Available online www.ejaet.com

European Journal of Advances in Engineering and Technology, 2019, 6(2):54-65

Research Article ISSN: 2394 - 658X

Design of an Automatic Transfer Switch for Households Solar PV System

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ABSTRACT

Friendly environmental energy sources campaign associated with their availability at almost zero cost have resulted in the increase of Renewable energy use throughout the world. In Africa and specifically in Democratic Republic of Congo and Uganda, Solar Energy constitutes a tremendous resource.

However, households who decide to acquire Solar PV systems end up facing two major challenges:

When it is cloudy usually after rain i.e. solar production is low yet there is need to use power.

When there is need during a normal day to supply a load which draws more current beyond solar PV system capacity.

This project responds to these challenges by providing a solution to households who wish to still have power even when there is no enough sun irradiance for their solar PV system. And also it provides solution to the need of drawing more current at a specific time, knowing that most households and small businesses rarely purchase solar PV system that meets their power load requirements.

The primary power source is the Solar PV system and the Mains (Grid), is therefore the secondary. When solar production is low (below 200V), the system switches to the Grid until it detects voltage within the allowable limits from the Inverter and switch back to solar. While powered by the Grid, if its voltage goes below the said-level, power is disconnected.

A Microcontroller controls the load and supplies. Two digital voltmeters and a digital Ammeter are incorporated as subsystem to measure the voltage of both sources and the current being drawnby the loads.

A Liquid Crystal Display (LCD) continuously displays the status of the system i.e. voltage of both sources and current being drawn.

Key words: Automatic transfer Switch (ATS), Photovoltaic system (PV), AVR Microcontroller, Digital Voltmeter, Digital Ammeter & Liquid Crystal Display

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1. INTRODUCTION

For the past 5 years, Renewable Energy sources market share has kept increasing. From 2014 to 2015, the global capacity was increased by *50GW* [1]. In Africa Solar Energy has seen a market boom. Because of the high Starting expenses of equipment [2], most households purchase a system capacity which is below their load requirement.

From the observation made on Solar PV system installations of some families in the town of *Beni* and *Muntwanga*, which are located in the Eastern parts of Democratic republic of Congo (D.R.C), the solar energy is used to power few lighting systems (bulbs) and only basic appliances such as TV, Radio, Decoders, though other appliances are found but not used at all. In most cases during evening time or during a rainy day, the system couldn't power its specified loads for 1 hour without fall of voltage. In spite of the way that there has been micro grid of 250 KW (in Muntwanga), most of families were asking for a system capable of switching to the micro grid automatically only for a specific amount of time.

In Uganda, the Solar Home Systems market is regarded as one of the biggest areas for commercially driven Solar PV business and has been considered for the past few years to have a high potential [2]. This shows the change in the Solar PV market pattern which was dominating by Institutional PV segment (rural health clinics) and Telecommunications/ Tourism segment, based on 2009 research [3].

For Urban customers (Kampala & Entebbe), solar companies provide equipment such as Solar PCU (Power Conditioning Unit), a device of multiple features (ATS included), hence expensive and not in the reach of most households. Solar PCU has the capability of charging battery and powering loads using Grid power. Yet, besides reliable electricity supply, households seek to minimize the Grid power consumption while purchasing Solar Home System.

ATS available on the local market dedicated to household' use have been designed and manufactured for Generators use as secondary power source. In the Solar Industry, ATS is a subsystem of Solar PCU. Though it is advantageous for some system capacity and countries with advanced power billing system, Solar PCU remains not relevant for Eastern/ Central Africa modest households.

