A Smart Control System For Solar Photovoltaic Power Supply in Rural Africa

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Abstract- Rural African communities are suffering from energy poverty despite their high potential energy resources. Renewable energy sources, particularly solar photovoltaic (PV), have to be deployed to ensure daily life activities. Associated with information and communication technologies, solar PV systems contribute in establishing a sustainable development for these communities. Controlling power supply is one of the sustainable solutions to be adopted. This paper focuses on developing a Smart PV Power Supply Control system (SPSC) for off-grid solar homes. The proposed SPSC is a Machine to Machine (M2M) communication-based system. It aims at controlling the power supply, through either WIFI or Short Message Service (SMS) network, depending on consumption quota exhaustion. The PV off-grid home system sizing is presented. The economic analysis including the billing process are described. Advantages and scenarios of the proposed system are detailed. The system architecture is investigated. Main function programs are explained via flowcharts. Three main application scenarios are validated on an off-grid real residential 60W load. Firstly, the power supply control test is made when internet access is available. Secondly, the test is performed only through SMS messages and lastly through delayed SMS messages. The proposed SPSC can be used in rural areas where internet penetration rates are low. It helps solar PV installer companies control the home power supply depending on bill payment and consumption quota. Thus, it provides an overall evaluation of the solar PV market in Africa and a particular evaluation of solar PV generation compared with other off-grid generation technologies.

Keywords African Rural Electrification; GPRS-GSM Communication Network; Machine-to-Machine Communication, Smart Power Supply Control System; Solar PV off- grid system.

1. Introduction

Rural communities in Africa are struggling to eradicate energy poverty [1] and to ensure an affordable, reliable, sustainable and modern energy access [3]. A sustainable energy system could not be established without the combination of renewable energy sources and new Information and Communication Technologies (ICTs) for an enhanced energy efficiency [4, 5, 6]. Sustainable energy systems are expected to alleviate energy poverty by providing affordable energy access, to promote opportunities for new jobs and to enhance social welfare [7, 8, 9, 10]. Recent statistics exhibited in the Price Waterhouse Cooper report show that almost one in five persons, in Sub-Saharan Africa, still has no access to electricity in 2015 [11]. Near to 85% among them, live in rural environments of developing low income countries [12-14] and the number is predicted to arise by 2030 [2]. Despite its huge solar potential as the sunniest continent in the world [15], Africa suffer from little development of renewable energy solutions, namely solar

Photovoltaic (PV) ones, and fossil fuel energy with high carbon emissions remain the primary energy source. In fact, in most African countries, the lowest daily mean radiation varies from 4kWh/day/m^2 to 8kWh/day/m^2 [15] and the global annual solar irradiation ranges between 1600 and 2500 kWh/m^2/year [16]. Thus, the solar PV is playing a crucial role in the electrification of rural African communities and in having power generation access [17]. In order to ensure a sustainable development for PV systems, rural African communities should tackle the new Internet of Things (IoT)-based energy landscape [18, 19] and embrace new ICTs for the monitoring and the management and particularly for controlling the PV power supply [20]. Many projects and applications have been developed using smart technologies. Fields of applications cover, mainly, irrigation systems [21], and smart solar home systems and smart farms [12,22, 23, 24]. The control of such systems is based on green ICTs [18] such as green Machine to Machine (M2M) communication, as an IoT technology enabler. These smart technologies need to be used as they help deploying an efficient energy policy compared to developed countries [25].

This paper deals with a Smart PV Power Supply Control system (SPSC) for off-grid solar homes in rural Africa. The proposed SPSC is an M2M communication-based system. The focus is on controlling the power supply, through either WIFI or Short Message Service (SMS) network, depending on monthly bill payment and consumption quota exhaustion.

This paper is organized as follows: An overview of the installed solar PV off-grid home system is described. Besides, the steps undertaken to design the installed PV system are provided in the second section. Third section investigates the importance of the suggested SPSC system, as well as the assets and the functions. The proposal architecture is explained. The developed functions and scenarios are detailed as well. The fourth section carries out the experimental validation scenarios. Finally, conclusion and outlook are presented.

2. Context and Motivations

There are essentially some steps to follow in order to design an off-grid home system. Firstly, it is necessary to choose which generation technology to adopt among the three known ones:

- Conventional generation technology, based on diesel generation;
- Non-conventional one, including PV and storage system, wind turbine and storage system and finally hydro power plant and storage system.
- Hybrid micro-grid that is any combination of PV, wind turbine, hydro power plant, diesel generator and storage system.

In this paper, we focus our study on non-conventional generation technology based on PV and batteries as storage system. Designing the whole system and then evaluating its technical and economic performances are important steps to ensure a sustainable PV solution for household electrification [14, 26, 27]. The usual steps of designing a solar PV off-grid system are depicted in the flowchart of Fig.1, from components sizing its components via mathematical "Eq. (1)" and "Eq. (2)" [14, 27] to the economic and performance evaluation via specific metrics and then its operating and billing process. The latter helps evaluate the adopted generation technology regarding another one, for instance, PV generation technology versus diesel generator for rural communities.

