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# IoT-Based Energy Management in a Laboratory- Scale Smart Microgrid Test Bench

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# IoT-Based Energy Management in a Laboratory-Scale Smart Microgrid Test Bench



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# IoT-Based Energy Management in a Laboratory-Scale Smart Microgrid Test Bench



## Introduction

### For rapid integration of renewable energy sources (RES),

- Microgrids that support flexibility, autonomy, and resilience may be required.
- decentralized energy management systems may be needed.

Then, it is necessary the research will focus on optimizing control & management of RES in these microgrids.



## What is Microgrid?

- A hybrid system that combines generation (PV), storage (battery), and controllable loads.
- It operates in grid-connected or islanded mode.
- It supplies dynamically the electrical energy and balances between loads and enhances reliability.

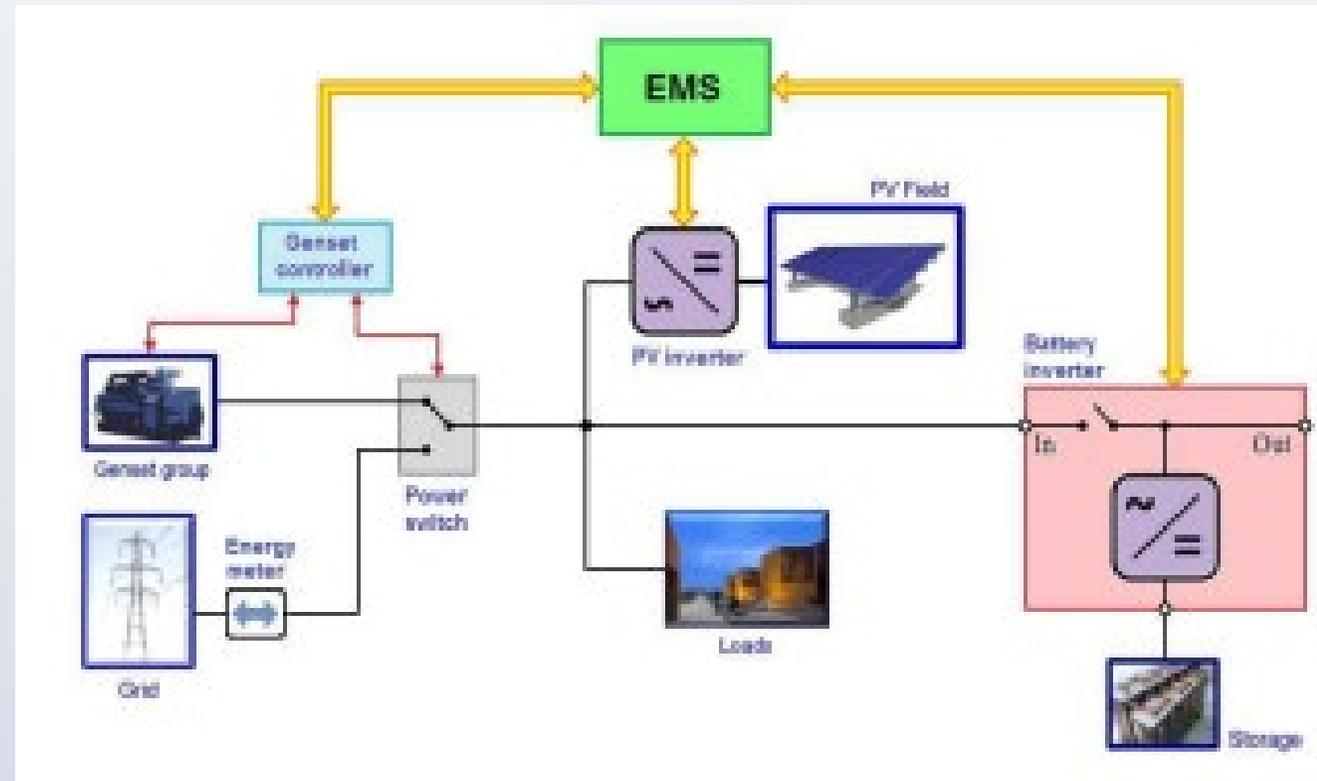


# IoT-Based Energy Management in a Laboratory-Scale Smart Microgrid Test Bench

## Introduction

The suitable configuration of Smart Microgrid for Arab countries, according to the results involved in MED-solar project realised in countries located in the Mashreq area (Lebanon, Palestine and Jordan), is shown in this figure.

**Reference :** G. Velasco & F. Casellas , F. Guinjoan, H. Martínez & R. Piqué «Grid-PV-Diesel Hybrid System Management: Application to MED-Solar Project Scenarios», Report of the ENPI-CBC Mediterranean Sea Basin Programme, 2015 (IEEE explorer)