2. MATERIALS AND METHODS

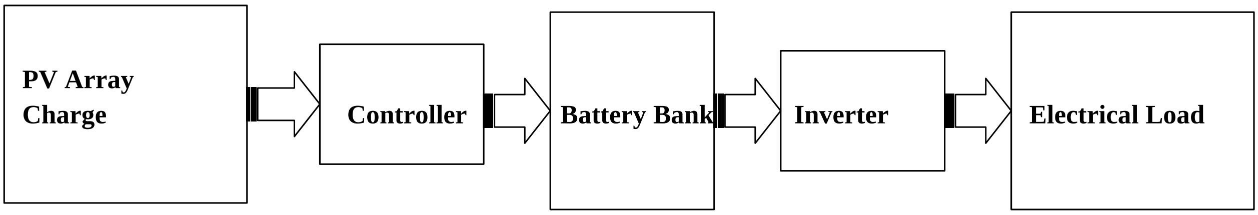


Fig. 1 Stand-Alone Home Solar PV system

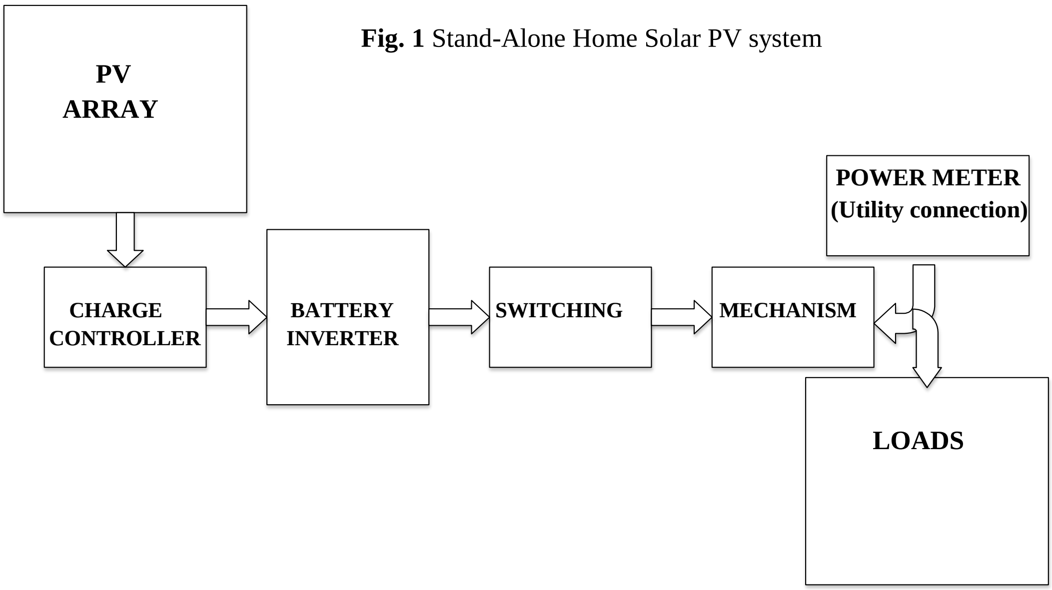


Fig. 2 Typical Hybrid Solar PV system block diagram

Components Description

The design and implementation of each of the fundamental circuit units and how the program was implemented to, control the plan and perform the required functionality.

From the above illustration, it can be seen that the significant parts of the system include the following:

- PV array (PV modules)
- Charge controller
- Battery bank
- Inverter
- Power meter
- Disconnect Switch

PV Panel

It consists of solar cells made of semiconductors materials and connected in series. The combination of cells gives a Panel and the combination of many panels form an Array.

Charge Controller

As it called, it controls or regulates the flow of current and voltage into the battery. It is connected between the panels and the battery, and rated in terms of maximum Amps and voltage it is meant to handle.

Batteries

They are used for energy storage.

Solar PV systems require the use of deep cycle batteries i.e. which can regularly deeply get discharged using most of its capacity and quickly get charged. Solar battery can be discharge up to 20%, however for the best lifespan, it is recommended to keep the average cycle at about 45%.

In contrast, a standard battery (car battery) is designed to deliver short, high-current burst for the starting of the engine. Though they are all lead-acid batteries i.e. consists of Sulphuric acid and plates made up of leads/

Inverter

It converts DC into AC electricity. They are categorized in three major types:

- String Inverters: PV modules are connected in series circuit before connection to this type of Inverter. It is the most affordable, can be coupled with charge controller, storage system.
- Micro-inverters: this inverter is installed on every PV module that composes the array.
  The output of the Micro-inverters is connected in parallel to the loads. It is the most expensive, as the DC output of each panel is directly converted to AC, there is no storage system in with this type of Inverter.
- Power optimizer systems: this is a hybrid system of the above two types. There is a Central String inverter where by the module are not connected directly to it but through an Individual power optimizer installed on each panel.

