital A/D Converter	2	$6.98
12V, 100AH Lithium Ion Battery	46	$20,699.54
	PCB Cost	$34.98
	Battery Storage Cost	$20,699.54
	Total (Equipment + Labor)	$45,734.52

4.2 Schedule

April 13 - April 19:
- Design Document
- Complete Initial Battery Bank 3D model (with ABE help)

April 20 - April 26:
- Design Review
- Create Bill of Materials
- Submit design of the battery bank storage to be built

April 27 - May 3rd:
- Complete initial PCB design
- Order parts for design

May 4th - May 10th:
- Final Report

- Set up TMS-DDS protocol to incorporate solar farm

May 11th - May 17th:
- Construct initial prototype
- Set up TMS-DDS protocol to incorporate battery storage

May 18th - May 24th:
- Test the initial prototype of the communication board
- Test the battery bank and power converters

May 25th - May 31st:
- Edit prototype design in preparation for final demo

June 1st - June 7th:
- Final demonstration (All)

June 8th - June 14th:
- Prepare final documents (All)

5 Ethics and Safety

The high power levels of our microgrid can lead to serious safety concerns if care is not taken. Each individual diesel generator that we will be utilizing will output power as high as 60kW, with a current limit of 800A. Extreme caution will have to be taken to ensure that the generators, and the grid as well, is operated in as safe of conditions as possible. Another safety concern that must be taken into account is that the end user of this product will be someone who receives minimal training to run and maintain the microgrid after the initial setup. This means that we must provide clear instructions on how to operate the microgrid, and also place safety measures to block any extreme hazards that should not be approached during operation.

Using diesel generators also leads to another safety risk for the individuals around them during operation. The diesel generators will give off toxic fumes, mostly in the form of carbon monoxide, so it will be essential to make sure that the area that has these generators are sufficiently ventilated to lessen the risk of breathing in the toxic gas. Also the diesel fuel is highly flammable, which will be that this fire hazard must be monitored to ensure the fuel is not unintentionally ignited.

The renewable energy source that is used to take over for diesel generators to make the microgrid more sustainable will also bring up safety hazards as well. The type of renewable energy source used will be based on the environment that the microgrid will be deployed in, but all of the renewable energy sources will be capable of high and extremely dangerous levels of voltage and current that can electrocute an operator.

An ethical issue that our project will face is the pollution caused by running diesel generators. We have an understanding that diesel engines in this capacity are not sustainable in areas with minimal power grid infrastructure in place, which is why renewable energy sources must be capable for our microgrid so that the diesel energy source will serve the purpose of being a back-up power supply in case of emergency. This is in accordance to the IEEE code of ethics, #1, “...to disclose factors that might endanger the public or the environment.” [2].

Another ethical issue that our project will face will be that we must have detailed documentation for safe operation of the microgrid. The assumption that we are under is that the individuals using the microgrid long term will not be an experienced technician. According to the IEEE code of ethics, #5, we are responsible “to improve the understanding by individuals and society of the capabilities and societal implications of conventional and emerging technologies…” [2]. This means that we must have clear instructions on how to initially train and operate the microgrid once the system has been deployed, as well as make sure the end user is clear about the purpose of each component and how to safely operate the equipment.

6 References:

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