# IoT-Based Energy Management in a Laboratory-Scale Smart Microgrid Test Bench

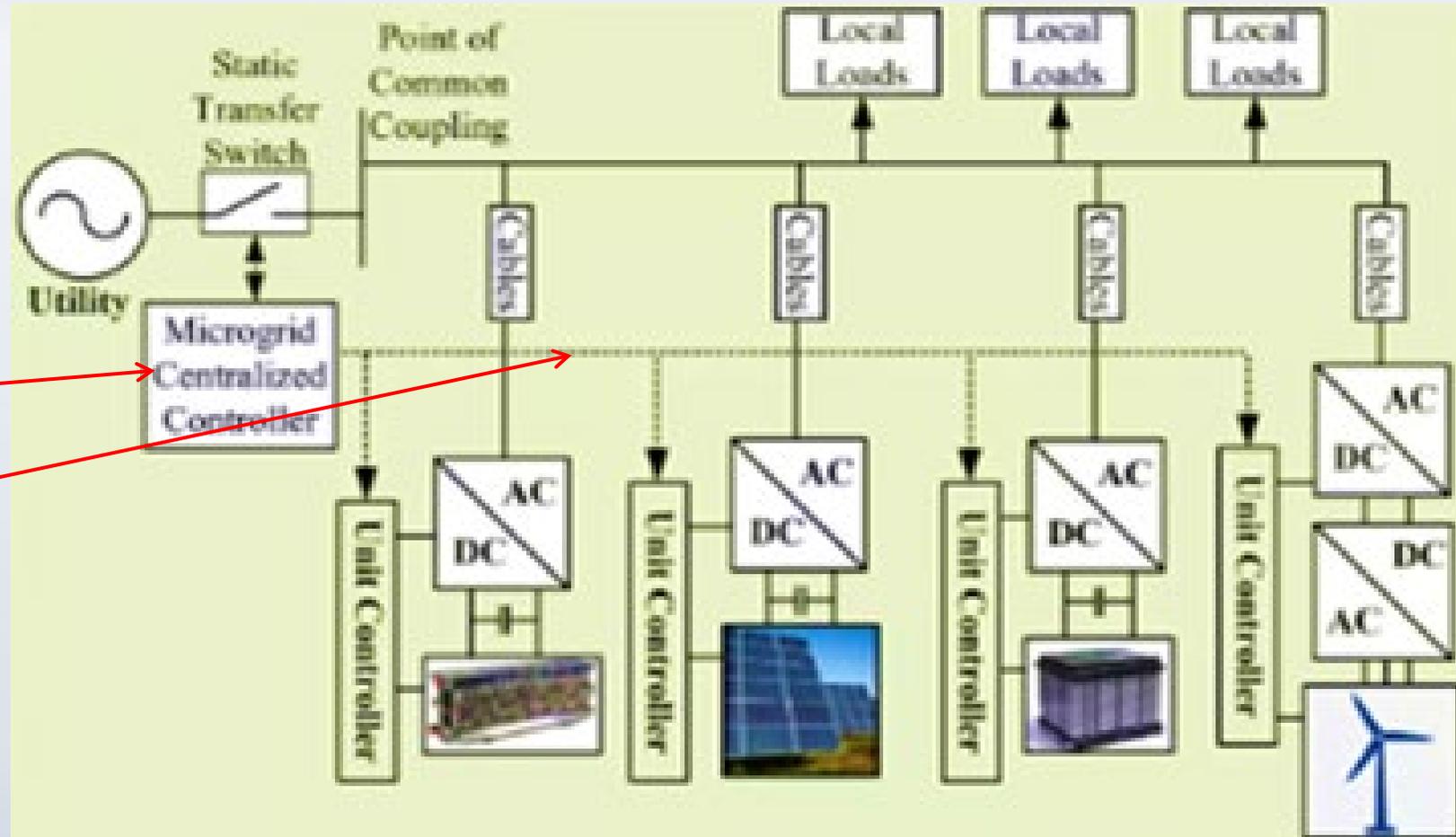
## Introduction

A smart micro-grid is a localized and decentralized energy system that integrates various distributed energy resources (DERs) even including renewable energies, advanced control systems such as:

**Energy Management System (EMS),**

and **communication technologies**

to efficiently generate, distribute, and manage electricity.



# IoT-Based Energy Management in a Laboratory-Scale Smart Microgrid Test Bench



## Introduction

### Research Gap

- Missing link: simulation-based studies  $\leftrightarrow$  real-world implementation.
- Existing test benches: high cost, low flexibility.
- real existing microgrids: limited to monitoring, not closed-loop control.
- Need: modular and IoT-enabled microgrid platform.

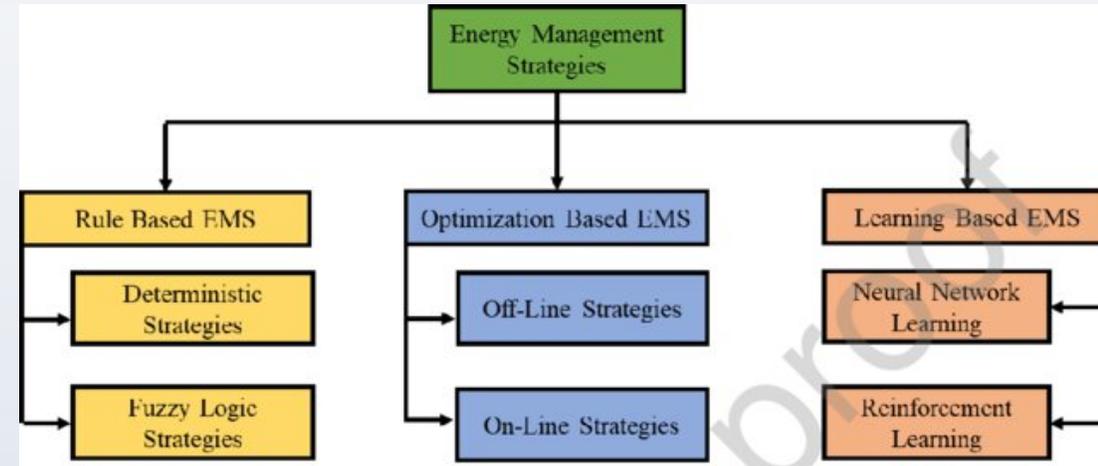


# IoT-Based Energy Management in a Laboratory-Scale Smart Microgrid Test Bench

## Introduction

### Limitations of Current EMS

- Rule-based EMS: Simple but not adaptive under dynamic conditions.
- AI-based EMS: Intelligent but computationally heavy and costly.
- Need: Lightweight, IoT-driven EMS for laboratories scale.