Solar Home Sizing

Solar Home Sizing consists of the evaluation of the energy consumption of a home to determine the system capacity and equipment needed for its solar PV installations.

The following are key points to consider:

- Site Assessment
- Load Analysis

Site Assessment

The site location where the panels will be installed must be carefully examined. The following are information needed to be collected:

Mounting Location: Solar panels can be mounted on roof (roof-mount), ground-mounted, wall-mounted or on a shade structure specially designed to support the modules.

Shading: shade reduce considerably the performance of a PV module since all cells are connected in series. The site for PV panels must be cleared from any obstruction to sun irradiance. Even a small shadow, such as of a single branch of a leafless tree can significantly reduce the power output of panels.

Orientation: to determine which orientation is most appropriate because the more surface area that is exposed to *direct sunlight*, the more output the PV panel will produce. Since solar irradiance is at a pick on the equatorial line, the simple technique is to face Solar panels to *true south* in the northern hemisphere and *true north* in the southern Hemisphere.

Tilt: this refers to the inclination of solar modules oriented toward the equatorial line to enable sun's rays hit them at a right angle, hence maximizing the amount of direct radiation. And it depends on location usually calculated based on the geographic latitude. For locations below 21°, the tilt varies from 0.0 to 22°. But for a fixed mounting, it is recommended a tilt from 5 to 15° to allow easy cleaning of modules by rain water [4].

Peak sun-hours/ Insulation over the year: The lowest Peak sun-hours of the year is the one considered for the PV sizing for the *Stand-alone* solar PV systems.

Required Area: For all the mounting choices, the available space to accommodate modules is very key because on average, a modern panel sizes approximately (1400 x 1000) mm.

Load Analysis

The Total Energy consumed by all appliances is calculated based on the average hours each one is used in a single day [4-5]. This gives *Kilowatt hours* or *Units* consumed. However, some Devices draw power even when they are not in use or when they are switched off. These are called Phantom loads.

The Phantom loads power consumption should also be included in this calculation.

An alternative and more effective way is to consider the monthly Utility Bills for the past 3 to 6 months to determine the pattern of power use.

Switching Methods

There are typical two methods for power switching mechanism:

Manuel Switching: requires an operator to physically flip a switch to transfer loads to the secondary source.

Automatic switching: trigger itself after sensing the primary source has lost or gained power.

An ATS is an electrical/electronic switch that senses when the primary power source is interrupted and automatically shifts loads to the secondary source, of course, as long as the later one parameters (voltage & frequency) are within prescribed limits [6].

A typical AT follows the following steps:

The normal power source fails, When power of the alternative source is stable and beyond the prescribed voltage (220-230V) and frequency tolerances (±2% of 50Hz), loads are shifted to the secondary source. When the primary source is restored within prescribed limits and for a minimum time, the loads are shifted back from the secondary to the main source.

Home ATS Design

Most of the available ATS for home use are designed for the use of Generator as the secondary power source.