In this paper, the PV power supply control system, is connected or disconnected according to monthly bills payment. This is developed to help evaluate the cost-effectiveness and the affordability of the proposed solar PV system for off-grid rural households. If the proposed solution has proven its low cost, efficiency and affordability for rural communities with low income, then it will be spread over the energy African market. The solar PV off-grid home system under study is sized to support the energy demand of the following appliances, shown in Tab.1.

Table 1. Calculation of the required residential demand load

Load	Number of loads	Power (W)	Total Power (W)	Use hours (h)	Energy need (Wh)
Refrigerator	1	150	150	12	1800
LED Projector	1	50	50	5	250
LED Lamp	5	15	75	6	450
TV LCD	1	120	120	5	600
Fans	2	60	120	5	600
computer	1	60	60	5	300
				Total	4000

The calculation of the required energy load is based on " Eq. (3)" [7].

$$Et = \sum_{i}^{n} Wi \times h \tag{3}$$

where:

Et = Required theoretical energy (Wh)
Wi = The equipment's rated power i (W)
h = Daily usage time (h)

Thus, the installed PV off-grid home system with its flow of energy and flow of information is depicted in Fig. 2, and it is composed of the components specified in Tab.2. Moreover, it involves residential appliances: a refrigerator, LED light, plug sockets for computers, fans, etc. as calculated in Tab.1.

Solar resource evaluation: Average daily input and monthly average daily solar irradiation

Estimation of peak electric load for residential houses: Required residential load demand

Determination of the off-grid PV System components: PV modules; Inverter; Charge controller and Batteries

Design of the off-grid PV system components:

- PV array sizing: $Ppv = Apv \times Ip \times \eta pv$ [14, 27] (1)

  Where: Ppv is the peak PV power; Apv is the required area of PV array (m2) and ηpv is the efficiency of PV panel in %.
- Inverter sizing: Depends on the total rated power of the AC load (20 % margin)
- Charge Controller sizing: According to the PV array short circuit current.
- Battery sizing: $Bsc = \frac{Nccd \times Lel}{\eta B \times Dd \times \eta I}$ [14, 27] (2)

  Where: Bsc is the battery storage capacity; $Nccd$ is the largest number of continuous cloudy days and Dd is the maximum permissible depth of discharge of the battery.

Determination of sizing results: PV modules number, technology, peak PV power (W_c), average power produced from the off-grid system (kW) in STC.

Economic Analysis: Life cycle cost; annualized life cycle cost; cost pay-back time, billing**.**

Off-grid PV system installation and operation

Monthly Billing Electricity

PV Power Supply Control according to billing payment and quota exhaustion

Fig. 1. Solar PV off-grid home system from sizing to consumption billing and power supply control

3. Proposed Smart Power Supply Control System

3.1 Overview and Functions

The solar PV off-grid power supply needs to be controlled and managed according to an economic criteria: the monthly electricity bill payment and the consumption quota.
The non-payment of the bill or the quota exhaustion implies a direct disconnection of the power supply. This control is ensured via the smart power supply control SPSC connected between the inverter and the outlet socket. A conceptual overview of the SPSC, its potential communication networks, WIFI and GPRS/GSM communication, as well as its main functions are given respectively by Fig. 3 and Fig. 4.

The proposed SPSC system has the following assets:

- ➢ Remote SMS notifications, power supply control and information;
- ➢ Visualization of current consumption and power supply state through the LCD screen.
- ➢ Secure communication between the SMS server and the SPSC; only entities with administrator level can communicate with the control system;
- ➢ Control via an android application on smartphone or via cloud server;
- ➢ Control via SMS messages through a basic mobile phone in case of unavailability of internet access.