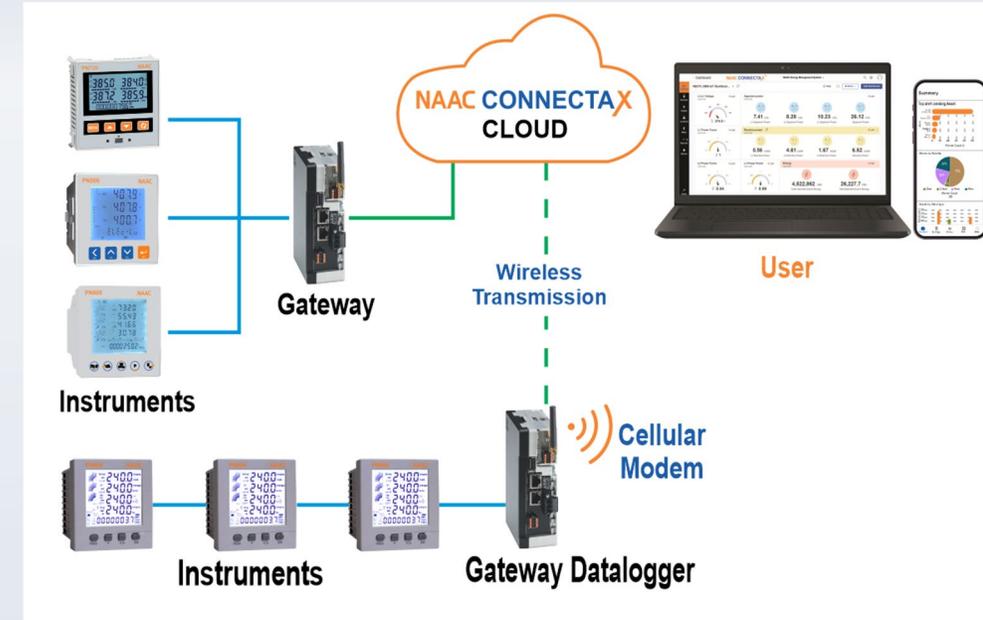
# IoT-Based Energy Management in a Laboratory-Scale Smart Microgrid Test Bench



## Introduction

### IoT Revolution in Energy Systems

- IoT enable real-time data.
- Use Ethernet/Wi-Fi for communication.
- Improve visibility, reduce cost, and support decentralized control.
- Most IoT-based systems: monitoring only — lack adaptive EMS control.



# IoT-Based Energy Management in a Laboratory-Scale Smart Microgrid Test Bench

## Introduction

### Study Objectives & Contributions

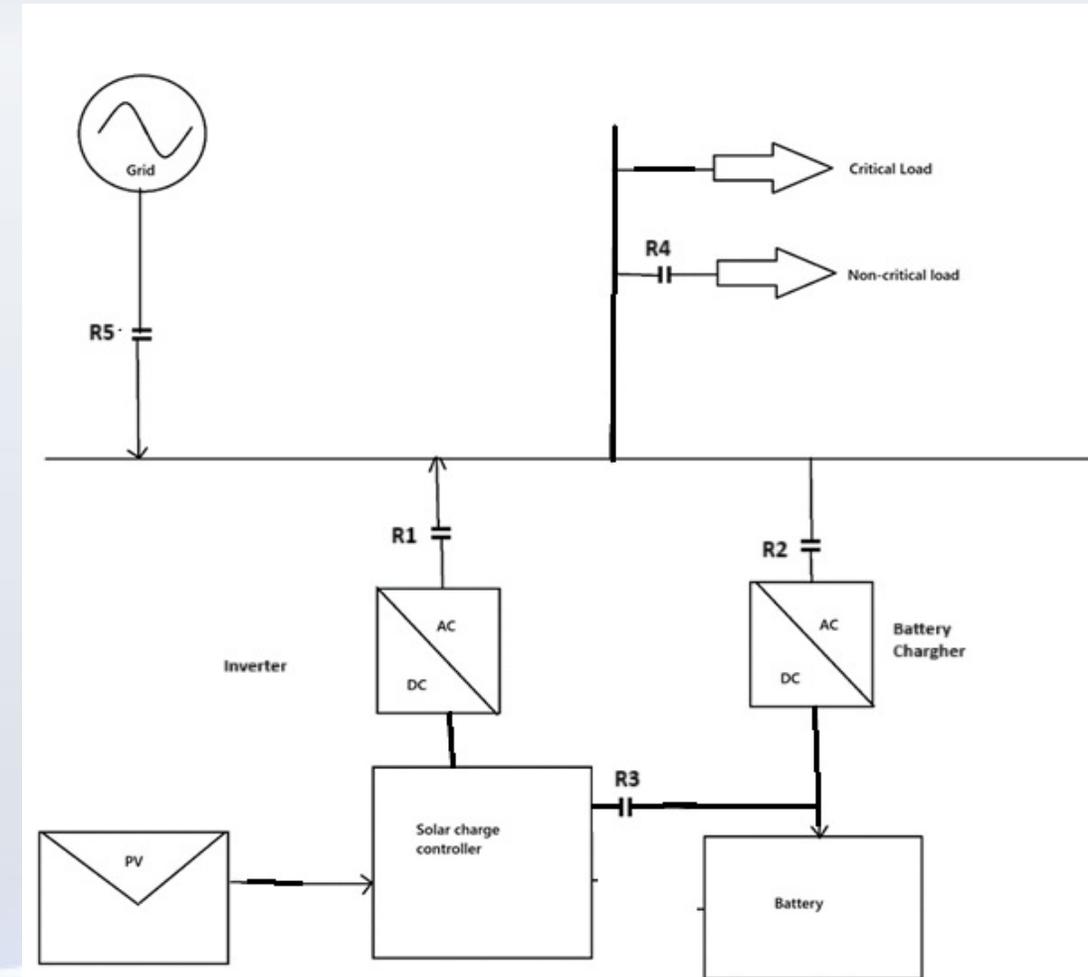
1. Develop hybrid microgrid test bench (PV, battery, grid, genset).
2. Create IoT-based metering (Microcontrollers + Ethernet).
3. Implement intelligent EMS for adaptive management and SoC control.
4. Validate under dynamic modes (renewable-dominant, grid-connected, islanded).