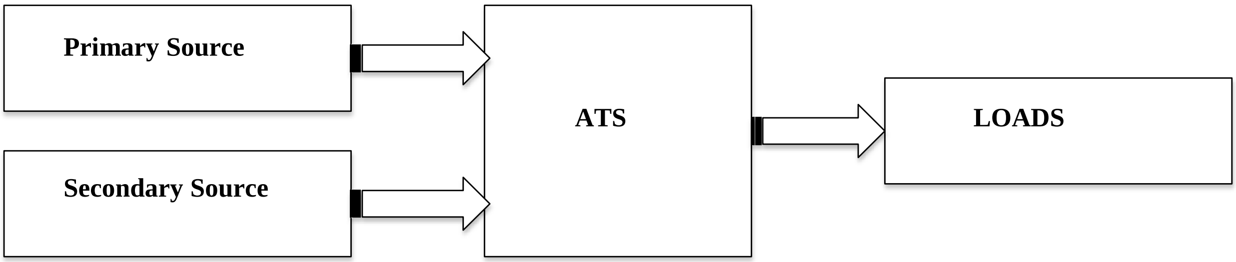


Fig. 3 Block Diagram for a Transfer Switch

ATS and Solar PCU

Local companies such as "*Solar Now* "and "*Ultra Tec"* provide solar systems with equipment known as *Power Conditioning Unit (PCU).*

A *Solar PCU* is an integrated system that provides charging of the battery bank through both solar and Grid/Generator. When the battery bank level goes below a set level, the *PCU* automatically transfer the load to the Grid power and charge automatically the Battery while powering loads.

It consists of the following parts functioning units:

Solar charger: to control the charging of the battery from the PV array

Inverter: to convert DC to AC

Grids/Generator Charger: this is a secondary charger in the *PCU.* It is function is to charge battery with Grid power when the solar output is low.

Output switching mechanism: When in the solar mode, AC is drawn from the Inverter, but when the Battery has been drawn out, the load is supplied by the Grid.

Monitoring capabilities via Internet

As such, a *Solar PCU* is a system of many sub-systems. Some Solar PCU have many features and advanced technology such as Synchronization of both power sources. Due to its multitasking capability, a Solar PCU is beyond the reach of a modest Central/East African household.

3. WORKING PRINCIPLES

System Study

The system was based on the useful literature that was obtained from relevant sources. A single phase solar system is suitable for household application and small businesses.

Data gathering and Analysis of system layout

This method was used to critically study various solar PV systems installations in *Beni-town* and *Muntwanga*, both cities in the Eastern Congo and installations in Kampala, the layout and size of system installed and their equipment used.

Interview

This method was used to get feedback from owners of already installed solar PV system. This focused on owner's satisfaction or complaint of the operation of the system.

Solar PV System design

Ugandan Household Sizing

The average electric power consumption for a Ugandan household is *93.6kWh* per month [7]. This gives a daily average *3.12kWh*. This research carried out by Candia Drazu, Mark Olweny and Goodman Kazoora demonstrates the pattern of different appliances used in a Ugandan Households.

The table below describes the rate at which various appliances are found and used in a Ugandan household.

Item Percentage of households (%)

Table -1 Appliances usage rate by Households

Item	Percentage of households (%)
Mobile Phone/ PDA	100
Computer (Desktop)	17.6
Computer (Laptop)	60.8
DVD Player/ Games console	56.9
Iron	82.4
Kettle	56.9
Microwave oven	23.5
Radio/ Hifi	78.4
Refrigerator/ Freezer	54.9
Television	82.4
Washing machine	11.8

From Table 1, Microwave oven, washing machine, Flat Iron and Kettle constitute high-energy consumption appliances and for an effective power savings, they shouldn't be used on a daily basis.

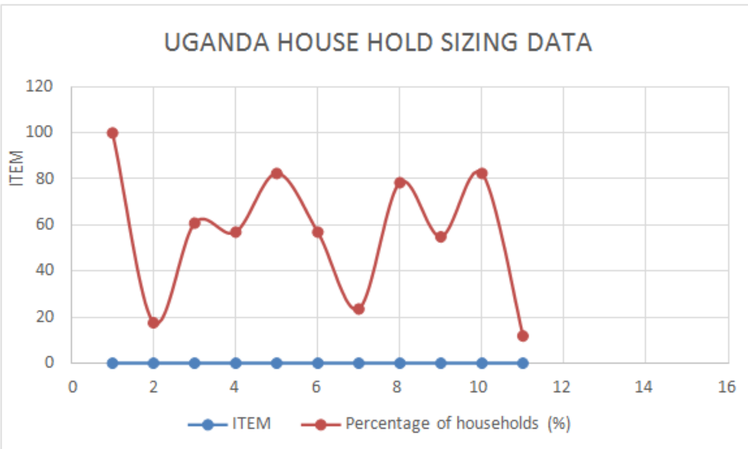


Fig. 4 A Graph of Uganda House Hold Sizing Data

The financial aspect of a solar PV system (to be demonstrated in later sections), balanced with the consideration of these appliances, shows the essence of this project. An ATS will cost far less than a system that caters for all these loads. For this reason, only the following items have been considered for our design.

