MAKERERE UNIVERSITY

DEVELOPING A MODULAR AND ADAPTIVE POWER ELECTRONICS SYSTEM FOR ENERGY CONSTRAINED AUTOMATIC WEATHER STATIONS

By

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Declaration

I Tobias Newman Muhanguzi, hereby declare that this research proposal entitled "Developing a Modular and Adaptive Power Electronics System for Energy-Constrained Automatic Weather Stations" is my original work and has not been submitted for the award of a degree or any other academic qualification in any university or institution of higher learning. Where the work of others has been consulted or used, it has been duly acknowledged and referenced in accordance with accordance with academic standards.

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Approval

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Abstract

Automatic Weather Stations (AWS) play a critical role in environmental monitoring, yet their deployment in remote and energy-constrained locations remains limited by rigid and monolithic power architectures. Conventional systems are often designed for single enrgy sources, leading to inefficiencies, frequent power interruptions, high maintenance costs, and poor adaptability to dynamic environmental conditions. This research proposes the development of a modular and adaptive power electronics system architecture tailered for energy-constrained AWS. The modular design introduces swappable converter topologies that allow scalable integration of multiple renewable energy sources, including solar, batteries, and supercapacitors, while simplifying upgrades, repairs, and fault isolation. Complementing this, an adaptive control strategy will be implemented to dynamically optimize power flow in response to load variations, source intermittency, and environmental disturbances, thereby enhancing system stability and efficiency. The study will involve system design, simulation, and prototype development, followed by performance evaluation under varying operating conditions. Expected outcomes include improved energy efficiency, fault tolerance, and operational autonomy, ensuring more reliable and sustainable weather data collection in resource-limited and off-grid regions. The findings of this research will contribute to advancing resilient power system solutions that support agriculture, public safety, infrastructure planning, and climate research.

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CHAPTER ONE: INTRODUCTION

1.1 Background

An Automatic Weather Station, (AWS) is a system designed to collect meteorological data autonomously. The World Meteorology Organization (WMO) defines an AWS as a meteorological station where weather parameters observations are automatically taken and sent. These automatic weather stations use advanced sensors and power electronic systems to measure various weather parameters such as temperature, humidity, wind speed and direction, atmospheric pressure, rainfall, and solar radiation. AWS units are often in remote locations, transmitting data in real-time or at scheduled intervals to central databases for analysis. Modern AWS technologies integrate microcontrollers, sensors, power supply systems, and wireless communication to transmit data to centralized databases or cloud platforms. Implementations may also involve the integration of Artificial Intelligence (AI) and Machine Learning (ML) for more advanced meteorological data collection and analysis (Jaber et al., 2022). These systems are critical in meteorological forecasting, agriculture, climate modelling, water resource management, and disaster preparedness (Selvam & Al-Humairi, 2024). In developing countries, AWS adoption has significantly improved data accessibility, although implementation is often hindered by energy limitations, since in most remote areas only solar energy resource maybe available which is intermittent, inefficient Charging Systems due to poor power conversion and inadequate energy storage management, and risk of vandalism. These challenges reduce the uptime and increase maintenance costs of AWS.

Power electronics research is increasingly moving from monolithic, and single purpose converters towards modular and adaptive architectures that can be decomposed, scaled, and reconfigured in the field while maintaining high efficiency and reliability. Modularity simplifies complex systems into interoperable submodules. The AWS submodules include; power supply units, sensors nodes and gateway board. Modular design enables plug and play assembly, fault isolation and life cycle upgrades without redesigning the entire systems. This paradigm is well established at high power system designs through modular multilevel converters (MMCs), whose submodules improve scalability, fault tolerance, thermal management, and control flexibility in HVDC and large stationary applications (Ahmadi et al., 2025; Zhang et al., 2020). At medium and low power, Modularity is increasingly expressed via multiparty and reconfigurable DC-DC converters that interface multiple sources/loads such as photovoltaic, storage and loads all on a single platform. Recent surveys catalog multiparty topologies, control coordination, and design guidelines, emphasizing benefits for space and weight reduction, and system level efficiency in IoT edge systems (Zhang et al., 2020). Parallel work on reconfigurable converters shows how switched-cell networks and adaptive Interconnections extend conversion ratios and fault ride through without sacrificing efficiency (Choi et al., 2020; Hu et al., 2025).

Adaptability of systems complements modularity by altering control laws and operating modes in response to component drift, ambient/thermal changes and load profiles. Adaptive and robust digital controllers for DC-DC converters including four quadrant and boost/buck-boost classes address plant nonlinearity and uncertainties by sustaining dynamic performance and protecting efficiency across wide operating ranges. More recently, machine learning-based methods are being integrated to blend model-based adaptation with data-driven decision-making (Fang et al., 2024; Mumtaz et al., 2017; Trinh et al., 2023).

In energy Constrained electronics design, adaptive power management involves switching modes (sleep/active/harvest), selecting interfaces (multi-protocol radios), and scheduling loads. Studies demonstrate self-learning power managers that tune duty cycles and operating points online, reducing energy per task without hardware changes. Surveys of energy harvesting IoT nodes emphasize the value of cross layer adaptability merging converter control with workload and communication decisions to maximize effective uptime (Fang et al., 2024; Gerndt et al., 2025; Rahmani et al., 2025).

Modular hardware naturally supports fault diagnosis and Fault Tolerant Control (FTC) through redundancy and graceful degradation and bypassing or rebalancing submodules. Recent reviews highlight common faults, for example, semiconductor failure, capacitor degradation, gate drive malfunction, and the corresponding FTC strategies required to solve them. The growing role of AI-assisted prediction and self-healing reconfiguration has increased reliability (Hu et al., 2025; Macías-Escrivá et al., 2013; Rahmani et al., 2025).

Reviews consistently argue that converter modularity and adaptive controls simplify commissioning, improve part loads efficiency, and future proof assets against evolving standards and resource mixes (Ahrens et al., 2021; Choi et al., 2020; Giuliano et al., 2023; Hinker et al., 2018; Mumtaz et al., 2017).