# Test Bench Architecture

## Overview of the Test Bench Structure

- Laboratory-scale hybrid microgrid platform emulates real microgrid behavior.
- Integrates PV generation, battery storage, inverter, and grid connection.
- Includes intelligent control (PLC + Arduino) with IoT-enabled monitoring.
- Supports testing, validation, and academic research applications.

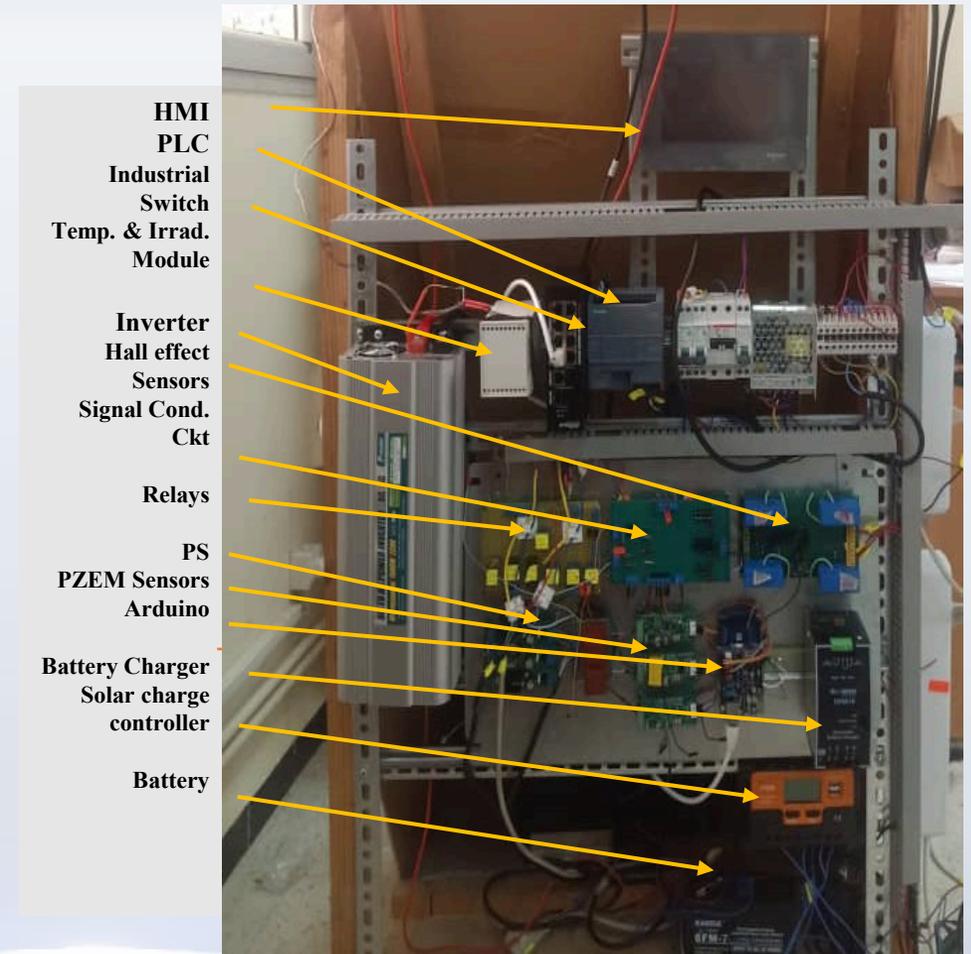


One line diagram of proposed test bench (Microgrid platform)

# Test Bench Architecture

## Main Hardware Components

- ☀️ PV Panel (Monocrystalline): Mounted on wooden frame for solar energy generation.
- 🔋 Battery & Power Conversion Units: Inverter, charger, PWM solar controller.
- ⚡ Contactors/Relays: Enable source switching between PV, battery, and grid.
- 💡 Loads: Include both critical and non-critical types.
  
- All components arranged on modular wooden and plastic frames.
- Clearly labeled wiring and modules ease testing and debugging.
- Power subsystem manages energy routing; control subsystem executes logic.