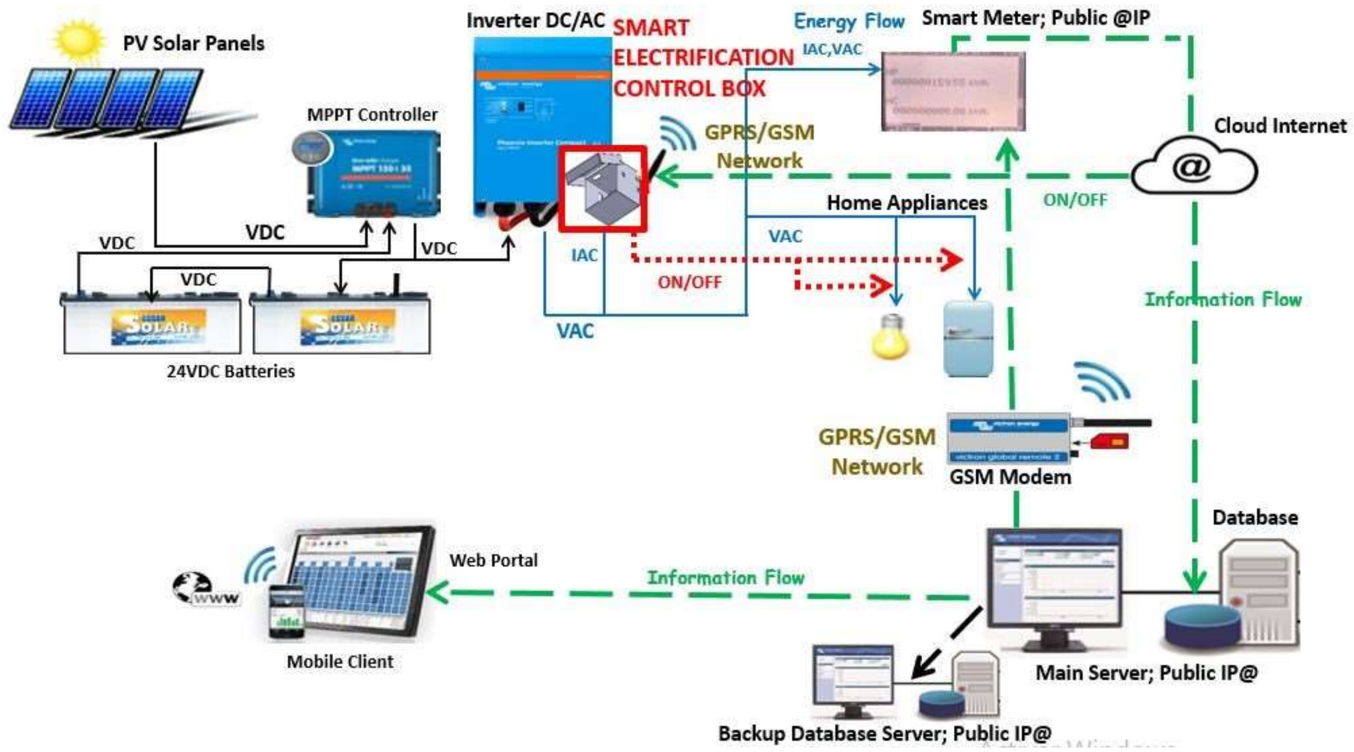

Fig. 2. Detailed architecture of the installed smart PV off-grid home system under study

Table 2. Technical specification of the installed PV home system under study

Component	Technical Specification
Solar PV system	• Peak Power 1.2kWc (in Standard Test Condition STC) • 4 Polycrystalline solar panels of 315 W_c each (in STC)
Solar inverter	• AC / DC • 24V/ 2000VA – 230 VAC
Charge controller	• MPPT • 150V - 35A (maximum values)
Backup batteries	• 2 connected in series • 12V – 200Ah (each)
Communication module	• GPRS/GSM network
Smart meter	• Ethernet MODBUS TCP communication network
Proposed SPSC system	• WIFI communication network • GPRS/GSM network

3.2 Proposal Architecture of the Smart Power Supply Control System

An M2M communication is used between the administrator information system server, specifically the SMS server and the SPSC system. The proposed system can be commanded via the GPRS/GSM modem as well as via the cloud. It allows remotely exchanging data, SMS and commands between two computing devices via the internet and via GSM network, which makes it an IoT application for controlling PV power supply. The SPSC system is a part of an information system for PV power supply management and control for off-grid homes, depicted in Fig. 5. The main server, mobile client and SMS server are beyond the scope of this paper, only the SPSC system (Electrification Control Box) is addressed. The SMS server is responsible for bills payment and SMS management, sending and receiving SMS. It communicates with the main server through GSM network. It is included in the application services layer and performs the billing process service. The SMS server calculates monthly electricity bill, detects whether the bill has been paid by the consumer, and whether the client didn’t reach the consumption quota limit. In case of non-payment or quota exhaustion, the SMS server sends an SMS alert to the client and a request of cutting off power supply to the SPSC system. Once the SMS command is received, the SPSC reads the sent data frame, extract the number to make sure it belongs to the allowed administrator number list and then extract the message command to check it into the desired commands list.

