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Design of an intelligent system for controlling and balancing renewable energy flows in an autonomous micro-grid

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Abstract. Pooling different renewable energy sources (hydrogen, solar, wind, geothermal, etc.) enables developing a standalone energy micro-grid. The energy flows from these various sources are neither constant nor equivalent. Therefore, control and balancing mechanisms should be established for optimal energy utilization through an intelligent system based on interconnected microcontrollers networked with sensors. Our contribution addresses this issue by proposing an original architecture of an intelligent and distributed control system based on a sensor network and a strategy to share the electric power through the micro-grid. In our work we consider a micro-grid powered by sources of wind turbine, pv panels and battery which energy flows are controlled and balanced through our system depending on power demand of the loads. Alternating Current (AC) bus and Direct Current (DC) bus are tied together by an inverter. A set of microcontroller-sensor-actuators (*which we named S.A.D for Sensor/Actuator Device*) are deployed at strategic points in the micro-grid providing constantly data from power generated and consumed, equipment health and status. A control algorithm developed in relation to a network control strategy is implemented by combining the performance different microcontroller boards. Relying on existing literature works, a review of solution approaches to the challenging problem, of the power flows balancing between the different energy sources and storage batteries embedding appropriate IoT technologies and exploiting energy big-data platforms, is presented.

Keywords: Micro-grid, sensor network, flow balancing, microcontroller, intelligent system, IoT, 5G

Introduction

Renewable energy micro-grids have proven to be an excellent alternative in terms of meeting energy needs around the world and especially in Africa where the traditional grid is showing its limits in providing electricity [1], especially in hard-to-reach areas [2],[3].

Depending of energy needs [4], different architectures are implemented [5] taking into account the available renewables energies.

Depending on the context, some micro-grids are deployed by pooling available energy sources. These micro-grids consisting of various types of the micro-generators as distributed generator [6] (wind turbine, photovoltaic (PV) array, fuel cells, diesel generator, and wave generator, CHP,…), [7] local storage elements (flywheel, energy capacitors and batteries) and loads. Storage devices play a key role in micro-grid control, reliability and stability.

So, with these different types of energy sources, the micro-grid architecture consists in an alternating current (hybrid AC) micro-grid with a direct current (DC) micro-grid, tied together by a bidirectional AC/DC converter [8]. Distributed generators can be connected to the AC or to the DC feeder. This architecture combines the advantages of the AC and DC micro-grid.

Since, the energy flows from these various sources are neither constant nor equivalent. control and balancing mechanisms [9], [10], [11] should be established for optimal energy utilization through an intelligent system based on interconnected microcontrollers [12] networked with sensors [13].

Our work was carried out on a micro-grid installed in a peripheral area of Lomé in Togo (West Africa), in a district where wind and sun conditions favor the production of wind and solar energy.

The contributions in our work are as follows: (1) Design of an improved system architecture for controlling and balancing energy flows. (2) Development of a strategy for controlling and balancing energy flows. (3) Development and implementation of a responsive, intelligent algorithm embedded on microcontrollers installed at strategic locations in the micro-grid. (4) Connection of the system to an IoT platform via 5G network to monitor, analyze, and process new data resulting from the algorithm's implementation.

Related work

Recent work in micro-grid focused on the management of various renewable energies sources. Giorgio Graditi et al. [14] developed a heuristic-based formulation of shiftable loads; Amin et al. [15] formulated a model predictive control; Lei Zhang et al. [16] projected two-scale dynamic programming strategy and subsequently Ashabani et al. [17] proposed nonlinear control for energy management in micro-grid. In [18], Jinsung Byun et al. envisioned intelligent cloud home energy management system (iCHEMS), in which the appliances shedding is fared in accordance with the assigned priority considering the renewable energy capacity.

K. Venkatraman et al. [19] developed a micro-grid controller integrating the output from multiple types of renewable energy conversion systems, namely, wind and solar along with diesel generator as well as battery storage with source and load control features using Field Programmable Gate Arrays.

Another renewables energies sources system energy management is done by using PI controller in [20], [21],[22],[23]. Somnath Das et al. in [10], implemented a control strategy with fuzzy logic controller for smoothing of the power fluctuation and at the same time to maintain the battery state of charge with in allowable limits.

Betha et al. [24] combined an autonomous PV and a wind turbine using a DC bus, and the generated output power from the system is fed to all connected loads, while the extra power is injected into the electric grid.