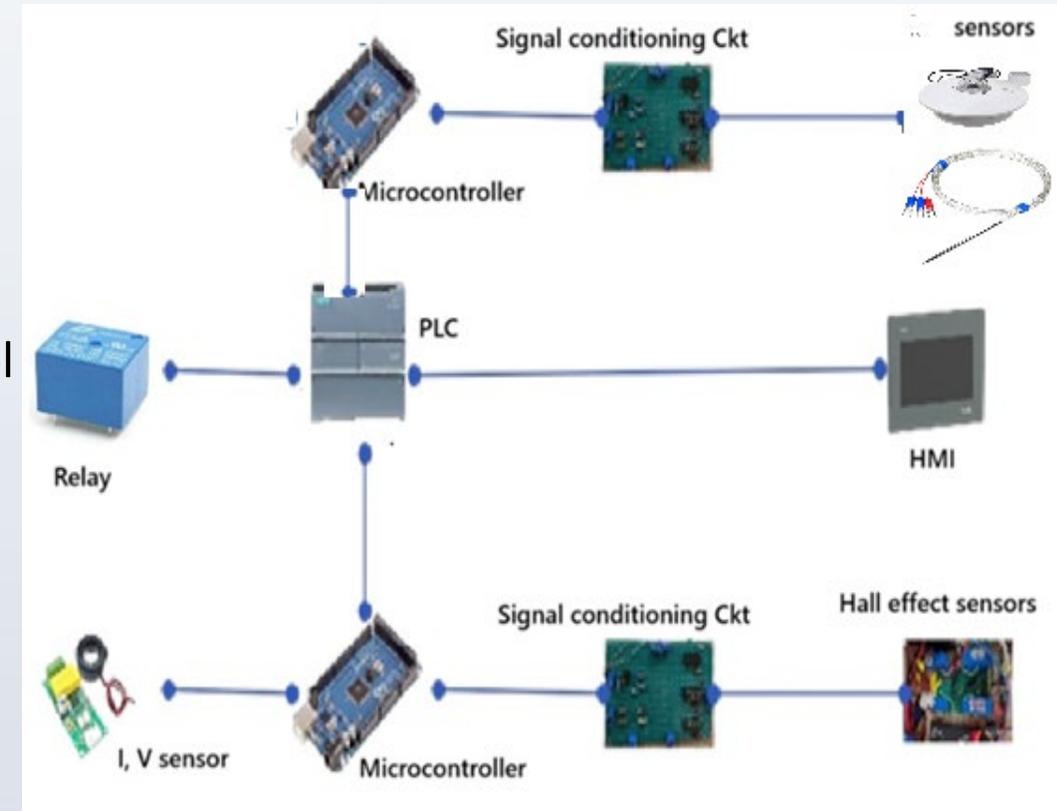
# Test Bench Architecture

## PLC-Based Central Control Unit

- Core of the real-time control system using Programmable Logic Controller (PLC).
- Executes sensor-based control logic and source switching.
- Communicates with the Human-Machine Interface (HMI).
- Schneider Electric Harmony panel used for display and control visualization.

## IoT Data Acquisition Layer

- Arduino Mega + Ethernet Shield handles analog voltage/current measurements.
- Data collected from PV panels, battery, and grid connection.
- Transmits sensor data to PLC using Modbus TCP/IP protocol.
- Enables real-time IoT-based monitoring and closed-loop control.



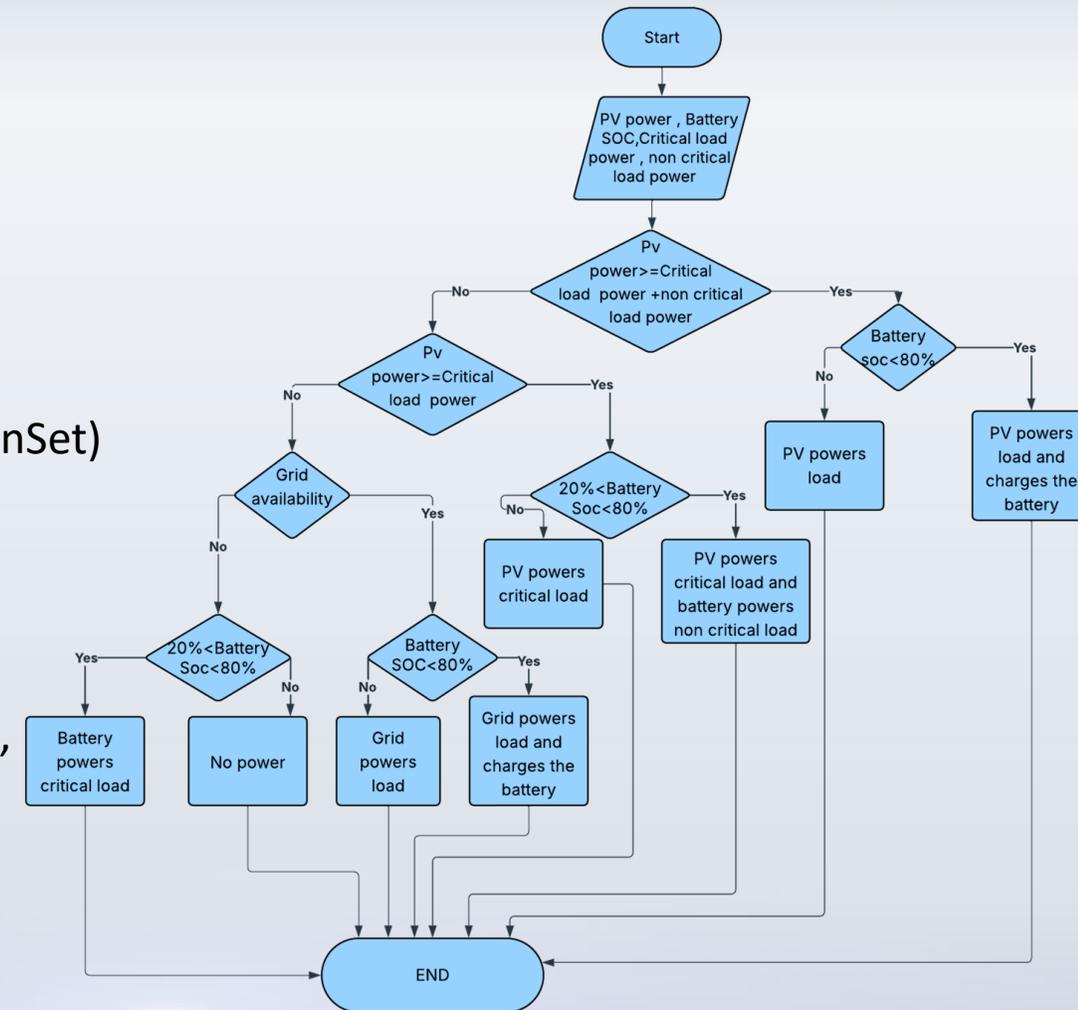
# Energy Management System (EMS)