1.2 Problem Statement

AWS operation is mostly in off-grid and energy constrained locations, making intermittent renewable energy resources (RER) the primary source of power. The current Monolithic AWS system design is unsuitable for incorporating multiple energy resources and lack hybrid communication for network stability. Therefore, AWS systems have low energy efficiency, limited reliability (due to frequent downtime), and high maintenance requirements.

By designing modular and adaptive power electronics system that can dynamically manage energy flow, support scalable integration of multiple energy sources, this will ensure robust operation for autonomous weather monitoring applications AWS current design challenges will be reduced, by increasing power availability and system uptime.

1.3 Objectives

1.3.1. Main Objective:

To develop a modular and adaptive power electronics system for off-grid and energy constrained automatic weather stations with hybrid communication protocols to subsequently optimize power usage.

1.3.2. Specific Objectives

1. To design and simulate a modular AWS system that will consist of power supply, communication subsystem, and sensor nodes.
2. To develop an algorithm that will adaptively optimize power efficiency by adjusting input power levels and duty cycles of the system.
3. To evaluate the performance and energy consumption of the developed AWS system in energy-constrained applications.

1.4 Research Questions

1. What are the design requirements for simulating and designing a modular, adaptive and hybrid communication AWS system?

2. What are the necessary parameters required to develop an algorithm that will adaptively optimize power efficiency of the AWS system?

3. What is the performance of the AWS system in energy-constrained applications?

1.5 Justification

Developing a modular and adaptive power electronics system architecture with hybrid communication is essential because existing solutions fail to meet the operational demands of off-grid remote environments and energy constrained applications. A modular and adaptive design will enable seamless integration of multiple energy sources and simplify the system into modules/subsystems. Real time adaptability to load variation and disturbances will enhance energy efficiency, fault tolerance (FTC) and system flexibility, this will ultimately improve reliability and sustainability of the AWS deployed in energy constrained and off-grid environments. Rural environments have varying network coverage, some areas have GSM, semi-rural areas have both LoRa and GSM coverage. LoRa is more suitable for transmission of larger packet sizes and variety of data formats and also has less energy consumption than GSM, making a hybrid communication design more reliable. WiFi and BLE, can be utilised for onsite communications and system configurations, thereby avoiding constant opening of the system. A customised gateway as opposed to already made/off-the-shelf gateways hinder project scalability and indigenisation of technology, this is why the gateway will be developed from scratch.

1.6 Significance

The modular and adaptive design will ensure optimal energy utilization, reduce power interruptions, reduce maintenance costs, enable easy system upgrade and component replacement. The adaptive energy management strategy will dynamically regulate power flow in response to load variations, intermittent energy availability, transmission modes and environmental conditions. The outcome of the design will improve the reliability, efficiency, and operational autonomy of remote weather monitoring systems, thereby enhancing the quality and continuity of meteorological data essential for applications in agriculture, public safety, infrastructure planning, and climatic research.

1.7 Scope

1.7.1 Design Scope

Requirement identification for the AWS system, development of two Prototypes, adaptive control strategy/algorithm development, and firmware development, system simulation and modelling, deployment and evaluation to assess system performance of four AWS, will not include development of Web Application.

1.7.2 Geographical Scope

The four AWS will be deployed in all regions of Uganda to collect relevant weather data

1.8 Conceptual Framework

A modular and adaptive AWS system operates at the intersection of energy efficiency, communication flexibility, and field sustainability. The system design will include:

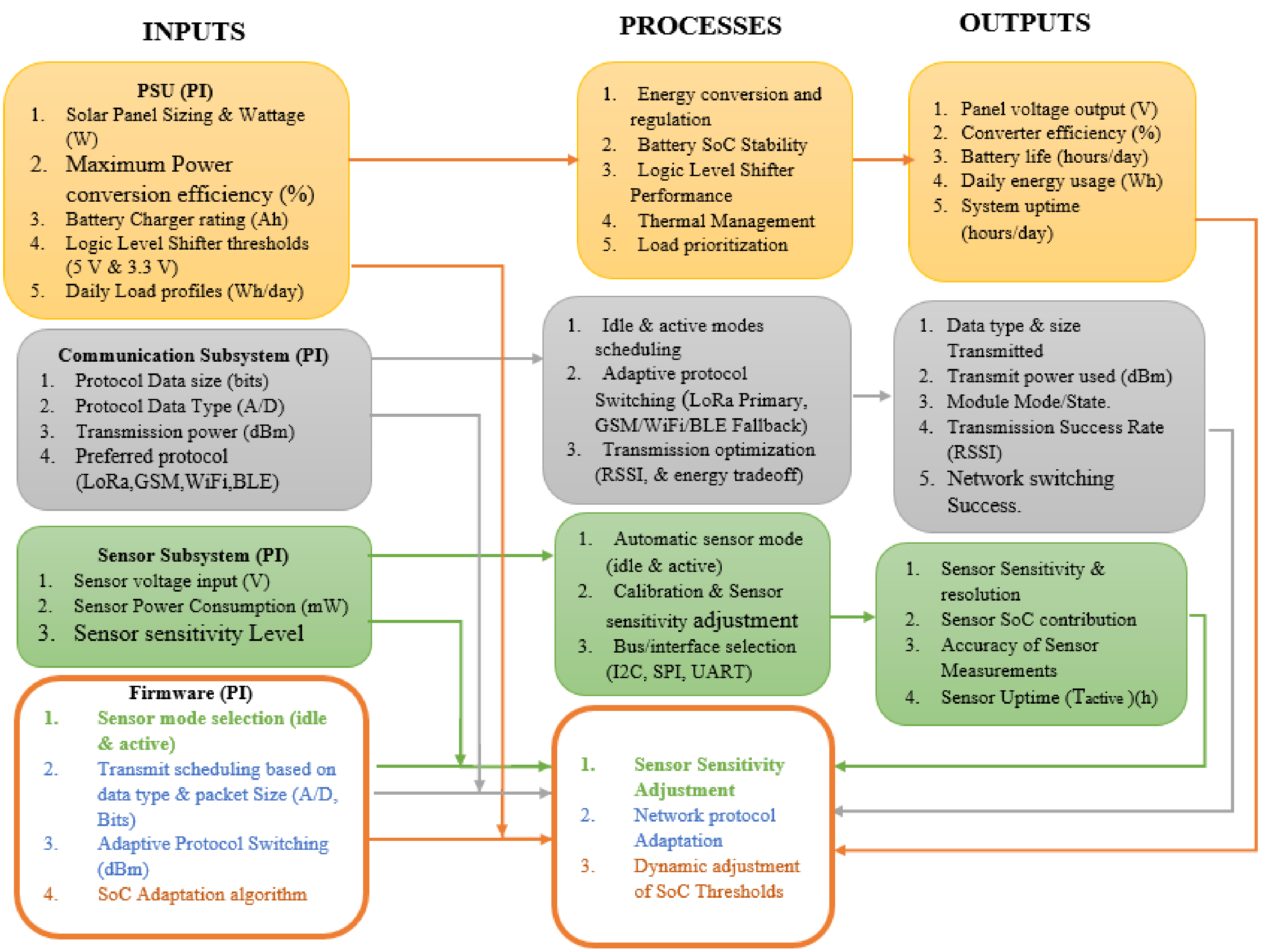

Figure 1. Conceptual Framework

CHAPTER TWO: LITERATURE REVIEW

2.1 Introduction

Automatic Weather Stations AWS are self-contained metrological measurement systems typically combining sensors, data loggers, power systems, and telemetry. They enable near real-time observations in remote or unattended regions (e.g. rural areas) where human operation is impractical. Over recent years, there has been growing interest in low-cost metrological stations (Ashima & Kamboj, 2019; Malozyomov et al., 2023; Nsabagwa et al., 2019).

Prototyping of low-cost AWS for natural disaster monitoring has shown that systems built using off the shelf IoT components can approach the accuracy of professional stations when properly calibrated. Rivera et al., (2023) also emphasize open-source designs and affordable sensor platforms for environmental monitoring in resource-constrained setting.

Thus, current AWS research is trending toward modularity, low power, flexibility, and IoT integration, which aligns well with your project's direction.

2.2 Modular and Adaptive Design in Power Electronics

One of your central aims is to leverage modular and adaptive power electronics in an AWS context. Below is a more detailed survey of relevant literature in that space.

2.2.1 Modularity

Modularity is where a complex system is broken down into manageable subsystems. Modularity in power electronics has emerged as a design principle that improves scalability, fault tolerance, and maintainability. Modular multilevel converters (MMCs) exemplify this approach by decomposing converters into interchangeable submodules, thereby reducing harmonics, simplifying thermal management, and improving reliability (Hu et al., 2025). However, MMCs also present challenges such as increased control complexity, high component count, and energy balancing requirements, which recent studies address through improved modulation strategies and fault management techniques (Zhang et al., 2020). Modular hardware portioning ensures modular PCB design, i.e., distinct boards for power management, sensing, and communication supports plug and play maintenance and upgrades, as shown in figure 2 below. In AWS contexts, use modular micro services in software to support upgrades and reconfiguration (Ahmadi et al., 2025; Chakraborty et al., 2009; Fang et al., 2024; Gozdur et al., 2021; Yildirim et al., 2025).

At lower and medium power levels, multiport DC-DC converters embody modularity by integrating multiple sources, e.g., PV, storage batteries, supercapacitors, and loads into compact converter stages. Comparative reviews highlight families of multiport topologies i.e. isolated and non-isolated, bidirectional, switched-capacitor, and switched-inductor variants that enable compactness, enhanced power flow management, and reduced system cost (Gevorkov et al., 2023; Harrison et al., 2024). These converters allow dynamic source-load coordination, but their design is Constrained by complex control requirements, efficiency trade-offs, and reliability under fluctuating renewable inputs

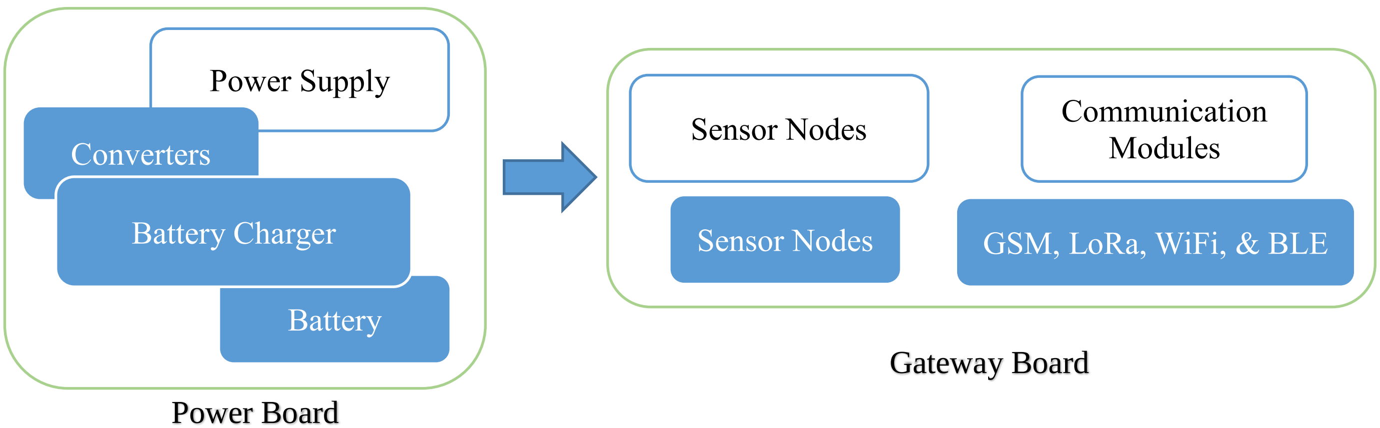

Figure 2: Modular AWS System

2.2.2 Adaptability

Adaptivity or adaptability in power electronics refers to automatic adjustment of control parameters and operational modes in response to changing conditions (e.g. input variation, load shift, component aging). In recent MMC research, Fang et al., (2024) propose a model-free adaptive control (MFAC) with event-triggered mechanism to reduce computational burden and switching losses. Their strategy avoids reliance on precise mathematical models and adapts to parameter mismatches.