Hajizadeh and Aliakbar Golkar [25] introduced an approach for active power sharing in a hybrid fuel cell/battery power source in order to improve the system’s efficiency and battery’s lifetime with an acceptable load.

Elmouatamind et al. [26] introduced a micro-grid system platform for efficient integration and management of renewable energy sources and storage devices.

Hangaragi [27] proposed a hybrid PV–wind system, which provides a sophisticated integration of the wind turbine and solar PV, in order to extract the optimum energy from the two sources, PV and wind.

In [28] a microcontroller network is implemented, interconnected to micro-grid sources. In this architecture, microcontrollers are connected to key elements of the micro-grid: collectors, energy storage devices and the energy management system among others.

These microcontrollers are the entry point to the sensor network. They are responsible for collecting the data and information produced at the level of the sensors, and for sending them via a VPN (Virtual Private Network) connection to the gateways. The latter proceed to transfer the data after the authentication and authorization procedures. These data, which are encrypted, are then conveyed to the heart of the sensor network for analysis and exploitation.

In our work, we used the performance of microcontroller boards, arduino and raspberry in order not only to make the system for controlling and balancing energy flows more efficient but also in case of addition of new components in the network and implementation of algorithms in arduino and python programming language for a dialogue between the platform and the cloud.

Micro-grid architecture

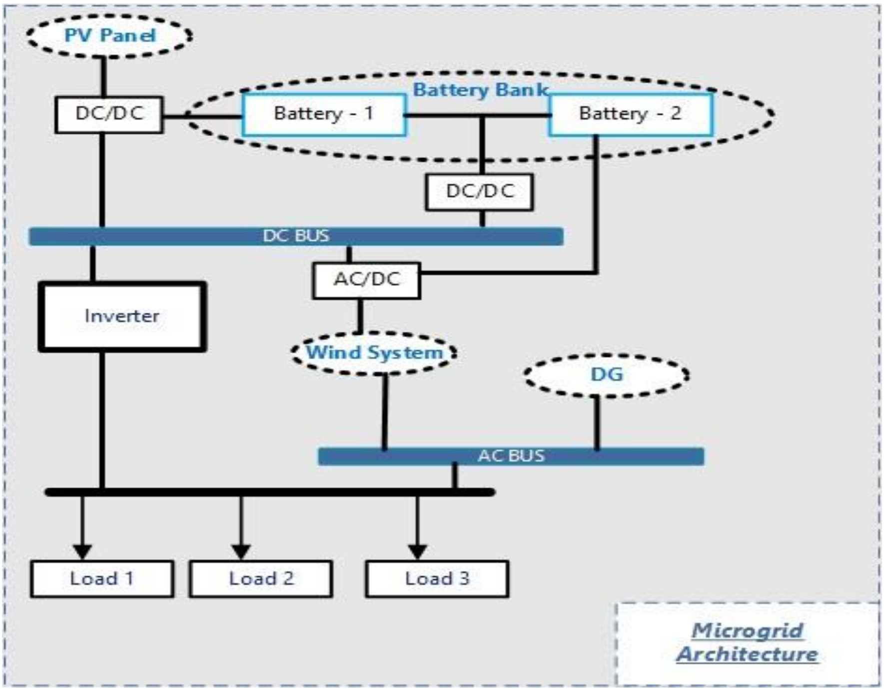

Figure 1. Micro-grid architecture

The micro-grid, subject of our study pools four energy sources. The priorities come from solar panels and wind turbines. The energy generated by these two sources is each stored in a specific battery. The two batteries, combined constitute a battery bank which is the third source of energy. This source is used in the event of a shortfall in solar and wind power generation. The fourth source of energy which is used upon in the ultimate event is the diesel generator. The architecture of the micro-grid is shown in Figure 1. The energy sources of this micro-grid are used to meet the needs of three different loads.

Proposed system and strategy

The proposed system interconnects with the existing micro-grid through specific nodes that we named S.A.D (for Sensor / Actuator Device). It is nothing more than a set of sensors and actuators linked to a microcontroller.

The S.A.D are placed in specific places depending on what we want to monitor and control. The S.A.D. are linked to a control and management center thus forming a network of microcontrollers. This control center is connected to the cloud to which it sends data for monitoring needs and which is also stored in a database which is analyzed for future uses.