## Software Design and Logic Flow

- Modular EMS software:
  - Arduino → Data acquisition
  - PLC → Control logic
  - HMI → Monitoring & override
- Control Algorithm: Finite State Machine (PV → Battery → Grid/GenSet)

## PLC Ladder Logic

- Ladder logic blocks: Inputs, Source Evaluation, Mode Selection, Actuation
- Features: Timers, Memory Flags, Fault Handling



Flowchart of Algorithm in the EMS System

# Energy Management System (EMS)



## Real-Time Data Acquisition & Modbus Communication

- Arduino Mega + W5100 Ethernet Shield
- Communication: Modbus TCP/IP (Arduino server → PLC client)

## Real-Time Monitoring & HMI

- PLC displays live parameters via HMI
- Relay mapping logic (Modes 01–07)

Modbus PTR											
	Name	Data type	Offset	Start value	Monitor value	Retain	Accessible f...	Writa...	Visible in ...	Setpoint	Comment
1	Static										
2	data	Array[0..19] ...	0.0				<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>		
3	data[0]	Int	0.0	0	0		<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>		
4	data[1]	Int	2.0	0	0		<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>		
5	data[2]	Int	4.0	0	0		<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>		
6	data[3]	Int	6.0	0	0		<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>		
7	data[4]	Int	8.0	0	0		<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>		
8	data[5]	Int	10.0	0	0		<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>		
9	data[6]	Int	12.0	0	0		<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>		
10	data[7]	Int	14.0	0	0		<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>		
11	data[8]	Int	16.0	0	0		<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>		
12	data[9]	Int	18.0	0	0		<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>		
13	data[10]	Int	20.0	0	2393		<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>		
14	data[11]	Int	22.0	0	3		<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>		
15	data[12]	Int	24.0	0	50		<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>		
16	data[13]	Int	26.0	0	499		<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>		
17	data[14]	Int	28.0	0	6		<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>		
18	data[15]	Int	30.0	0	21		<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>		
19	data[16]	Int	32.0	0	1700		<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>		
20	data[17]	Int	34.0	0	120		<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>		
21	data[18]	Int	36.0	0	1646		<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>		
22	data[19]	Int	38.0	0	-1700		<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>		

Received Scaled Data

Modbus PTR	Value
MIDB3.DBX0.0	0.0
*Modbus PTR	0.0
data	0.0
data	0.0
Voltage_AC1	0.0
Current_AC1	0.0
Power_AC1	0.0
Freq_AC1	0.0
PF_AC1	0.0
Voltage_AC2	0.0
Current_AC2	0.0
Power_AC2	0.0
Freq_AC2	0.0
PF_AC2	0.0
Voltage_PV	17.0
Current_PV	12.0
Voltage_Batt	16.46
Current_Batt	17.0
discharge_current	-17.0
grid_voltage	239.2
grid_current	0.03
grid_power	0.4
	49.9

Reliable, adaptive, and cost-effective EMS

Real-Time Monitoring in PLC via Modbus TCP/IP

# Functional Testing Scenarios and Validation

## Testing Objectives

- Validate EMS real-time adaptability and reliability.
- Observe source selection, relay activation, and HMI feedback.
- Assess efficiency, response time, and robustness under dynamic conditions.

Component	PLC Output Signal	Functionality
Relay 1	Q0.0	Inverter connection
Relay 2	Q0.1	Battery charger activation
Relay 3	Q0.2	Battery connection
Relay 4	Q0.3	Non-critical load supply
Relay 5	Q0.4	Grid connection

## PLC Signal Assignment and Component Functionality

## Sample Test Scenarios

- Relay mapping to PLC outputs for inverter, charger, and battery control.
- Four test cases (TC1-TC4) validated EMS expected vs observed results.

Test Case	Initial Conditions	Expected Behavior	Observed Result	Status
TC1	PV ON, SOC High, Grid ON	Use PV for all loads, charge battery	Matched expected	Pass
TC2	PV OFF, SOC Medium, Grid ON	Battery supplies critical, grid supports non-critical	Matched expected	Pass
TC3	PV OFF, SOC Low, Grid OFF	System enters shutdown (Mode 08)	System shut down	Pass
TC4	PV ON, SOC Full, Grid ON	Use PV for loads only, stop charging	Correctly managed	Pass

## Sample Test Scenarios and Observations

# Functional Testing Scenarios and Validation



## EMS Operating Modes (01–07)

Mode 01: PV powers all loads.

Mode 02: PV charges battery and powers loads.