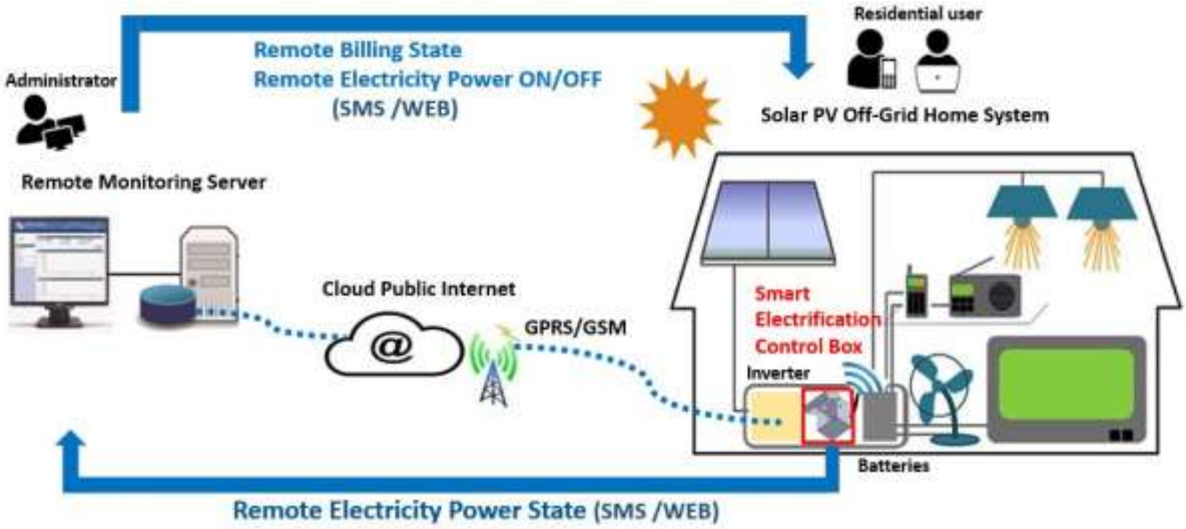

Fig. 3. An overview of the proposed SPSC system concept

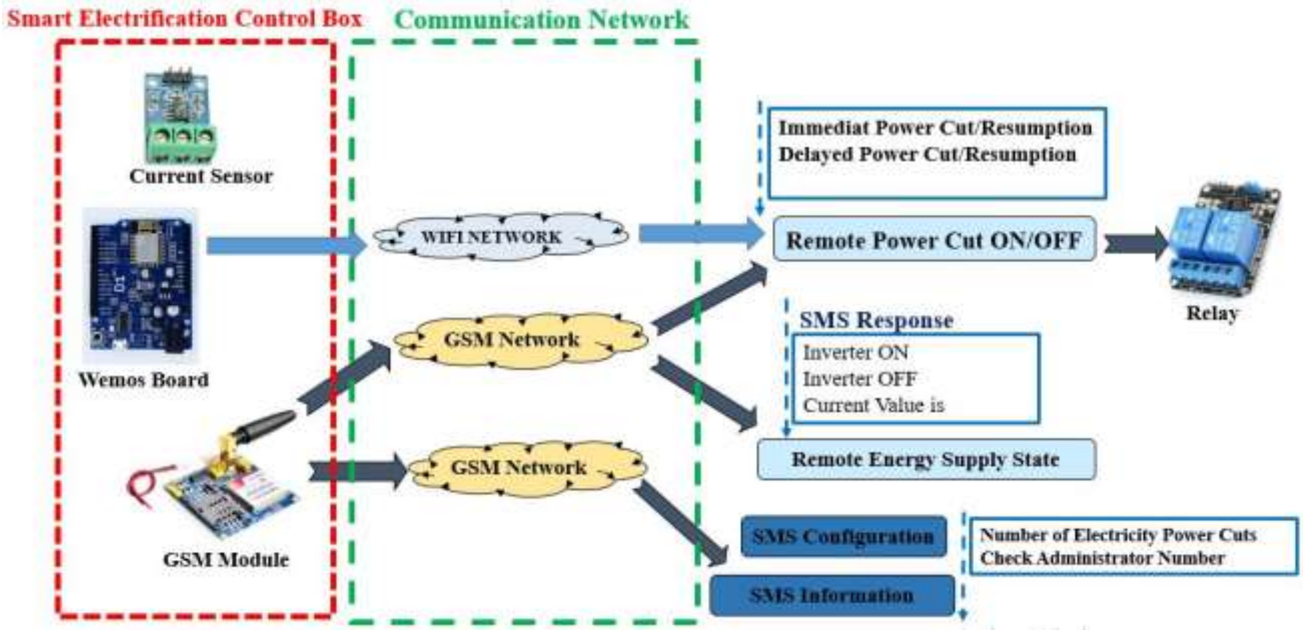

Fig. 4. Main functions of the suggested SPSC system

Finally, it executes the required command of cutting off the power supply. The command can be to power on loads once the bill is paid or the quota is loaded. In addition, further scenario is to power on / off loads after a certain period of time or after reaching the limit of current consumption set by the administrator. In this case, the residential consumer can benefit from power supply with constraints until the bill is paid or quota is loaded. The SPSC system sends an SMS response to the SMS server indicating the power supply state and the consumed current calculated by the included current sensor. Furthermore, data exchange can be performed through the cloud in case there is an accessible WIFI communication.

The SPSC system is equiped with a WIFI module included in the WEMOS baord and with a GSM network to send SMS messages from any simple mobile phone in case no internet access is available which is most common in rural African areas. In fact, according to Internet Word States [28], internet penetration rate for 2017 is under 16% for 18 countries among 54 African countries. This very low internet access rate is and the low internet use are explained by the survey [29]. Aside from the poor infrastructure, many other constraints on internet penetration are described in [30], among them the heavy internet cost including internet tariff, computer hardware cost and transmission cost. Likewise, the low bandwidth in most rural areas induces a bad quality of transmission leading to the low rate of internet use and even difficulties to getting internet access. Internet is thus not affordable in most cases, and if available, it is too slow to use. To tackle the issue of internet availability and connectivity, it is possible to communicate through SMS