A. Proposed architecture

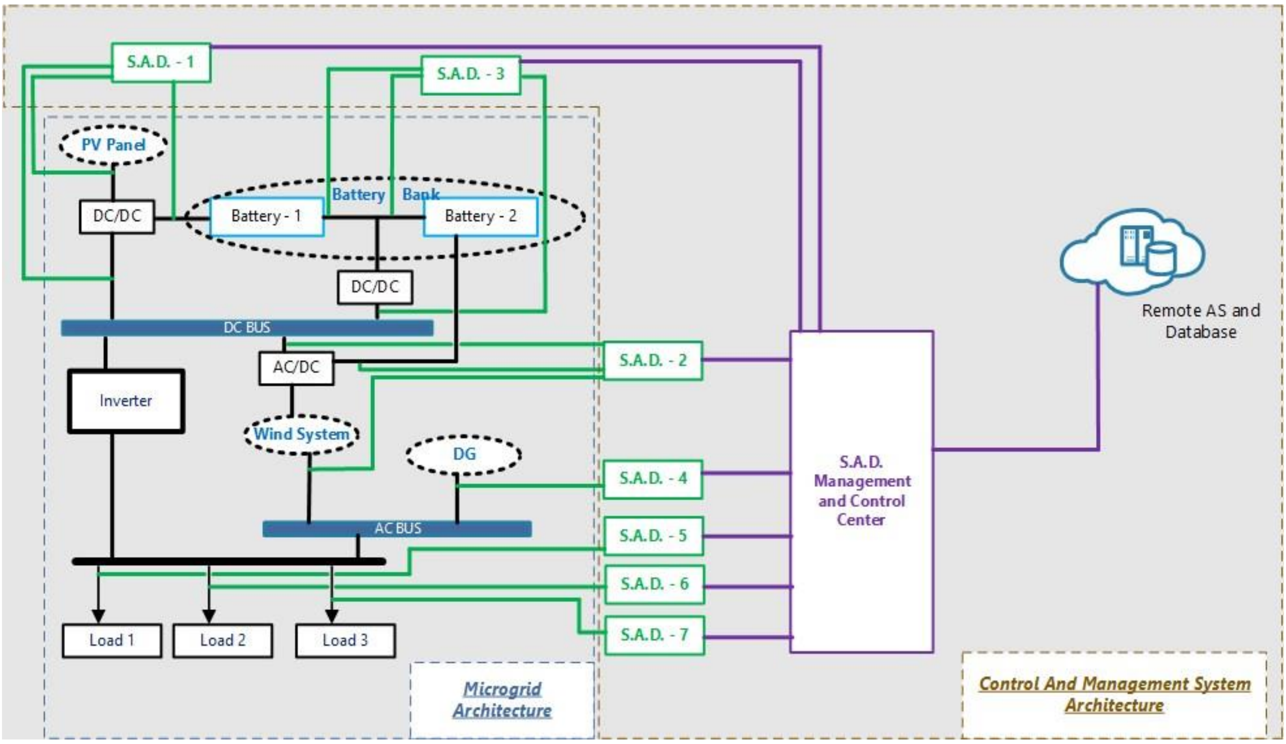

Figure 2. Control and management system architecture

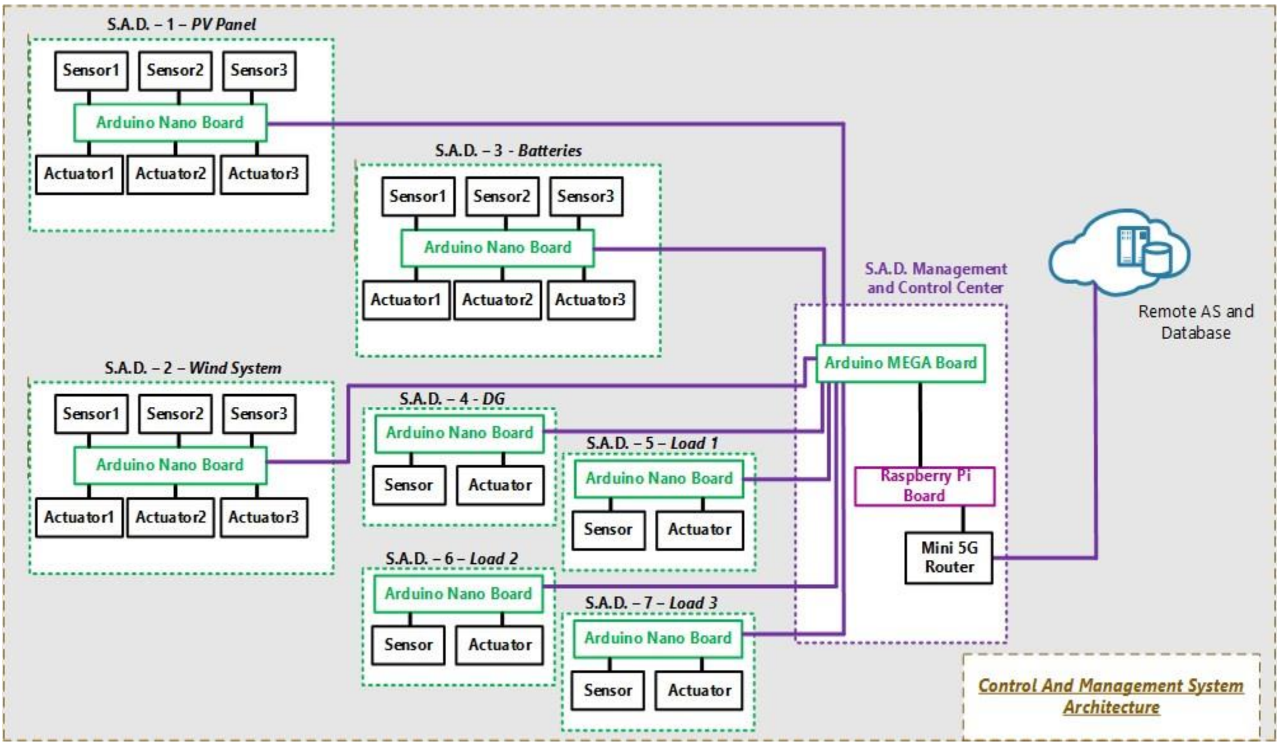

Figure 3. Control and management system architecture details

Figure 2. shows us the general architecture of the micro-grid connected to the network of microcontrollers formed by the S.A.D.. Thus presenting the architecture of the control and management system of energy flows.

The Sensor / Actuator association for each S.A.D depends on the source or the load to be controlled; therefore varying the number of elements to be connected to the microcontroller as shown in Figure 3.