Item Quantity Watts Hours/day Watt- hours/day

Table -2 Typical Households average solar PV system loads

Item	**Quantity**	**Watts**	**Hours/day**	**Watt- hours/day**
TV set	1	120	5	600
Decoder	1	30	5	150
DVD player	1	28	3	84
Freezer	1	190	5	950
Lights (indoor)	5	5 (25)	4	100
Security lights	3	5 (15)	12	180
Laptop	1	100	5	250
Total		508		2314 Wh

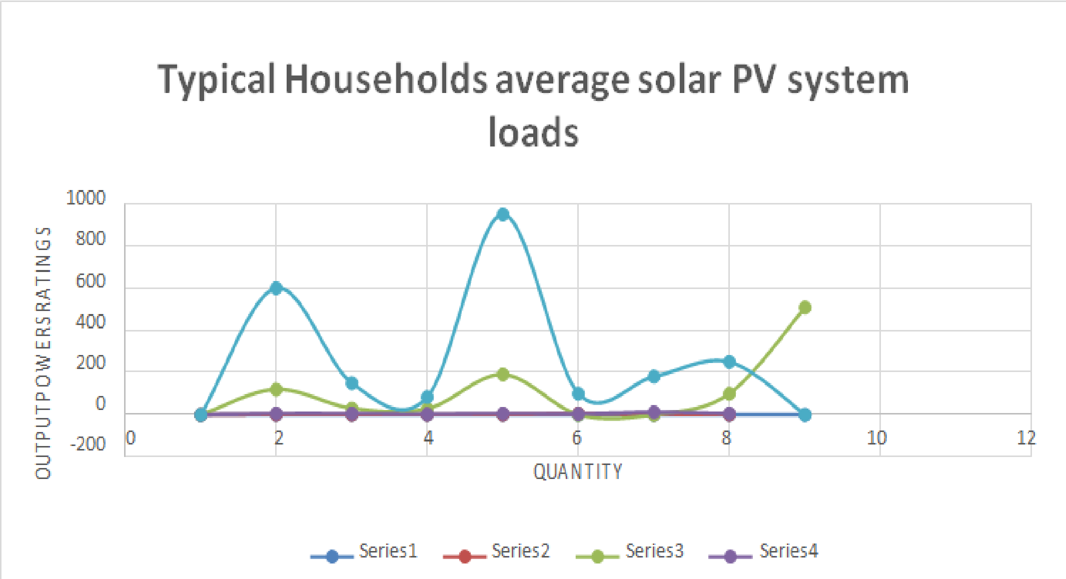


Fig. 5 A Graph of Households average solar PV system loads

However, some devices can still draw power even when they are not in use or are switched off. These are called *Phantom loads*.

Appliances or device Typical load when off but

Table -3 Phantom loads

Appliances or device	**Typical load when off but plugged in (Watts)**	**Duration (hrs.)**
LCD TV set	2	20
Cellphone charger (when not charging)	6	24
Laptop	6.5	
Decoder 20	17.8	
DVD player	1	
Total	33.3	