Adaptability in power electronics manifests through real time adjustments of the converter control and operation. Adaptive controllers such as gain-scheduled (GS) and robust adaptive laws have been shown to improve efficiency during continuous/discontinuous conduction transitions and enhance dynamic performance under uncertainties (Chaoui et al., 2020; Fang et al., 2024; Trinh et al., 2023; Villagrán et al., 2017). At the system level, adaptive energy management frameworks support energy harvesting nodes by predicting available energy, dynamically scheduling tasks, and preventing brownouts (Ashraf et al., 2020; Singh et al., 2025).

More broadly, control model surveys e.g., Macías-Escrivá et al., (2013) examine various converter control paradigms e.g. PID, sliding mode, adaptive, and model predictive, highlighting trade-offs in performance, computational load, robustness, and implementation complexity.

In distributed energy resources systems (DERs), adaptivity is a divide and conquer approach that has been applied for instance, Chakraborty et al., (2009); Choi et al., (2020); & Dehghani Tafti et al., (2023) cast a dynamic virtual power plant control problem into adaptive sub-problems and designed local controllers with parameter varying adaptation. Although their domain is broader, the approach illustrates how adaptivity and modular decomposition can be combined

2.2.3 Micro Energy Harvesting, Storage & Adaptive Management

When the energy budget is tight as for the case of off-grid AWS, micro energy harvesting (MEH) and adaptive energy management are critical (Khan et al., 2024; Yamin et al., 2023) provides a comprehensive review of micro-energy harvesting topology (solar, vibration, and thermal), design challenges (matching, conditioning, and storage losses), and strategies to increase overall system efficiency. This can be applied to AWS to increase power availability, thus increase system uptime (Choi et al., 2020; Derbali et al., 2023; Lopez-Gasso et al., 2022; Sadowski & Spachos, 2020).

In IoT or micro-power applications, power management circuits must dynamically switch modes (e.g. sleep, active, boost) and adapt to harvested energy availability. Some studies in analogous domains (e.g. wave energy converters) combine energy conversion, storage, and adaptive supercapacitor/boost conversion strategies to deliver stable output despite highly intermittent input (Ashraf et al., 2020; Olabi et al., 2022) .

2.3 Hybrid communication and Protocol switching

From this proposed Modular and adaptive power management design, multiple communication modules will be included as well. The system will be able to dynamically switch among the programmed communication modes such as LoRa, GSM, and WiFi depending on signal strength, power availability, data urgency, or data type (da Silva et al., 2025). This requires the power system to accommodate the variable loads and transient current demands.

2.4 Modelling, Simulation and Validation approaches

Before hardware implementation, the modular and adaptive designs will be validated through rigorous modelling and simulation. This will include circuit level and system level simulation tools like MATLAB/Simulink and ngSPICE. These will be used to evaluate converter performance (efficiency, transient response, stability) and the Battery State of Charge (SoC). Co-simulation frameworks will allow combining electrical, thermal, and control models to assess real-world behavior under varying conditions. Hardware in the loop (HIL) testing and small-scale prototypes will be used to validate modular control logic before full deployment as in (Difronzo et al., 2021; Lamo et al., 2021). This will lead to determining which algorithm (MFAC or GS) is best suited for this design and will be developed using MATLAB. The equations below will guide in component selection, calibration and value setting.

2.4.1 Basic power & energy relations

Energy consumption over a time interval Δt is given by

$$E = P \times \Delta t$$

Equation 1 Energy Consumption

Where; P is Instantaneous electrical power (W) which is a product of voltage (V), and current (A). E is energy (Wh) for Δt in hours, or (J) for Δt in seconds

2.4.2 DC-DC Converter steady state voltage relation (CCM)

For the Buck converter,

$$\mathrm{V_{out}} = \mathrm{D} \times \mathrm{V_{in}}$$

Equation 2. Duty Cycle of Buck Converter

Where; D is duty cycle ($0 < D < 1$), V_{in} is input voltage, V_{out} is desired output voltage

2.4.3 Converter efficiency and losses

Efficiency is given by, $\eta = \frac{P_{out}}{P_{in}} = \frac{V_{out} I_{out}}{V_{in} I_{in}}$

Equation 3. Converter Efficiency

Power loss, is given by;

$$P_{loss} = P_{in} - P_{out}$$

Equation 4. Power Loss

Other losses of the prototype will include conduction and switching losses

2.4.4 Inductor current ripple

For Buck converter $\Delta I_L = (V_{in} - V_{out}) \times \frac{D}{L \times f_s}$

Equation 5. Inductor current ripple

Where; ΔI_L is peak-to-peak inductor ripple (A), L is inductance (H), f_s is switching frequency (Hz). Choosing L so that the ripple $\Delta I_L \approx 10\%$ to 30% of maximum load current

2.4.5 Output capacitor ripple

This will be used to estimate output voltage ripple while assuming triangular inductor ripple and mostly supplied by capacitor during switching transitions, $\Delta V_{out} \approx \frac{\Delta I}{8 \times C \times f_s}$

Equation 6. Output capacitor ripple

Where; $\Delta V_{out} \approx \Delta I$ is inductor ripple (A), C is capacitance (F), and f_s is switching frequency (Hz)

Will design by choosing C so that ΔV_{out} is within sensor and MCU tolerance that is (e.g. <50 to 100mV)

2.4.6 Battery/ SoC update

Charge/discharge energy update over interval Δt seconds

$$E_{batt}(t + \Delta t) = E_{batt}(t) + [P_{charge}(t) - P_{load}(t) - P_{loss}(t)]\Delta t$$