The microcontroller network as well as the control strategy are shown in the following sections.

B. Microcontroller network

1. Sensor / Actuator Device (S.A.D.)

Figure 4 is an internal image of the S.A.D showing the connections of the microcontroller to the sensors on the one hand and to the actuators on the other hand.

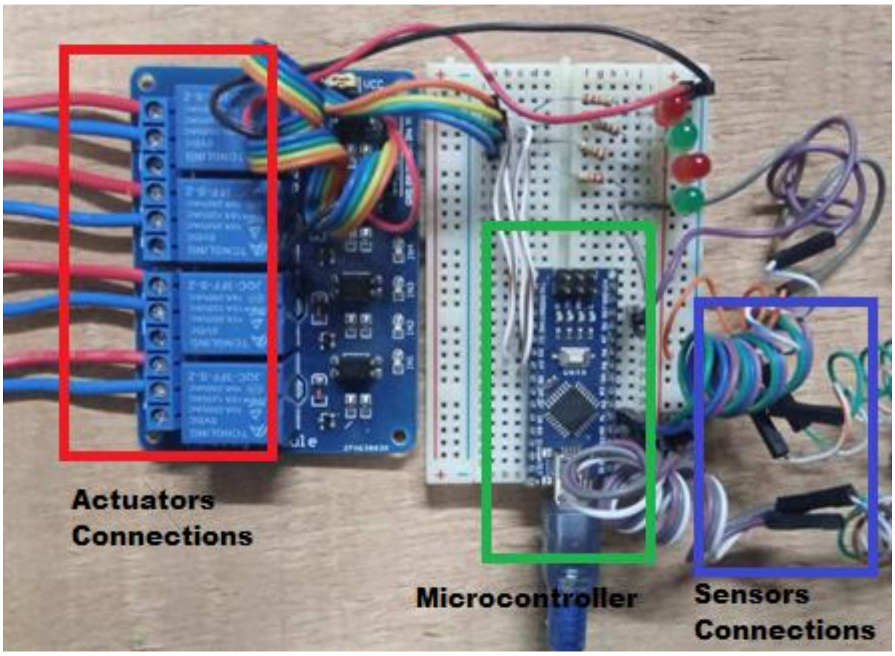

Figure 4. Sensor / Actuator Device

Each S.A.D in the network has a specific role to play depending on its location in the network. Table 1 summarizes the roles of each sensor and actuator of each S.A.D.