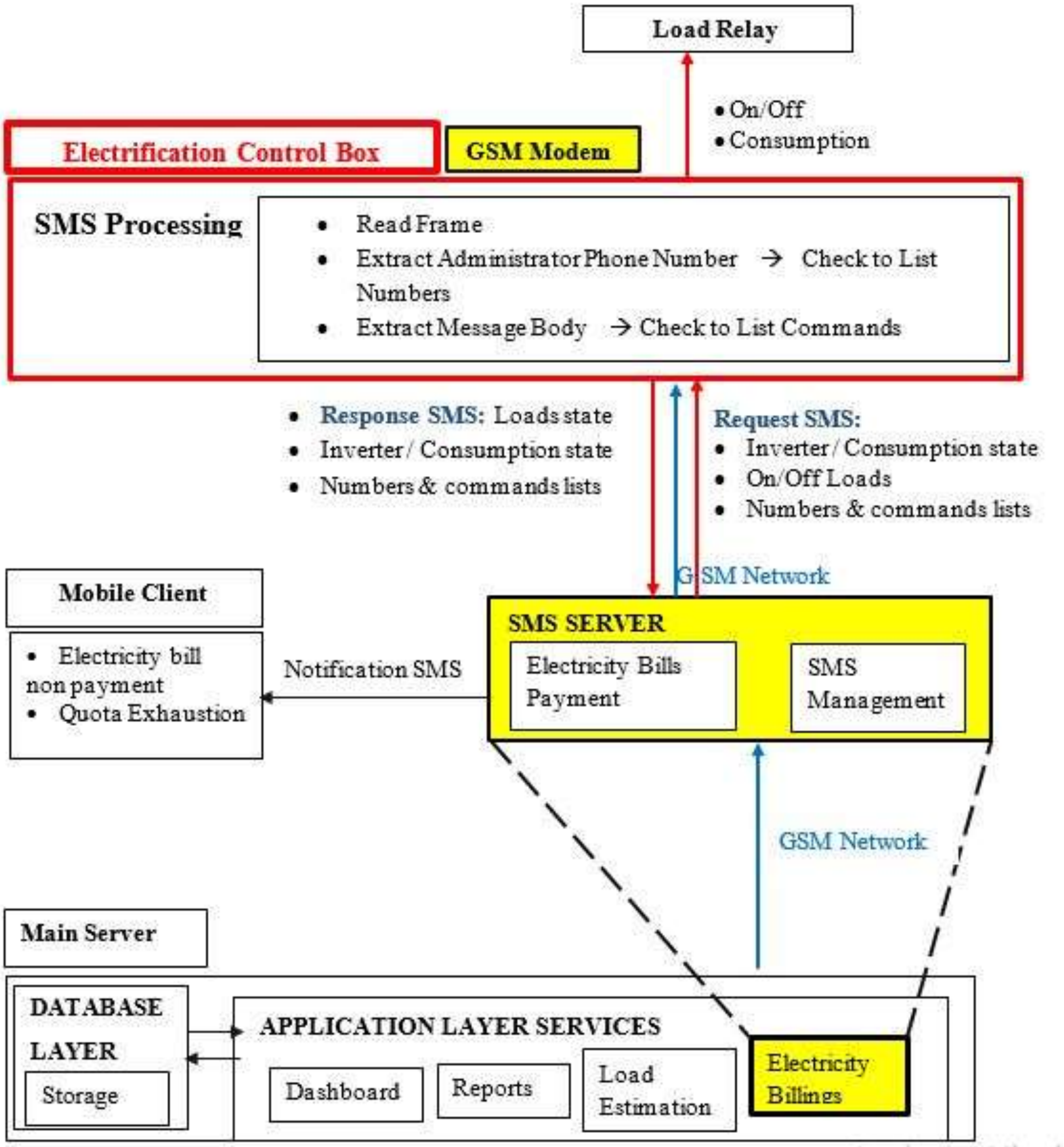

Fig. 5. Architecture of the proposed information system for PV power supply management and control for off-grid home

messages via our proposed SPSC system which makes it suitable to most rural African areas particularly in Subsahrien countries .

4. Control Scenarios Functions and Experimental Validation

4.1 Scenarios Program and Functionalities

The program of SPSC system and SMS processing is implemented in a WEMOS board. It is illustrated in the flowchart of Fig.6 and explained in Tab.3. First, the SMS is processed. Data in the serial communication port of the GSM modem are read. Secondly, the SIM card number and the command message are extracted from the SMS command data frame. The required action is performed according to the SMS message command after checking the authorization of the SMS sender. Finally, an SMS message is sent as a response the SMS server for validation.

4.2 Subroutine Programs

In this sub-section, some of the subroutine programs are detailed.

➢ **Getstring** : This function returns a string of characters

Parameters: (void)

Return type: String of characters read by the GSM modem.

The function “Getstring” checks if data are available in the serial communication. Then it transforms and returns a character string as shown in the flowchart of Fig.7.

