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Research Article

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Efficient and intelligent use of a hybrid power system (HPS): Grid - Diesel - Photovoltaic

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Abstract This paper is about a proposed solution to solve the electricity supply difficulties of a higher education institution, the UFR-SET (Training and Research Unit in Science and Technology) of the UIDT (University Iba Der Thiam of Thiès). To do this, we designed a hybrid electrical system with three sources (the operator's electrical network, diesel, and a photovoltaic system) to better meet demand. The management system in place is an intelligent automatic switchover plan. The inventory was done to identify the realities and constraints of the site, i.e. the energy needs and the existing installations (operator's electrical network and diesel with non-automated management). In this study, we proposed to join to the existing one a photovoltaic solar energy solution to constitute an intelligent HPS with a Raspberry Pi card and an Arduino card associated with different types of sensors.

Keywords hybrid electrical system (HES), photovoltaic, diesel source, electrical network, Raspberry Pi, Arduino

Introduction

In West Africa, the energy issue is a pressing one. Several explorations are being undertaken to harness renewable energy to meet economic and energy challenges [1]. Solar photovoltaic energy installations can be used particulary to relieve congestion in national electricity production and distribution networks. In this work, we propose a hybrid solution based on embedded systems to optimise the availability of electrical energy. A contextual scenario will be applied to the UFR of Sciences and Technologies of Iba Der Thiam University of Thiès to better illustrate the problem [2]. The main objective is to propose a solution for the optimization of energy sources and the improvement of electrical consumption based on a planning protocol and on embedded systems to better manage the different phases of switching between the system components [3], [4]. The study focuses on the administrative block called "Block A" [5], [6].

Study of a hybrid power supply solution

A three-step process is followed: Scenario presentation, existing situation critical and drafting of solutions

Existing scenario

Block A is composed of twenty-three (23) rooms including two (02) computer rooms, one (01) meeting room and twenty (20) offices. One part of the building is used as a laboratory for remote practical work.

The average working hours at the UFR-SET are as follows

- Teaching staff: 05 hours per day.
- Administrative, technical and service staff: 07h per day

Table 1 below gives the energy balance for "Block A".

Table 1: Energy balance for "Block A"

Appliances	Nomber	Unit power (W)	Total power (W)
Fixed station for computer rooms	40	902	36 080
Fixed computer for teachers (Offices)	20	902	18 040
Small Printers	25	672	16 800
Large printers	3	3 825	11 475
Electric cooker	5	1 000	5 000
Fixed computer for secretary	4	902	3 608
Refrigerators	12	78	936
PC - Students (Computer room)	20	38	760
Lamp	41	18	738
Fans	8	75	600
Laptop computers for teachers	10	38	380
spotlight	2	110	220
Speaker	2	100	200
Air conditioning	20	1 260	25 200
Microwave	5	900	4500
TV	1	75	75
Total		**10 895**	**125 950**

Electrical loads are only powered by the operator's power grid (P.G). At outage event, the main circuit breaker of the generator (GE) is manually activated to supply the "Block A". The P.G is of SDMO type (J33-50Hz with a power of 33 kVA/ 24 kW).

Critical situation analysis

The total electrical power of "Block A" is 125.95 kW. Air conditioning and office equipment account for most of the energy consumption. In addition, the office doors are not airtight, which means that hot air is constantly entering the building, causing a bad air conditioners system.

Draft solutions

The first solution is to adopt some energy-saving actions, which will considerably reduce energy consumption. Optimising energy consumption involves pooling IT resources, individual appliances, and installing thermal insulation systems, etc.

The second solution is a technical one, involving the implementation of a hybrid power supply solution (HPS) by adding a solar photovoltaic energy system as a back-up to the existing grid [8].