Table 1. S.A.D roles in the network

N° S.A.D	Source / Load	Sensor / Actuator	Roles
1	PV Pannel	Sensor 1	Sense power from PV pannel
		Sensor 2	Sense voltage and current between DC/DC converter and DC Bus
		Sensor 3	Sense voltage and current between DC/DC converter and Battery 1
		Actuator 1	Control link between PV panel and DC/DC converter
		Actuator 2	Control link between DC/DC converter and AC Bus

		Actuator 3	Control link between DC/DC converter and Battery 1
2	Wind Turbine	Sensor 1	Sense power from Wind turbine
		Sensor 2	Sense voltage and current between AC/DC converter and DC Bus
		Sensor 3	Sense voltage and current between AC/DC converter and Battery 2
		Actuator 1	Control link between Wind turbine and AC Bus
		Actuator 2	Control link between AC/DC converter and DC Bus
		Actuator 3	Control link between AC/DC converter and Battery 2
3	Battery	Sensor 1	Sense voltage and current from Battery 1
		Sensor 2	Sense voltage and current from Battery 2
		Sensor 3	Sense voltage and current between DC/DC converter and DC Bus
		Actuator 1	Control flow from Battery 1 to battery bank
		Actuator 2	Control flow from Battery 2 to battery bank
		Actuator 3	Control link between DC/DC converter and DC Bus
4	Diesel Generator	Sensor	Sense power from Diesel Generator
		Actuator	Control link between Diesel Generator and AC Bus
5	Load 1	Sensor	Sense Load 1 voltage and current
		Actuator	Switch ON/OFF Load 1
6	Load 2	Sensor	Sense Load 2 voltage and current
		Actuator	Switch ON/OFF Load 2
7	Load 3	Sensor	Sense Load 3 voltage and current
		Actuator	Switch ON/OFF Load 3

2. S.A.D. Management and Control Center

The S.A.D. Management and Control Center consists of an Arduino MEGA board to which all the S.A.D. of the network are connected. It exchanges data with the raspberry board which is connected to the cloud through a 5G mini router as shown in Figure 5.

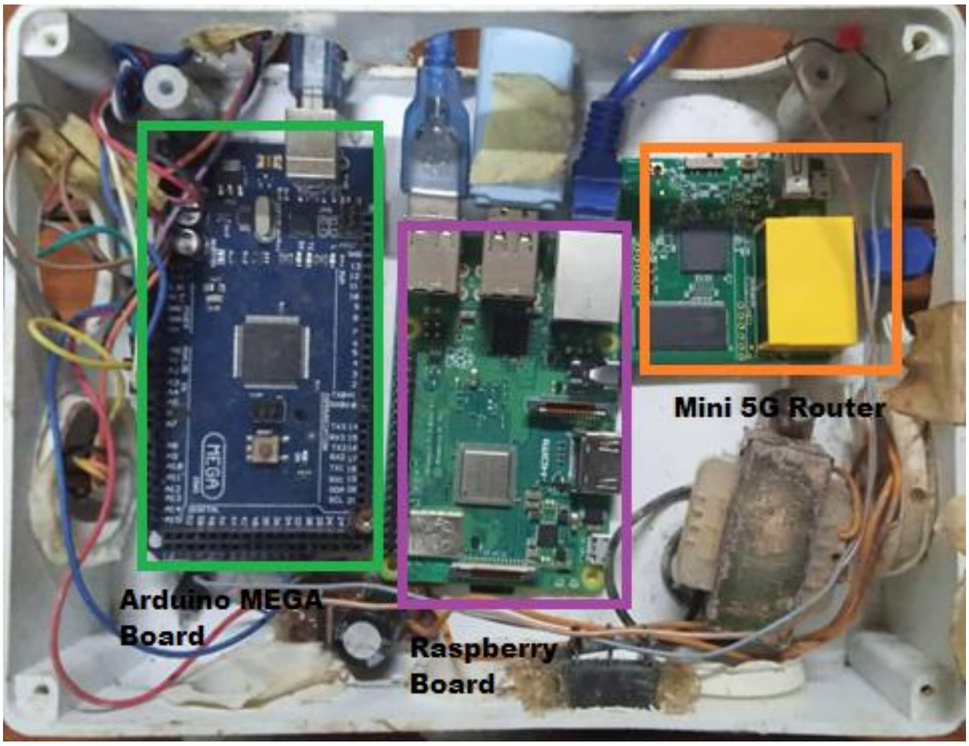

Figure 5. S.A.D. Management and Control Center

C. Flows control strategy

The S.A.D senses the flows generated and calculates the powers of energy supplied by the sources on the one hand, and the powers of energy required by the loads on the other hand.