Mode 03: PV supplies critical load; battery powers non-critical load.

Mode 04: PV supplies only critical load.

Mode 05: Battery supplies both loads (PV unavailable),

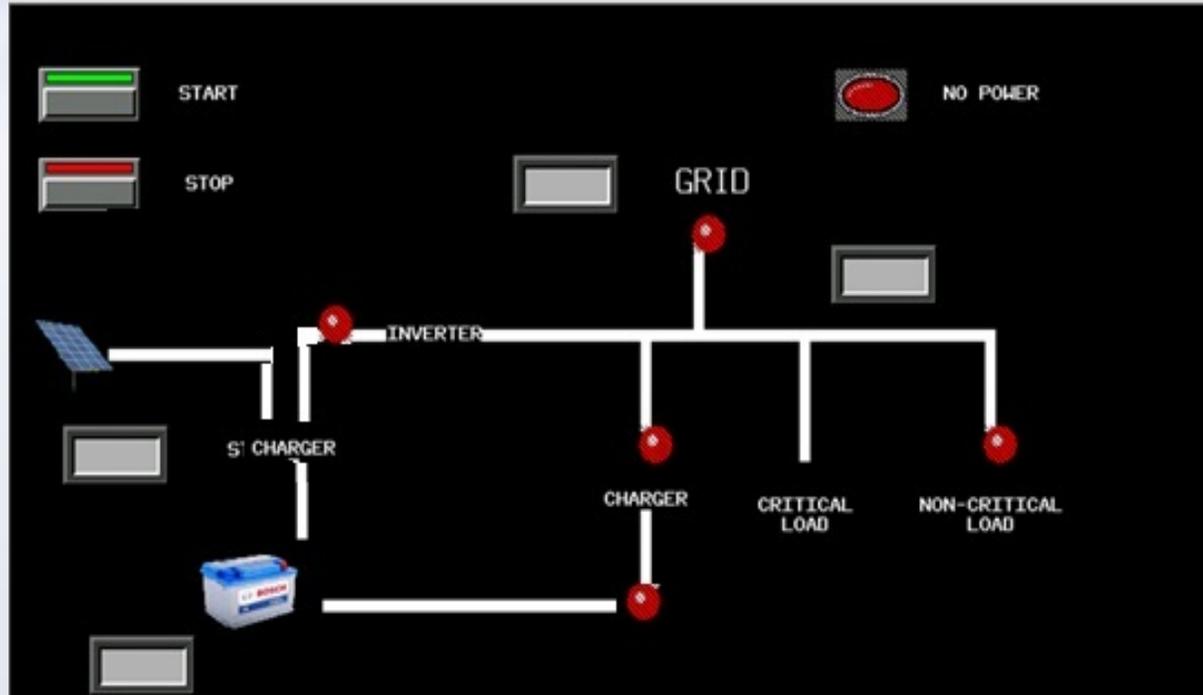
Mode 06: Grid powers both loads and charges the battery (PV unavailable, battery SoC low),

Mode 07: Battery/Grid or safe shutdown modes.

Mode	Relay 1 (Q0.0)	Relay 2 (Q0.1)	Relay 3 (Q0.2)	Relay 4 (Q0.3)	Relay 5 (Q0.4)
Mode 01	X			X	
Mode 02	X	X		X	
Mode 03	X		X		
Mode 04	X		X		
Mode 05			X	X	
Mode 06		X	X	X	X
Mode 07					

Relay Activation in Different EMS Modes

# Functional Testing Scenarios and Validation



HMI Front Panel

	Name	Data Type	Data Source	Scan Group	Device Address	Alarm Group	Logging Group
1	BATTERY	BOOL	External	S71200CPU1212...	Q0.2	Disabled	None
2	BATTERY_VOLTAGE	REAL	External	S71200CPU1212...	DB4.DBW88	Disabled	None
3	CHARGER	BOOL	External	S71200CPU1212...	Q0.1	Disabled	None
4	GRID	BOOL	External	S71200CPU1212...	Q0.4	Disabled	None
5	GRID_POWER	REAL	External	S71200CPU1212...	DB4.DBW108	Disabled	None
6	LINE_POWER	REAL	External	S71200CPU1212...	DB4.DBW48	Disabled	None
7	NO_POWER	BOOL	External	S71200CPU1212...	M0.2	Disabled	None
8	NONCRITICAL	BOOL	External	S71200CPU1212...	Q0.3	Disabled	None
9	ON_OFF	BOOL	External	S71200CPU1212...	M0.0	Disabled	None
10	PV_PANAL	BOOL	External	S71200CPU1212...	Q0.0	Disabled	None
11	PV_POWER	REAL	External	S71200CPU1212...	MW0	Disabled	None
12	satrt	BOOL	External	S71200CPU1212...	DB5.DBX0.0	Disabled	None
13	stop	BOOL	External	S71200CPU1212...	DB5.DBX0.1	Disabled	None

HMI Configuration

## HMI Visualization and Monitoring

- ✓ Developed using Schneider HMIGXU3512 in Vijeo Designer.
- ✓ Displays PV power, SoC, load status, and relay states.
- ✓ Manual override and reset buttons included.

# Functional Testing Scenarios and Validation

## Performance Evaluation Metrics

- Efficiency improvements via smart source prioritization.
- Response time and control accuracy measured.
- System robustness tested under variable conditions.

## Response Time and Measurement Accuracy

- ✓ Control latency: 1.2–2.0 seconds; Data refresh rate: 1 Hz.
- ✓ Measurement accuracy >98% across voltage and current channels.