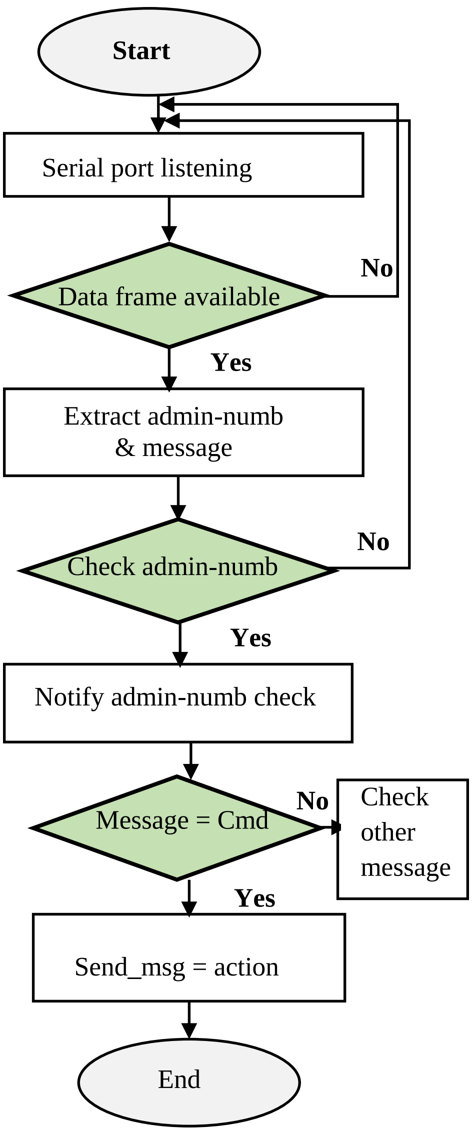

Fig. 6. Flowchart of the SMS processing and power supply control program

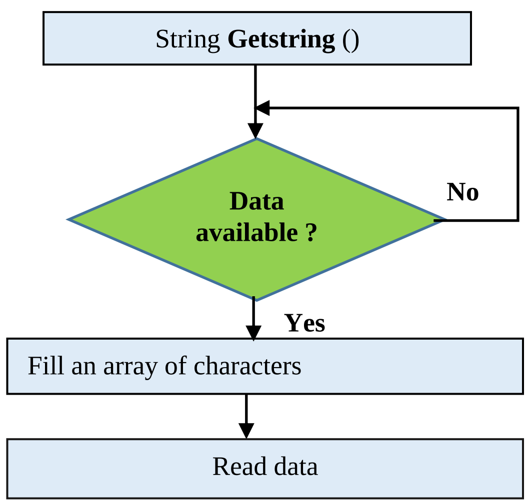

Fig. 7. Flowchart of Getstring function

Table .3. Potential message commands and required actions

Message	Action
INV ?	Give actual power supply state (on/off)
INVON ?	Verify if load is on
INVOFF ?	Check if load is off
INVON	Connect power supply source
INVOFF	Disconnect power supply source
Conso	Give the actual current consumption
INVON@X	Power on the load after delay in X minutes
INVOFF@X	Power off the load after delay in X minutes
INVON=X	Power on the load for duration of X minutes
INVOFF=X	Power off the load for duration of X minutes
C<ON@X	Power on load if the current consumption is less than the set limit after a delay of X minutes
C>ON@X	Power on load if the current consumption is more than the set limit after a delay of X minutes
C<OFF@X	Power off load if the current consumption is less than the set limit after a delay of X minutes
C>OFF@X	Power off load if the current consumption is more than the set limit after a delay of X minutes
ShowCmd	Give list command
AdminList	Give administrator number list
Reset	Reinitialize all parameters

- **ExtractFirstframe:** This function checks whether there is a new SMS command mssage, then notifies it and returns the data frame of the sent message.

Parameter: The SMScommand message, a string type.
Type return: String of the notification frame and a string of data frame of the message to be read. The flowchart of this extract function is depicted in Fig.8.

- **SendNumber:** This function returns the SMS sender SIM card number extracted from the SMS sent message data frame.

Parameter: SMScommand which is a string containing the sent message data frame;
Type of return: A string containing the SIM card chip number of the sender. The SendNumber function is presented in Fig. 9.

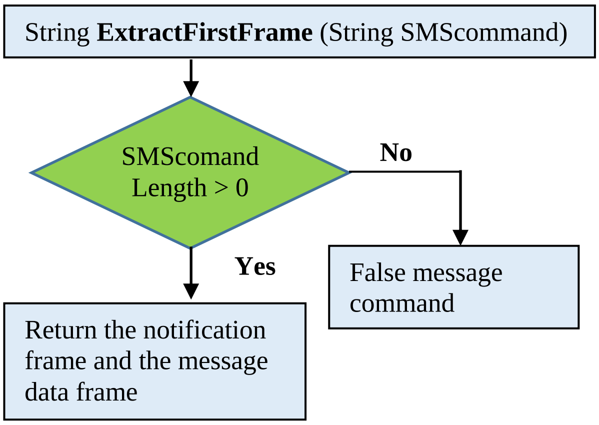

Fig. 8. Flowchart of Extract-first-frame function

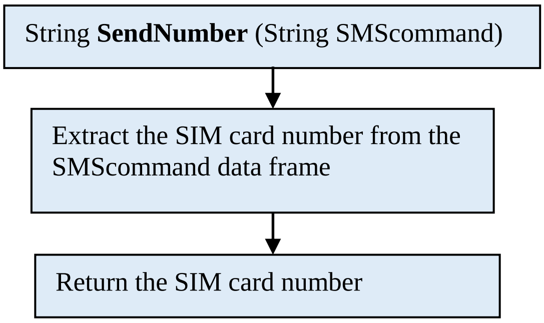

Fig. 9. Flowchart of the Send-number function

➢ **ExtractMessage:** It gives the body of the message, that means the required command, extracted from the received message data frame;
Parameter: SMScommand which is a string containing the sent message data frame of the command;
Return type: a string containing the body of the message.
The flowchart of this ExtractMessage function is shown in Fig.10.