Equation 7. Instantaneous Battery Charge

This will be in J, over long periods of time Wh will be considered

State of Charge expressed as a % or fraction, $SoC(t) = \frac{E_{batt}(t)}{E_{batt,nom}}$

Equation 8. Percentage SoC

Where; $E_{batt,nom}$ is nominal energy (Wh or J)

Current based SoC update for embedded systems

$$SoC\,(t + \Delta t) = SoC\,(t) + \frac{I_{charge} \times \Delta t}{Q_{nom}}$$

Equation 9. Instantaneous SoC for Embedded systems

Where; I_{charge} is charge current (A), Q_{nom} is battery capacity (Ah), and Δt is in hours

However, using coulomb counting with occasional calibration via voltage-based SoC for better accuracy

2.4.7 Solar energy and PV Sizing

This will consider, instantaneous power harvested, and daily harvested energy

Instantaneous power harvested is given by

$$P_{solar} = \eta_{panel} \times A_{panel} \times G$$

Equation 10. Instantaneous power harvested

Where; η_{panel} is panel efficiency (0 to 1), A_{panel} is the panel area (m^2), and G is solar irradiance ($W/\,m^2$).

Daily harvested energy, $E_{daily} \approx \eta_{panel} \times A_{panel} \times G_{day} \times T_{sun}$

Equation 11. Daily harvested energy

Where; T_{sun} is effective sun hours (h), and G_{day} is average irradiance during those hours

This solar analysis should be derated for temperature, soiling, aging and shadowing or panel inclination considerations.

2.4.8 Energy budget for communication

This will analyse energy requirements for each type of transmission protocol, considering energy per transmission, and idle power to calculate the average communication power.

Energy per transmission is given by, $E_{tx} = P_{tx} \times t_{tx}$

Equation 12. Energy per transmission

Where; P_{tx} is transmit power draw (W), and t_{tx} is transmit duration (s or h)

Average communication power with periodic transmission will be given by

$$P_{comm,avg} = \frac{E_{tx}}{T_{period}} + P_{idle}\left(1 - \frac{t_{tx}}{T_{period}}\right)$$

Equation 13. Average communication power

Where; T_{period} is time between transmissions, P_{idle} is average sleep/idle power.

This average communication power will be used to set frequency given the available power (selection between 5 V and 3.3 V)

2.5 Research Gaps and Opportunities

Many adaptive control strategies have been applied to electronic systems but not specific to AWS, thus the need for lightweight, event triggered, model free adaptive controllers optimized for low power embedded hardware (Fang et al., 2024). While modular architectures support fault isolation in high power and more complex systems, their translation to micro scale AWS hardware (with cost, size, energy constraints) is underexplored. An AWS with hybrid communication protocols, variable energy demand and multiple energy sources remain understudied. This research aims to provide insights into these design gaps.

Research opportunities remain in lightweight adaptive control algorithms for resource constrained systems, co-designed for modular topologies and adaptive controllers to optimize efficiency, and integration of self-healing fault tolerant control with real time adaptive power management.

CHAPTER THREE: METHODOLOGY

3.1 Introduction

This study adopts a design science research approach, combining simulation, prototyping, and field testing to develop and validate a modular and adaptive power electronics system architecture for energy constrained Automatic Weather Stations AWS. The methodology is structured into four phases; system requirements and specifications, prototype development, firmware development for adaptive control algorithms, field deployment and evaluation. Will use quantitative tools for data analysis as described below.

3.2 System Requirements and design specification

A requirements analysis will be conducted to identify specifications for power, communication, and sensing subsystems as shown in table 3, appendix III.

3.2.1 Power subsystem (Converter and Storage)

From figure 3 shown below, a Continuous Conduction Mode (CCM) buck DC-DC converter will be modelled to handle 12 V input form the solar panel, stepping down to 5 V. The Low Drop Out (LDO) will step down the 5 V to 3.3V outputs. An ESP32 (in particular ESP32-WROOM 32U) microcontroller that accepts both 5 V and 3.3 V will be chosen. Communication modules accept input ranging from 3.3 V to 5 V. A logical level shifter (BSS138) will be used to provide a varying output that will power the components with either 5 V or 3.3 V through the MCU Development kit. Energy storage modelling will include ; Battery Management System (BMS) will consist of charger, Lithium-ion batteries sized based on AWS duty cycles and solar availability, supercapacitor integration to support transient peak loads, SoC estimation and cycle analysis under variable (intermittent) solar input. In an aera with grid connectivity DC can be used, and a Multiplexer (MUX), is used to switch between the two sources.