Parameter	Measured Value	Reference Value	Accuracy (%)
PV Voltage	11.8 V	12.0 V	99.0%
Battery Current	1.92 A	2.00 A	98.4%
Grid Voltage	226.5 V	230.0 V	98.5%

The accuracy of analog voltage and current measurements

# Functional Testing Scenarios and Validation

## System Robustness and Reliability

- ✓ Stable transitions between PV, battery, and grid with no downtime.
- ✓ Automatic fault detection and load shedding logic.
- ✓ Modbus TCP/IP communication stable for 8-hour continuous test.

Performance Metric	Outcome
Energy efficiency	15–20% grid energy reduction
System response time	~1.2–2.0 seconds
Measurement accuracy	>98% for all electrical parameters
Communication reliability	100% uptime during long test
Fault handling & recovery	Fully autonomous



## Achievements

- Developed and validated a smart microgrid test bench integrating:
  - ✓ PV generation, battery storage, grid/GenSet backup
  - ✓ IoT-based metering using Arduino and Ethernet Shield
  - ✓ Intelligent EMS for adaptive source management and load prioritization
- Demonstrated real-time, reliable, and efficient performance in both grid-connected and islanded modes
- Validated as a cost-effective, scalable solution for academic and research use

# Conclusion



## Academic and Research Impact

- ✓ Serves as a hands-on educational platform for students and researchers
- ✓ Enables simulation-to-reality bridging in smart grid training
- ✓ Facilitates testing of adaptive EMS and IoT control algorithms
- ✓ Affordable and modular design suitable for scalable lab applications



## Future Enhancements

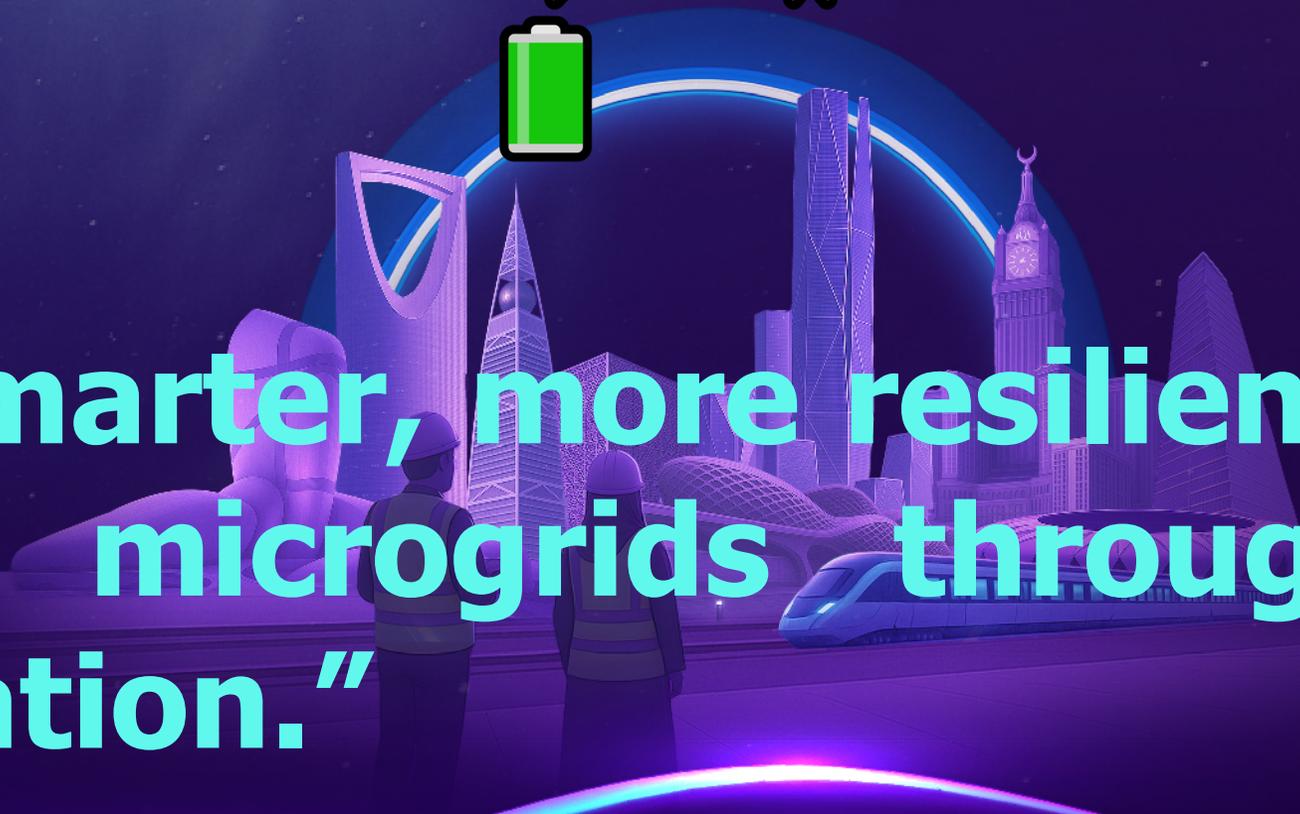
- ✓ 🔍 Predictive Control: Integration of forecasting and AI-based algorithms
- ✓ 🛡️ Cybersecurity: Strengthening data and network protection in IoT-based EMS
- ✓ 🌐 Large scale: Expanding system to multi-microgrid or distributed energy management
- ✓ ⚙️ Enhanced Automation: Improved load scheduling and fault detection



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“A step toward smarter, more resilient, and sustainable microgrids through IoT-driven innovation.”



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