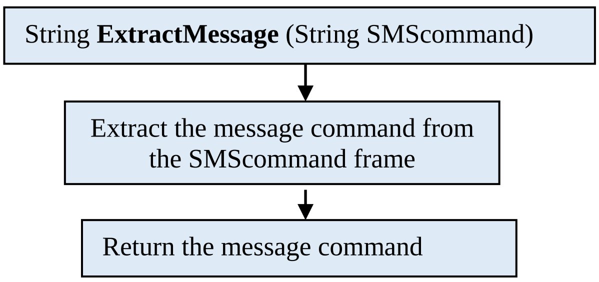

Fig. 10. Flowchart of Extract-message function

➢ **CheckAdmin:** It checks the SMS sender chip number retrieved from the received message data frame in the administrator list of numbers;
Parameter: (void)
Type of return: Boolean if the SMS sender chip number is one of the information system administrator numbers or not.
This function makes the proposed SPSC system secure, since no SMS commands are approved and authorized except those sent from an administrator number. The flowchart of this function is given by Fig.11.

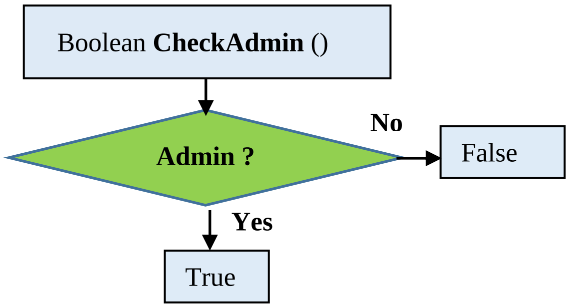

Fig. 11. Flowchart of Check-admin function

4.2 Experimental Scenario Validation

The experimental validation of the SPSC system is performed on a residential 60W light bulb. Three scenarios are applied: First of all, a WIFI communication control, then a direct power-on scenario control via SMS message and finally a power off scenario control after a condition of delay or of current value limit via SMS message as well. The application scenarios are respectively shown by Fig. 14, Fig. 12 and Fig.13. The SPSC system can calculate the current consumption and the total voltage and current distrosion.
The experimental validation of the three proposed scenarios demonstrates that the administrator of the system information, which can be the PV installer company, can remotely control the PV power supply of the residential load either via internet network or via the GSM network and SMS messages commands if the internet access is not available. The supply source disconnection can be performed immediately or after a delay, depending on the administrator choice.

5. Conclusion and Outlook

This paper proposes an SPSC system based on M2M communication that can be used to remotely control the PV power supply in rural African areas where GSM communication network is more likely spread. The proposed system focuses on controlling the off-grid power supply of solar home systems depending on billing payment or consumption quota exhaustion. The control can be performed through both WIFI communication and SMS messages from a basic mobile phone. Steps of sizing the PV off-grid system are presented. The importance of billing process and controlling power supply are explained. The SMS processing is detailed as well as the data exchange between the SMS server and the SPSC system is investigated. Experimental validation through a residential load in a PV off-grid house is performed. Future works focus on testing multiple power supply control systems to command many PV off-grid houses in a rural African community context. The proposed SPSC system is proven to be low cost and efficient and can be used in most rural African homes.

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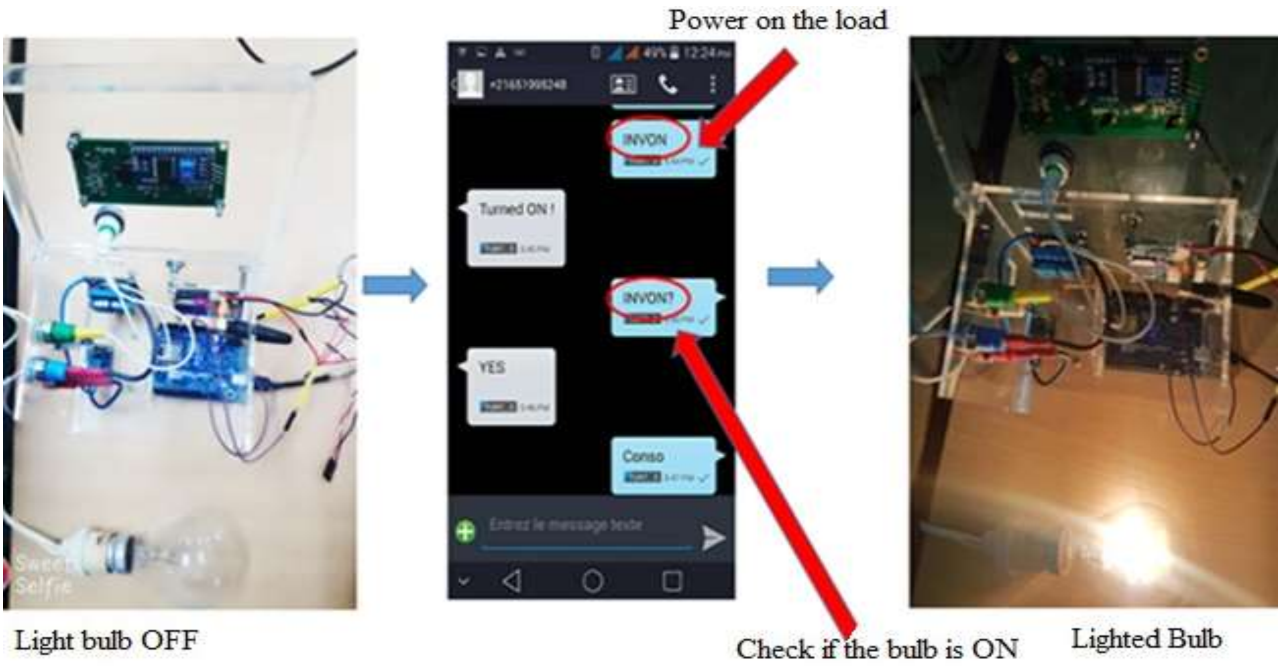