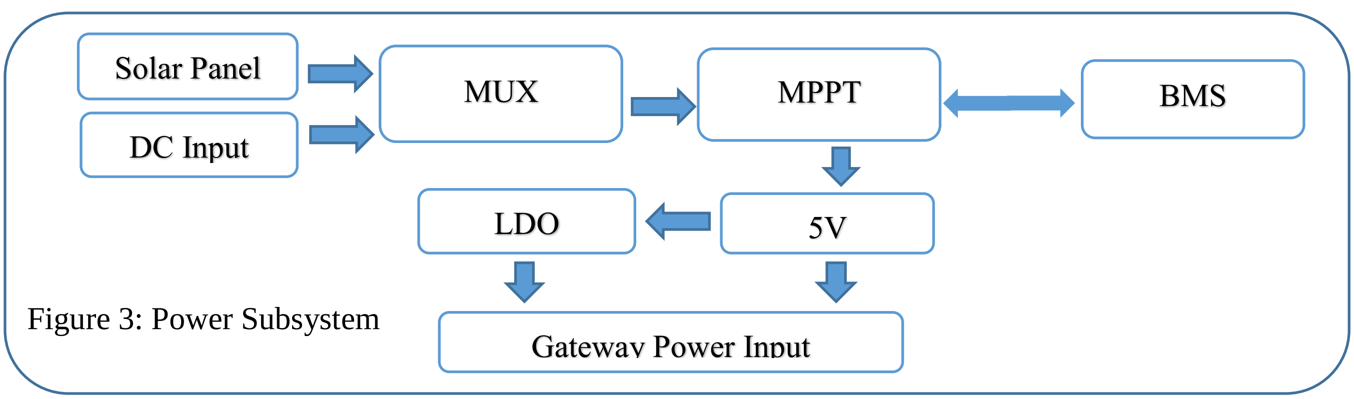

Figure 3: Power Subsystem

3.2.2 Sensor and communication subsystem

From figure 4 shown below, ESP32-S3 microcontroller will be used, and will be connected using a development kit during prototyping to the gateway board. Selected sensors will include; DHT22 for humidity/temperature, BMP280 for barometric pressure, anemometer for wind, soil moisture sensor, rain gauge and solar radiation sensor. All the sensors, communication modules, Real Time Clock (RTC), and SD storage will be connected to the MCU, through the gateway board. Communication modules will include LoRa for default transmission, and GSM as fall back for redundancy.

KiCAD and Altium Designer will be used to design the PCBs. Subsystem boards will include; power subsystem (converter and energy storage), sensor board with multi-sensor interface, and communication board with LoRa, and GSM modules. The design will ensure efficient board stacking for compactness, thermal efficiency and IP65-rated enclosures for EMI insulation and will enable serviceability through easy replacement.

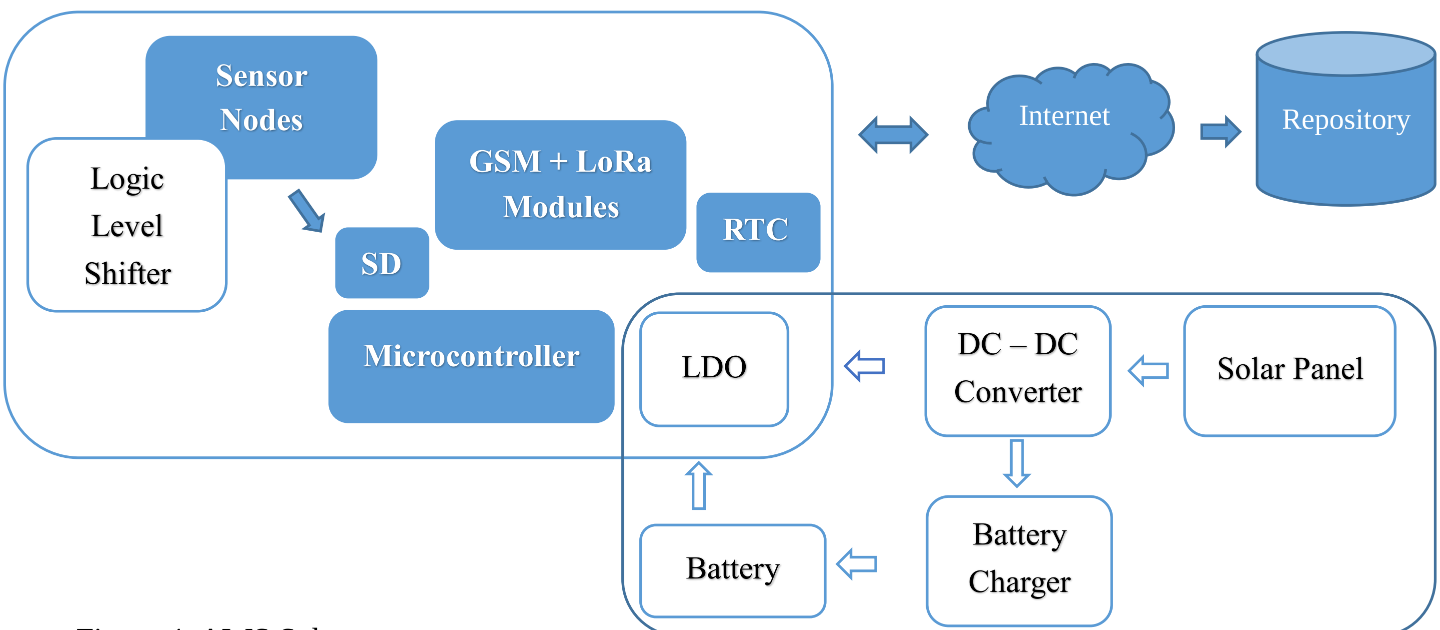

Figure 4. AWS Subsystems

3.3 Adaptive control algorithm

Control strategy will include Gain scheduled adaptive control, Model Free Adaptive Control (MFAC), and Machine Learning-assisted methods

Simulation tasks will include; evaluating algorithm response to fluctuating solar input, implementing duty cycle adjustments based on SoC and load variation, and finally, modelling power management modes (active, sleep, and harvest).

3.3.1 Firmware and Adaptive Power control

The firmware will be developed using ESP IDF and Arduino framework. The basic design functions will include; Adaptive duty cycling and sleep states, hybrid communication switching (between LoRa to GSM to WiFi). The firmware will enable local storage to SD card and RTC for timestamping during network failure and logically switching between battery and back up supercapacitors during overcharge and under charge to maximize power. The firmware will also enable Over the Air (OTA) firmware updates and perform Fault Tolerant Control (FTC) and run-through of the modular system.

3.4 Prototype development

Fabrication of PCB developed in KiCAD using surface mount components and modular connectors. Integration of the different subsystems will be interconnected via standardized interfaces. Testing will involve validation of voltage regulation, communication range and success rates, and sensor accuracy. Figure 5 shows the prototype development stages.