These data are the inputs for the strategy of control and balancing of energy flows in the micro-grid.

The strategy is summarized as follows:

First, the powers generated by the sources and calculated are compared to the powers of the loads:

P_{solar} : PV pannel power

P_{wind} : Wind power

P_{DG} : Diesel Generator power

P_{S-W} : Solar and Wind total generated power

The voltage at the output of the battery bank is also taken into account.

V_{bat} : Battery Bank Voltage

$V_{bat-min}$: Minimum Battery Bank Voltage

$V_{bat-max}$: Maximum Battery Bank Voltage

In principle, the power of each load is taken into account the total power is then calculated.

P_{L1} : Load 1 power

P_{L2} : Load 2 power

P_{L3} : Load 3 power

P_L : Loads Total power

At the initial state, powers are computed as follows:

$$P_L = P_{L1} + P_{L2} + P_{L3}$$

$$P_{S\text{-}W} = P_{solar} + P_{wind}$$

For the control flow balancing:

If $P_L > P_{S\text{-}W}$ then Check V_{bat}

If $V_{bat} > V_{bat\text{-}min}$ then switch ON link between DC/DC converter and DC Bus

If still $P_L > P_{S\text{-}W}$ and $V_{bat} = V_{bat\text{-}min}$ then switch OFF link between DC/DC converter and DC Bus and switch ON DG

If $P_L \geq P_{DG}$ then switch OFF Load 3

If still $P_L \geq P_{DG}$ then switch OFF Load 2

If P_{solar} available and $V_{bat} \leq V_{bat\text{-}min}$ then swith ON link between DC/DC converter and Battery1

If still $V_{bat} \leq V_{bat\text{-}min}$ then check P_{wind}

If P_{wind} available and $V_{bat} \leq V_{bat\text{-}min}$ then swith ON link between AC/DC converter and Battery2

If $V_{bat} > V_{bat\text{-}min}$ and $V_{bat} \leq V_{bat\text{-}min}$ then swith OFF link between DC/DC converter and Battery1 and swith OFF link between AC/DC converter and Battery 2

If $P_L < P_{S\text{-}W}$ then switch OFF DG switch OFF Load 2 and OFF Load 3

This strategy is translated into an algorithm and implemented in a python script that runs on the raspberry board and arduino code on arduino board. The information is displayed on a monitoring interface accessible via the cloud.

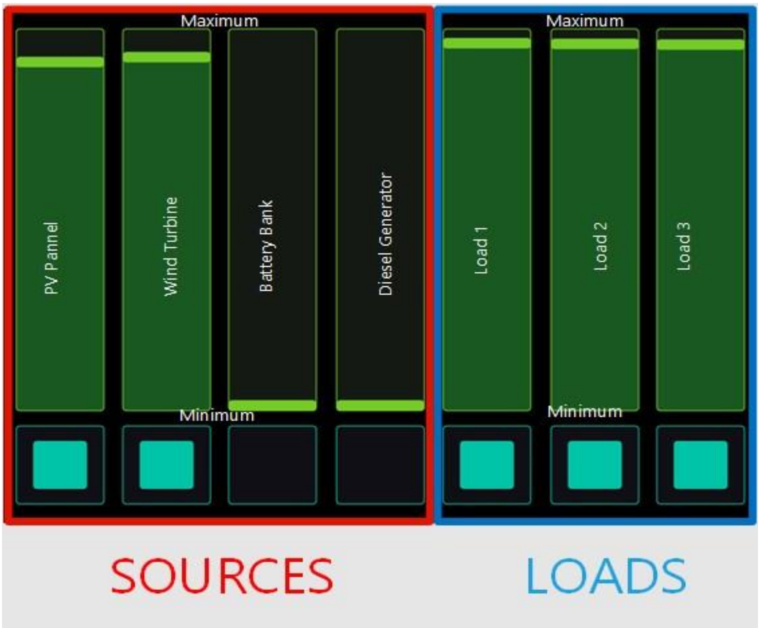

Figure 6. Monitoring Screen

On this screnn, P_{solar} and P_{wind} are at maximum of power. In this case, the generated power $P_{S\text{-}W}$ can easily supply all of loads (Load 1, Load 2 and Load 3). So, Battery bank and Diesel Generator are not used.