Photovoltaic field sizing and hybrid system design

Appliances	Number	Unit power (W)	ks	Total power (W)	Duration (hours)	Ej (Wh)
Fixed station for computer rooms	20	902	0,6	10 824	2	21 648
Fixed computer for teachers (Offices)	10	902	0,6	5 412	3	16 236
Large printers	3	3 825	0,6	6 885	2	13 770
Electric cooker	1	1 000	1,0	1 000	0,16	160
Fixed computer for secretary	4	902	0,6	2 165	7	15 154
Refrigerators	1	78	1,0	78	8	624

PC - Students (Computer room)	20	38	0,6	456	2	912
Lamp	41	18	1,0	738	6	4 428
Fans	8	75	1,0	600	4	2 400
Laptop computers for teachers	10	38	0,6	228	5	1 140
Projector	2	110	1,0	220	4	880
Spotlight	2	100	1,0	200	4	800
Microwave	1	900	1,0	900	0,50	450
Total	**123**	**8 888**		**29 723**	**48**	**79 010**

The power balance of the A-block carried out earlier gave a power value of 125.95 kW. To optimise the system design, the solar system, due to its high-energy consumption, will not support air conditioning **[7], [8]**. Table 2 gives the daily energy requirement for the PV array sizing.

Table 2: Summary of the daily energy requirement for UFR-SET

Dimensioning of PV system components

- Module sizing :

The modules sizing is done by determining the peak power to be installed. This power is a function of the total energy requirement **Ej**, the locality sunshine level of the system **Ei**, and the overall energy yield **k** of the various components (batteries, regulator, etc.) of the photovoltaic system. It is given by the following expression [9]:

$$P_c = \frac{E_j}{k \cdot E_i} \qquad \text{Equation 1}$$

Avec :

- **Pc** = calculated peak power (Wp or Watt-peak) ;
- **k** = overall system performance: [15];
- **Ei** = average radiation of the room in kWh / d.m² (for Senegal Ei is, on average, equal to 5.7 kWh/d.m²).

This gives :

$$P_c = \frac{79010}{0.65 \times 5.7} = 21325\ Wp \qquad \text{Equation 2}$$

If we choose 200Wp/24V monocrystalline panels, we will need about 100 modules to satisfy this power.

Sizing number of batteries required

The capacity C of the batteries reflects the operating time of the system without the solar panels and is expressed in Ampere-hours (Ah) [9].

$$C = \frac{N_j \cdot E_j}{dp \times V} \qquad \text{Equation 3}$$

With :

- Nj = number of days autonomy without solar input
- Ej = daily energy in Wh / d ;
- dp = maximum allowable discharge coefficient;
- V = operating voltage (in volt) related to the installed power and generally equal to the operating voltage of the field for Pour Nj=1 et dp=0.75, we obtain :

$$C = \frac{1 \times \frac{79010}{2}}{0.75 \times 5.7} = 1097.36\ Ah \qquad \text{Equation 4}$$

The capacity of the selected batteries must be increased to 25% of the calculated capacity in order to avoid deep discharges that are harmful to the batteries. Thus, we have:

$$C = 1097.36 + \frac{1097.36 \times 25}{100} = 1371.70\ Ah \qquad \text{Equation 5}$$

Using 200Ah/48V batteries, it takes about 7 batteries to satisfy the demand.

Sizing inverter

An inverter is a device for transforming a DC voltage into an AC voltage. The power of a PV inverter is related to the open circuit voltage of the PV generator and the peak power of the electrical loads to be supplied connected to its AC output. The power of the inverter is given by the relationship below.

$$P_{inv} = 1.2 \times P_{loads}$$ Equation 6

$$P_{inv} = 1.2 \times 29723 = 35667\,W$$ Equation 7

The choice was made for following equipements:

- Hybrid inverter; 10KVA/8kW/48V/120A /MPPT model;
- Charge/discharge regulator inverter. We need about five (5) of them, connected in parallel, for the photovoltaic field setting up. Therefore, we have five (5) subfields in total.

Sizing of the cable cross-section

In order to transport energy from modules to charge controller, the cables used are designed to withstand the special conditions associated with their use. The cable cross-section, S, can be expressed as follows:

$$S = \frac{\cdot\rho \cdot L \cdot I}{\varepsilon \cdot V_A}$$ Equation 8

With :

– ρ : Resistivity of the cable in Ω.m. This depends on the material. It is 1.8 ×10-8 Ω.m for a copper cable; ;
– L : Cable length;
– ε : maximum voltage drop in percent;
– V_A : voltage ;
– I : Current flowing through the cable (in Ampere). It is recommended to take

$$I = 1.25 \times I_{sc} \times N_{pp}$$ Equation 9

Npp being the number of panels in parallel and Isc the DC current.