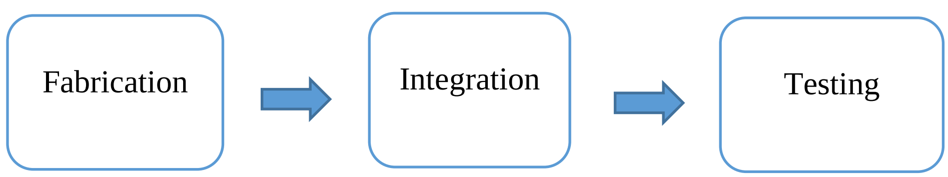

Figure 5. Prototype Development Stages

3.5 Field deployment and Performance evaluation

This section will describe a mathematical model to evaluate system uptime as a percentage which is the continuous operation time relative to deployment period. Energy efficiency in (mWh/day) to represent the consumption across subsystems. Communication reliability (%) successful data transmissions over total attempts. Fault tolerance will measure the system recovery from simulated module failures. Environmental resilience will measure the performance of the system under temperature, humidity, and precipitation variations.

Basic power & energy relations such as DC-DC converter steady state voltage relation, converter efficiency and losses, inductor current ripple, output capacitor ripple, battery/ SoC update, solar energy and PV sizing, energy budget for communication and system average power. Will be recorded using quantitative methods like correlation, regression and hypothesis testing to predict the relationship between the developed AWS system and the current WIMEA-ICT AWS (Byamukama et al., 2017). Simulation tools like MATLAB/Simulink, Python modules like Matplotlib, ngSpice, and Altium Power Analyzer will be used to analyze the efficiency and load profile, voltage ripple and transient response, thermal behavior under continuous load, fault resilience under overload and short circuit.

3.5.1 Simple control rules based on SoC

This describes a minimal logic SoC-based mode switching for firmware development to conserve energy, refer to Equation 9. Instantaneous SoC for Embedded systems

If $SoC > SoC_{high}$: implies normal operation with all sensors and frequent transmissions

If $SoC_{low} \leq SoC \leq SoC_{high}$: implies reduced duty with less frequent transmissions

If $SoC < SoC_{low}$: implies minimal safe mode with only essential sensors and storage of data locally and no or minimal transmission

The thresholds can be set as e.g. SoC_high = 0.6, SoC_low = 0.2

3.5.2 Fault tolerance and redundancy

This can be assessed from an energy viewpoint, if the system has two energy storage sources (batteries and supercapacitors). A simple power sharing/schedule can be formulated as follows

$$P_{load} = P_{batt} + P_{sc}$$

Equation 14: Energy storage utilization

Where the control policy will force P_{sc} to supply short bursts to the MCU to cut off P_{sc}, when P_{batt} is at full capacity, this will prevent battery over-charge, and bring back P_{sc} when the charge reduces to a nominal value of P_{batt}

3.5.3 System average power

This will be used to attempt to calculate system average power by considering the state of the sensor nodes, that is, active and idle/sleep state duty cycles. From equation 13, we can estimate;

$$P_{avg} = P_{active}\left(\frac{t_{active}}{T}\right) + P_{sleep}\left(1 - \frac{t_{active}}{T}\right)$$

Equation 15. System Average power

Where; T, is cycle period used to calculate battery lifetime, which will be used to determine System Uptime.

Which is given by

$$\text{Battery lifetime (hours)} \approx \frac{E_{batt,nom}}{P_{avg}}$$

Equation 16. Battery Life

3.6 Data collection and analysis

Data sources will include energy monitors like INA219, SD card logs, and communication success logs. Data will be analysed using tools like Python (NumPy, Pandas, and Matplotlib) and MATLAB. The analysis will focus on efficiency trends versus load conditions, effectiveness of adaptive algorithm under different scenarios, and statistical comparison with convectional monolithic AWS.

3.7 Validation of research outcomes

This section will involve benchmarking the designed AWS with the WIMEA ICT AWS system, verification to ensure the objectives of improved energy efficiency, reliability, and fault tolerance are met. Sensor data accuracy through timestamping and sensitivity mitigations like pick-up resistor value adjustment, etc. Documentation of data to identify limitations and provide recommendations for improvement.

3.8 Ethical Consideration

The research will ensure protection of participants, data integrity, and environmental responsibility. All field evaluation will be conducted with informed consent from local authorities and stakeholders, ensuring transparency and respect for the community norms. Data collected from weather stations will be used solely for research purposes, with strict confidentiality maintained. The study will also minimise environmental impact, ensuring that the development and testing of hardware systems adhere to sustainability principles, including responsible disposal of electronic waste. Furthermore, the research will respect intellectual property rights and ensure proper citation of sources.

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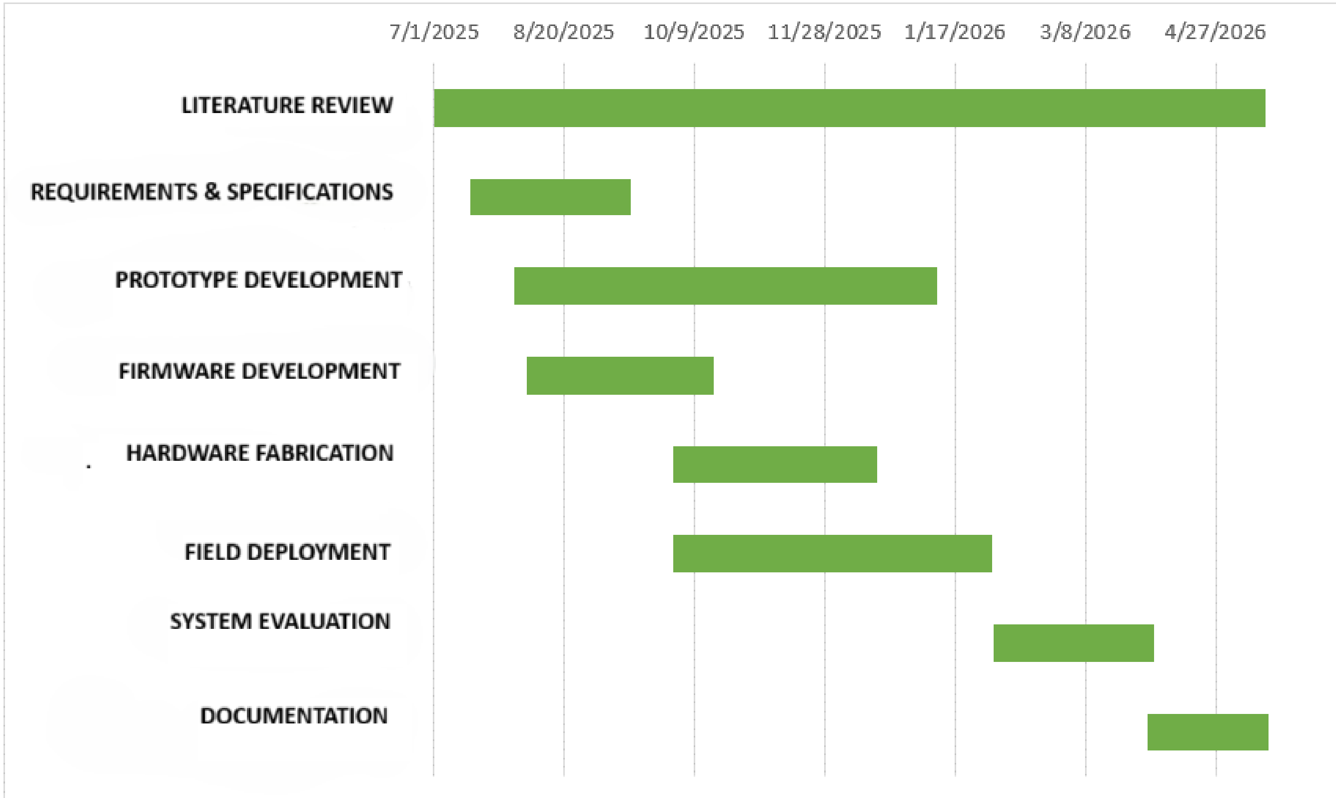
APPENDIX I: PROPOSED WORKPLAN