Simulations and results

Table 2. Sources informations

N°	Sources	Values (Voltage – Current – Power)
1	PV Pannel	137 V - 5 A - 685 W
2	Wind Turbine	126 V - 14.5 A -1827 W
3	Battery	124 V - 3 A
4	Diesel Generator	240 - 3.5 A - 840 W

A. Case 1: Wind Turbine OFF

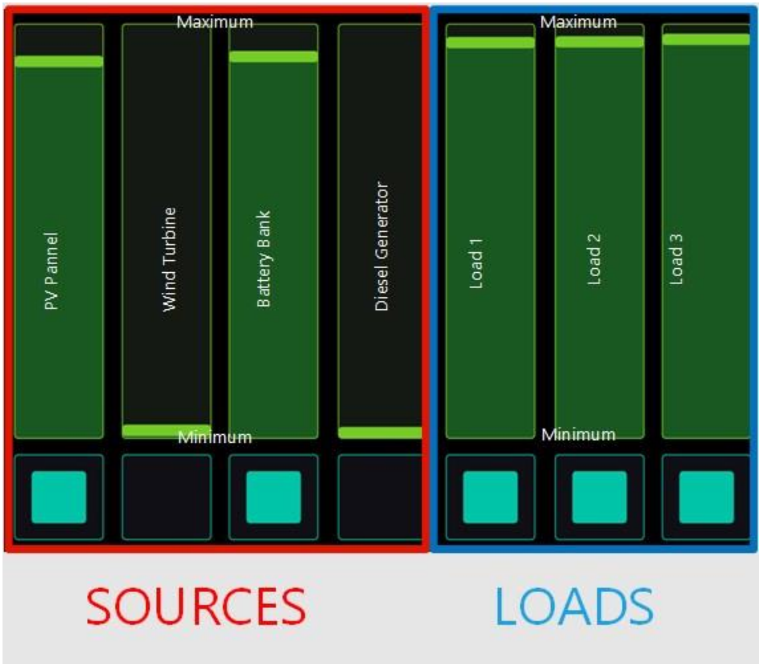

Figure 7. Monitoring Screen with PV panel Source and battery bank ON

The power generated is not sufficient to supply the loads, the battery bank is then used.

B. Case 2: PV pannel OFF

In this case, Wind turbine and PV panel are OFF and Battery voltage is not enough, so we swith ON Diesel Generator.

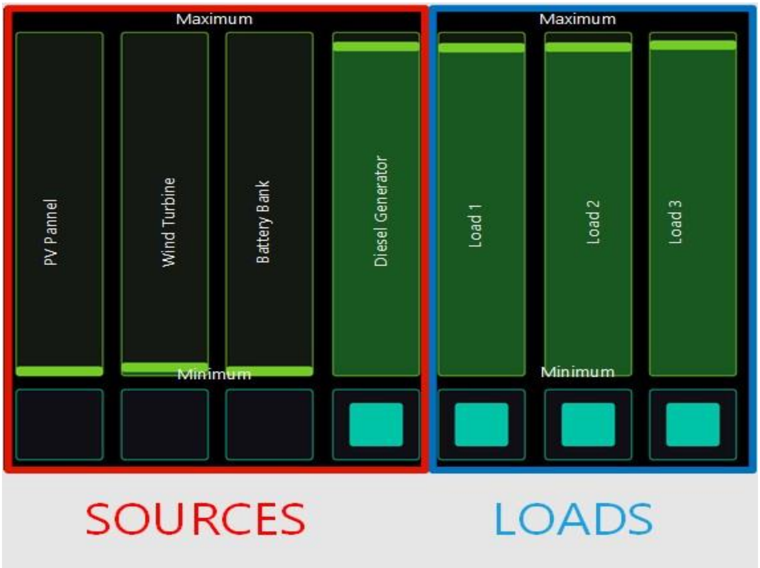

Figure 8. Monitoring Screen with DG ON and all loads ON

C. Case 3: Diesel Generator ON

With the DG being ON if the power generated does not cover the loads, we switch Load 3 OFF (Figure 9.) and if it is still not sufficient, we switch Load 2 off (Figure 10)