Let **PA** be the portion between the PV array and the junction box and **PB** the portion between the junction box and the inverter. Tables 3 and 4 give the cross-sections of the system circuits.

Table 3: Cable section for the different PA and PB part

Portion	**Curent** I_{CC} (A)	**Tension** V_{OC} (V)	**Cable length** (m)	**Calculated cable section (voltage dip** ε=0,01**)**	**commercial Section**
PA	6,30	45,82	8	1,97 mm²	2,5 mm²
PB	31,5	183,28	10	3,09mm²	4 mm²

Table 4: Cable section between inverters and batteries

Cable length round trip (m)	**Intensity** (A)	**Voltage** (V)	**Calculated cable section (voltage dip** ε=0,01**)**	**commercial Section**
6	120	48	27 mm^2	35 mm²

Hybrid Electric System Design –HES

The **HES** is made up of three different energy sources subject to a priority order. First comes the photovoltaic, then the electricity grid and finally the generator - GE. The supply of loads from several sources simultaneously is not allowed and the batteries are only recharged by the solar system. The SEH must be under the control of an automatic management system that supervises the connections of different sources according to their capacity to meet the energy need and the schedule set up. Apart from the sizing of the PV system, neither of the two existing sources will be modified. They will only be connected to each other to form the SEH [3], [4].

Figure 1 shows the three sources connected to the supported loads.

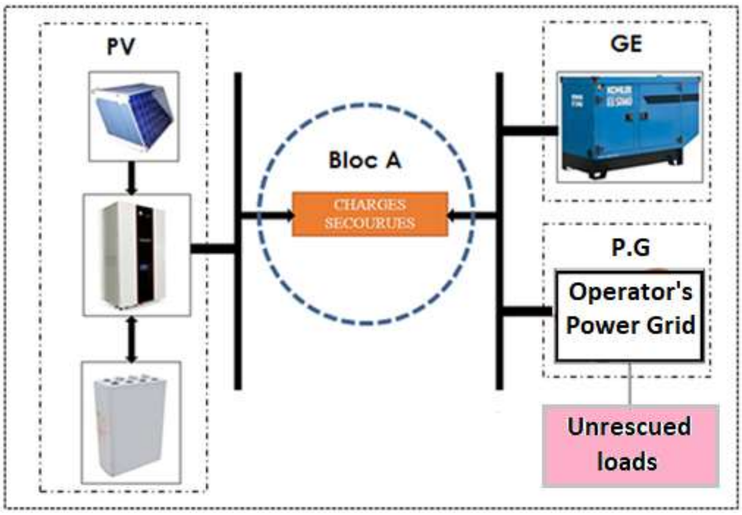

Figure 1: Interconnection system of the different sources

The system for managing the switching between different sources is an embedded system based on Arduino UNO for the collection of decision variables and on Raspberry Pi 3B+ for relay control and data visualisation. The system is subject to an operating protocol.

System Operation Protocol

We have three sources. The operating protocol adopted is presented below:

- As long as the sunlight conditions are favourable, the PV supplies the loads;
- When the energy produced by the panels is insufficient and the batteries are discharged, the PV is disconnected from the loads and the BR takes over until the batteries are charged again;
- In case the PV and the BR are absent, the SG takes over. It operates until one of the two priority sources recovers;
- During the holiday period, instructions are given to avoid unnecessary consumption: appliances not in use are switched off and disconnected from the power supplies; the generator is switched off. During this period, only the PV and BR supply the loads.