Fig. 12. Experimental validation of second application scenario via an SMS message

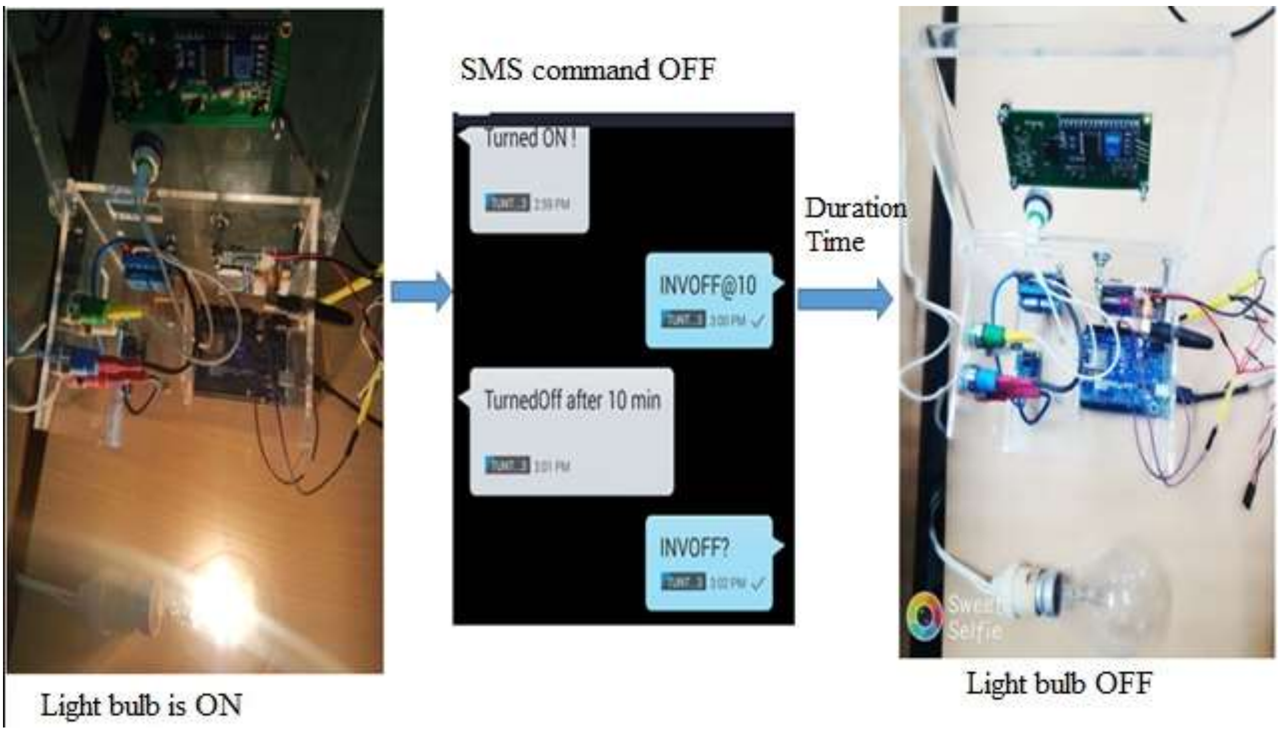

Fig. 13. Experimental validation of third scenario of load power control after delay via SMS command

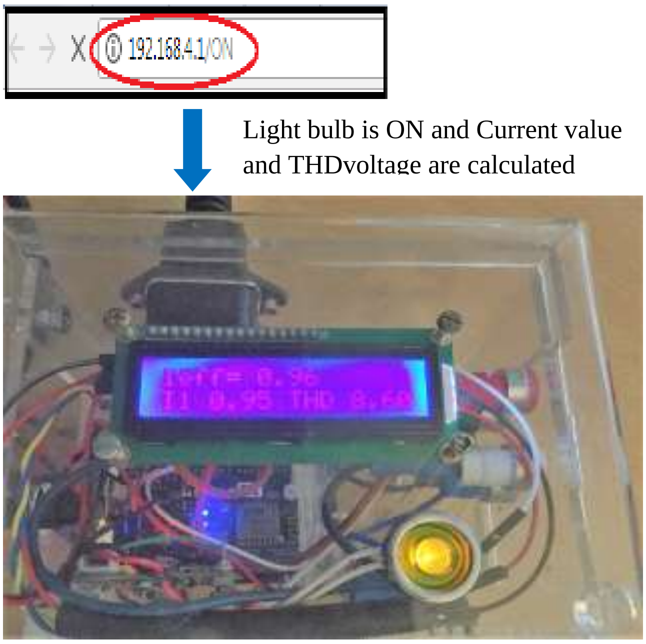

Fig. 14. Experimental validation of first scenario load control via WIFI network

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