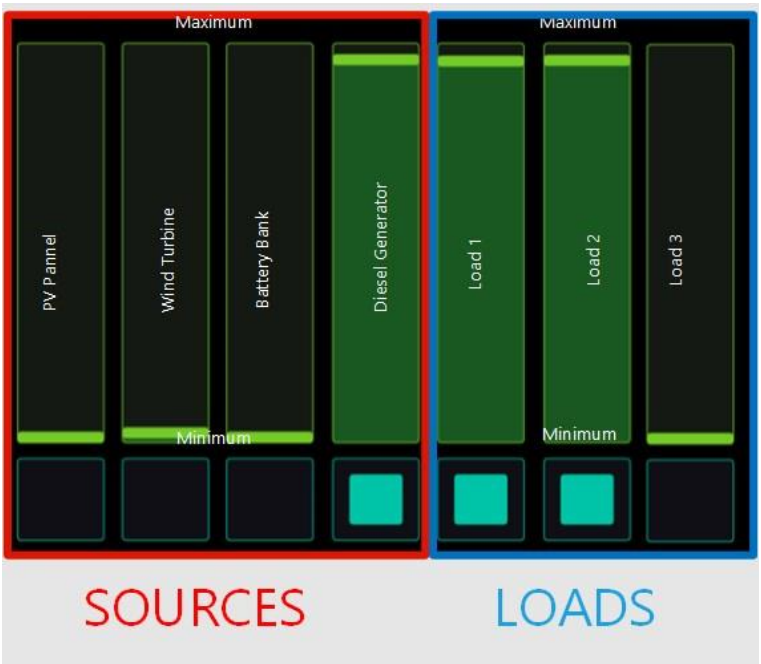

Figure 9. Monitoring Screen with DG ON and Load 3 OFF

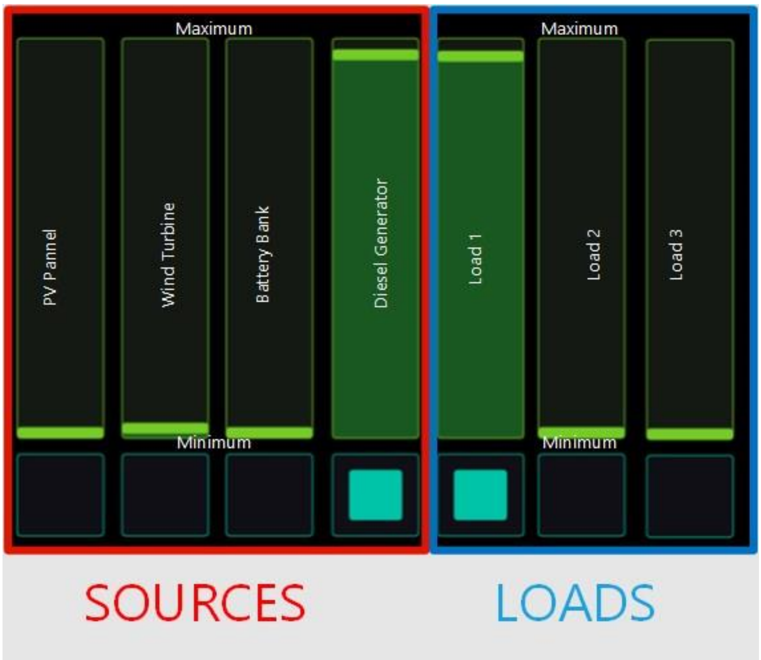

Figure 10. Monitoring Screen with DG ON and Load 2 and Load 3 OFF

Conclusion

In our work, we designed a microcontroller architecture interconnected to the renewable energy micro-grid.

A strategy is then implemented for the control and balancing of energy flows in the micro-grid.

The set of microcontroller-sensor-actuators (*S.A.D*) are deployed at strategic points in the micro-grid providing constantly data from power generated and consumed, equipment health and status.

The arduino and raspberry boards offer performance that collects data from the various equipment to which the sensors are connected. This data then travels to the cloud for analysis.

In the outlook, the power data will be analyzed and compared to the values collected over a given period, so as to detect the state of health of the equipment in order to take decisions in real time.

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