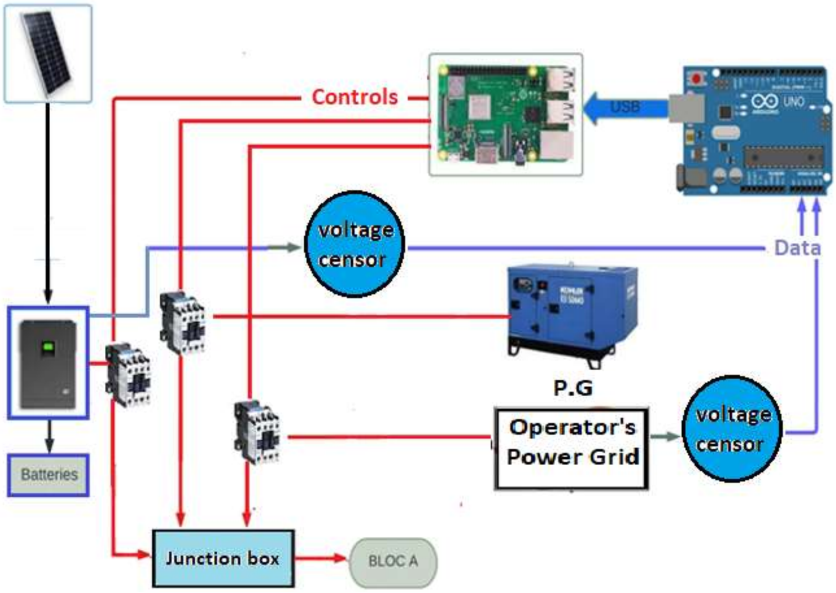

Figure 2: Source control by an embedded system

The operating procedure is based on two switching plans: the first plan is related to the availability of solar energy and BR, while the second plan is related to the hours of use of the first two energy sources (PV and BR).

Primary plan: switching according to PV energy,

The operation consists of connecting/disconnecting the electrical loads to the PV generators according to the state of charge of the batteries. Data on the voltage-battery charge level relationship is presented in the table below for lead-acid batteries.

Table 5: Relationship between voltage and charge level of a lead acid battery.

Battery voltage (Volt)	Battery state of charge
14,5	Overloaded
12,8	100% load
12,5	70% loas
11,8	20% load (unloaded condition, not recommended for use)

The chosen inverter is of the hybrid MPPT type, it provides the functions of charging/discharging the batteries, MPPT tracker, connection/disconnection of a source if necessary. It is also possible to put a voltage detector on the power lines at the output of the inverter to detect the presence and absence of voltage.

Secondary Plan : Switching according to the time of day

The PV generator has been sized to meet the daily requirement of "Block A" with a back-up provided by the battery bank for 50% of the daily requirement. The PV generator should therefore more than cover the energy demand of "Block A". The operating plan is given below.

- From 8am to 10pm: power supplied by the PV array;
- From 22:00 to 08:00: supply from P.G.

System control

Supply of loads

To control the supply of loads from one source at a time, we need a device that can detect the presence current in the event of an outage. Two voltage sensors are needed: one for the PV and one for the P.G. We therefore designed a voltage sensor using a voltage divider bridge.

We have set up a voltage matching device that takes the parameters from the RE and at the output of the inverter on a socket and converts the voltage value from 230V to about 5V-2A. The output is connected to a step-down bridge circuit to provide another analogue output which is connected to an Arduino pin for detecting the presence or absence of electricity [10]. The schematic of the device is given in Figure 3.