APPENDIX II: PROPOSED BUDGET

The first budget in table 1, shows the Bill Of Materials (BOM) required to set up two lab prototypes, sensors are available and other soldering tools. Table 2 shows the BOM after the prototype has been tested, the PCBs will be modified and final deployable system cost.

Table 1: Proposed Budget for Prototype development

GATE WAY BOARD				
Component name	**Description**	**Quantity**	**Unit price (UGX)**	**Total price (UGX)**
ESP32-WROOM-32U	Development Board	2	120,000	240,000
SM7000E	GSM	1	195,000	195,000
Ai-Thinker RA-08H	LORA	1	40,000	40,000
MEM2067	Micro SD	1	10,000	10,000
MAX 485 MODULE	RS485	2	10,000	20,000
RESISTOR PACK	resistors	1	30,000	30,000
CAPACITOR PACK	capacitors	1	150,000	150,000
JST XH 2.54 4 Pin	4 pin connector	5	3,500	17,500
JST PH 2.54 2 Pin	2 pin connector	5	1,500	7,500
JST XH 2.54 3	3 pin connector	5	2,500	12,500
push buttons	push buttons	10	500	5,000
2N2222A –NPN	npn transistor	10	500	5,000
GL5506	ldr light sensor	5	1000	5,000
A3144	hall effect sensor	2	4,500	9,000
REED switch	reed switch	1	6,000	6,000
LED PACK	LEDs	1	35,000	35,000
diodes	rectifier diodes	10	500	5,000
screw terminal		10	1,500	15,000
SUB-TOTAL				**807,500**
POWER BOARD				
Component name	**Description**	**Quantity**	**Unit price (UGX)**	**Total price (UGX)**
BQ24650RVAR	solar mppt	2	59,000	118,000
XL4015 5A	5a buck converter	2	20,000	40,000
LM1117T	3.3V regulator 0.8A	4	4,000	16,000
T73 JQC-3FF-S-Z	power mux relay	4	5,000	20,000
3S 40A CMB	3S bms	1	40,000	40,000

4S 40A 18650	4S BMS	1	40,000	40,000
LM393	voltage comparator	5	1,500	7,500
screw terminal		2	1,500	3,000
3 Pin ON/OFF Slide	slide switch	5	2,000	10,000
LIR2032 Rechargeable Button Battery 3.6V	coin cell	2	5,000	10,000
18650 Rechargeable Lithium Ion Battery		10	5,000	50,000
jumper wires		3	10,000	30,000
bread board		2	10,000	20,000
perf board	solder board	4	6,000	24,000
Single Core Tinned Copper Wrap Wire 30 AWG 8	wire	1	27,000	27,000
solder cleaner		1	20,000	20,000
lithium battery holder	3s holder	3	6,000	18,000
pc817c	optocoupler	5	1,000	5,000
solder wick		1	10,000	10,000
power switch	switch	5	2,500	12,500
SUB-TOTAL				**521,000**
GRAND TOTAL 1				**1,328,500**

Table 2: Proposed budget for Station deployment

No.	Item description	Quantity (Lot)	Unit cost (UGX)	Amount (UGX)
1	PCB Printing and Shipping	4	250,000	1,000,000
2	Solar panel and Mounting Frames	4	50,000	100,000
3	Transportation and installation	8	50,000	400,000
4	Data collection tools	1	400,000	400,000
5	Contingency fund	1	500,000	500,000
6	Printing and binding of final report	2	50,000	100,000
	GRAND TOTAL 2			**2,500,000**
	GRAND TOTAL			**3828500**

APPENDIX III: PROPOSED BUDGET

Table 3. List of development tools and requirements

S/N	Category	Tools/Software	Purpose
1	Simulation	Altium Power Analyzer (PDN), ngSpice (Circuit Simulator)	Power electronics simulation
2	Design	KiCAD (intermediate) and Altium (Advanced)	PCB design
3	Programming	ESP-IDF, Arduino IDE	Firmware development
4	Adaptive controller	MATLAB	Adaptability Algorithm
5	Hardware	ESP32-S3 (MCU), BSS138 (Logic Level Shifter), SM7000E, INA219, GSM, LoRa modules, Environmental Sensors.	Sensor and communication subsystem
6	Storage & Logging	SD card modules, RTC	Data logging and timestamping