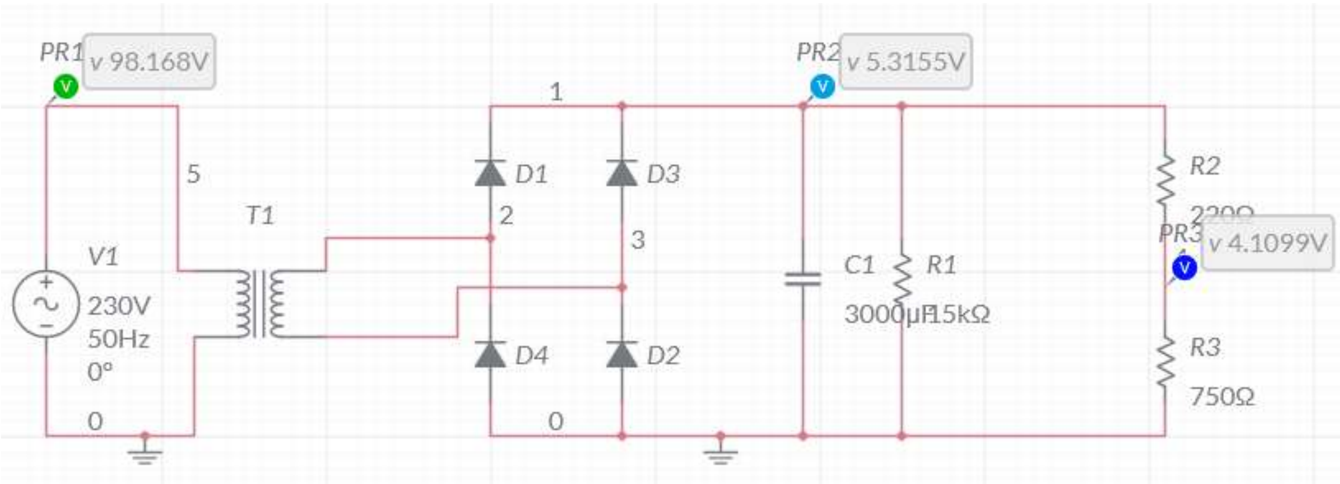

Figure 3: Overall diagram of the voltage matching device between the P.G source (or inverter) and the Arduino board

At the output of this device we obtain a voltage of 4.09V (≈ 4.10 V) and a current of 5.45 mA. The measurement of this voltage gives us information about the current presence or not from PG or PV field

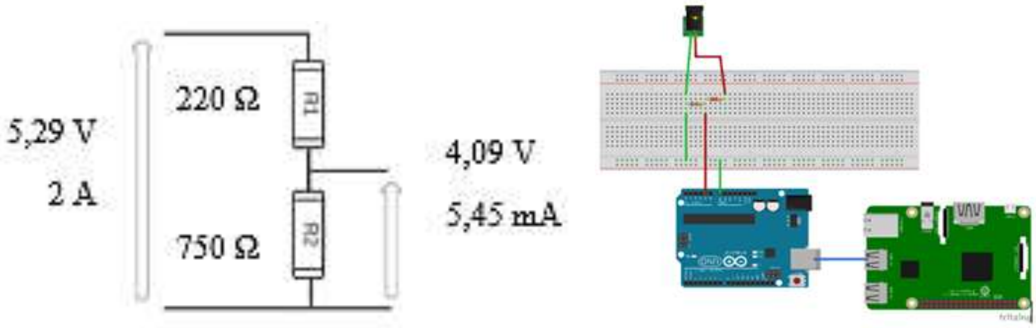

Figure 4: Diagram of the voltage divider bridge connected to the Arduino board

Tilt Control

In addition to the contactors used at the output of each energy source, the automated system is responsible for activating the relay corresponding to the source in charge of the power supply. The coils are energised by the electrical signal from the Raspberry Pi after processing the data received from the voltage sensors through the microcontroller. The Raspberry PI also serves as a hoop for monitoring the parameters used [10], [11], [12].

System algorithm and software design

System algorithm

Based on the operating protocol and the individual components determined, we develop the system's operating algorithm. It is subdivided into two subroutines a and b :

- Sub-programme "a" corresponds to the scenario between **8am and 10pm** called Ha.
- Sub-programme "b" corresponds to the scenario between **10pm and 8am**, named Hb.

Let :

H: time of day;

U.am: voltage transmitted by the voltage detectors located upstream of the circuit breakers;

U.av: voltage transmitted by the voltage detectors located downstream of the circuit breakers;

Upv: PV generator voltage;

Ure: P.G voltage;

KM1: PV contactor;

KM2: BR contactor;

KM3: GE contactor.

Figure 5 shows the main algorithm of the system, Figures 6 and 7 show the Algorithms labelled "sub-program a" and "sub-program b" respectively

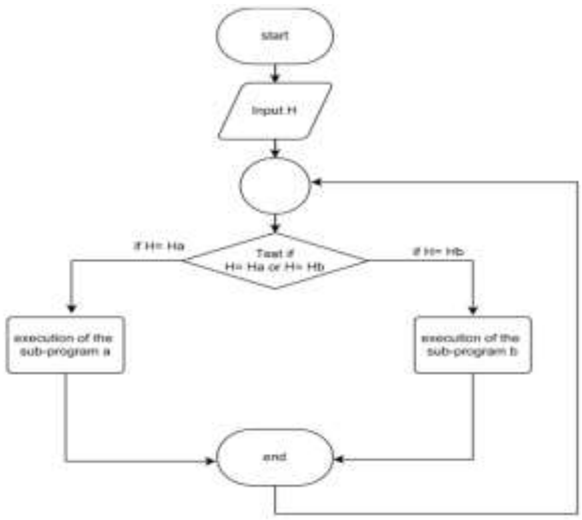

Figure 5 : Main algorithm

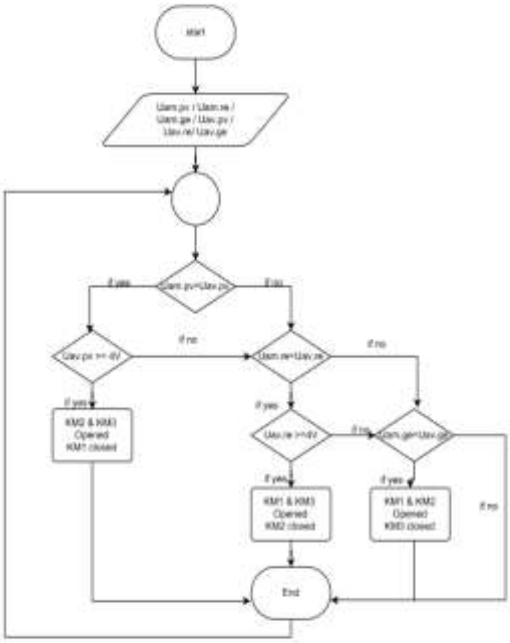

Figure 6 : Algorithm "subroutine a"

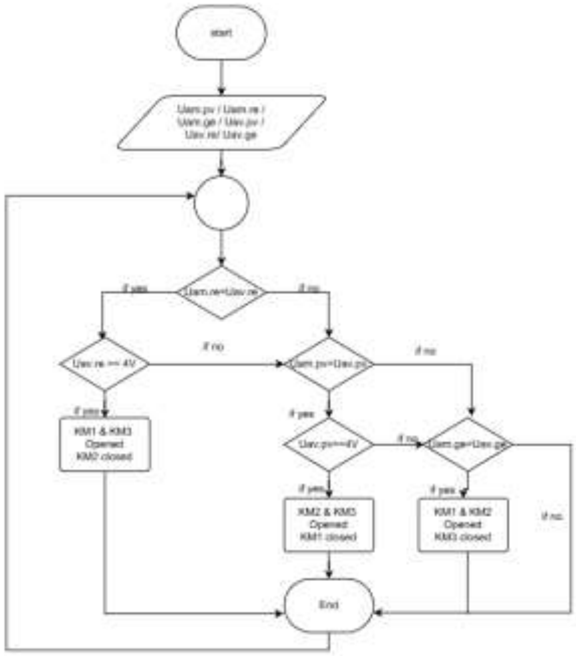

Figure 7 : Algorithm "subroutine b"

The proposed algorithms entitled "subroutine a" and "subroutine b", respectively, allow the system to be controlled according to the operating procedure based on the two switching plans. The priority order is modulated according to the availability of the sources and the time of day. The system implemented ensures high availability of electrical energy for the UFR-SET, which is essential for the proper functioning of the institution's services.

Conclusion

The aim was to offer the UFR SET administrative building possibility to use electricity in an optimal way and to be able to have a renewable energy source and to better manage the different energy sources available in the SEH. We have sized a solar photovoltaic energy production park and regulated an automatic management plan to optimise the hybrid electric system put in place. The on-board system is open to be extended to other additional sources.

For the continuation of this work, it may be possible to provide a remote visualisation system for performance evaluation and at the same time monitor parameters such as humidity, temperature in the SEH environment and other site meteorological data.

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