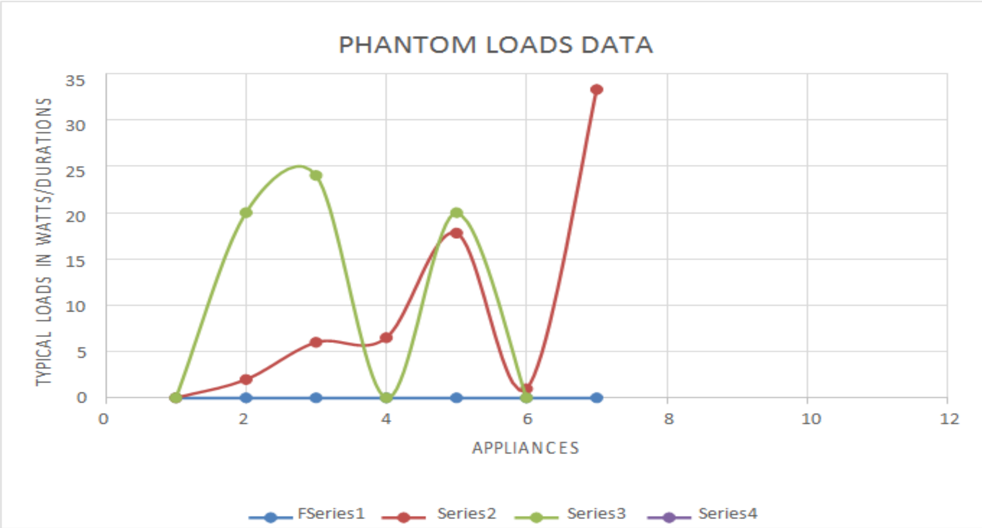


Fig. 6 Phantom Loads Data

Proper measure such as "Unplugging of unused appliances" should always be taken seriously to avoid *Phantom loads* consumption. Considering only TV set, Cell phone Charger and decoder, Phantom loads gives 25.8W and 540Wh.

PV design and calculations

i. System Capacity

From the above section, we have the system capacity:

Energy consumed by loads: 2314Wh + 540Wh= **2854Wh** and

Peak load: 508W + 25.8W= **533.8W**

Note: Most of the solar equipment doesn't work at 100% efficiency.

For instance, an Inverter has an average of 87%efficiency. Since, it will be drawing energy from the battery, the battery bank capacity should be able to cater for the remaining 13% of loss.

2854Wh x (100:87) =**3280Wh**

This implies:

- Energy consumed by loads: 2854Wh
- Energy drawn from the battery: 3280Wh

ii. PV Array sizing

The module sizing is based on the lowest Peak sun-hours of the year and for this case is the month of October (6.2Kw/m^2).

(3280Wh x 1.25) =**4100Wh**

4100/6.2= **661W**, minimum PV array watts.

Note: 1.25 factor accounts for the battery charge and discharge efficiency losses over the life of the battery.

Considering a module of *270Wp – AEG Germany (Polycrystalline type),*

661W/270Wp= 2.4 modules, taken **3 modules**.

iii. Battery sizing

Considering a **24VDC**GEL-type battery system configuration,

3280Wh/24V= 136.7 Amps-hours.

For 1 "*day of Autonomy*" at 50% *Depth of Discharge,*

136.7h x 1 x (100/50) = **273.4Ah**, for a battery bank

I consider *220Ah, 12V – Victron Battery,*

220Ah x 2= *440Ah* (4 batteries: both series and parallel connection).

iv. Charge controller sizing

For maximum operation, the MPPT charge controller is preferable. We choose 45A Charger Controller.

810Wp / 24VDC= 33.75A, 20% increase to cater for safety,

33.75A + 20% of 33.75 = 40.5A

Victron *BlueSolar Charge Controller* ***MPPT 150V/45A*** is suitable for this system.

v. Inverter sizing

The Inverter should be of *String-type Inverter* of a *Modified Sine-wave* output type and selected to match the PV system with the following characteristics:

- Peak power: 533.8W
- System voltage: 24VDC

This should be an *Inverter only* i.e. without charging capability.

At a default average efficiency of 87%, the inverter size should be:

533.8W x (100/87) =613.56W.

A 700Wor 800VA Inverter is suitable for the system.

Considering future increase in loads *Victron* ***1600VA, 24V*** is highly recommended.

vi. Wiring and other equipment

Losses are always available whenever current pass through a conductor. And it is known as IR^2 loss. However, a well-designed wiring for a Solar PV System should not have a voltage drop of more than 5%. This implies that on a 24VDC system, voltage loss should not be more than 1.2V.

Other equipment is as well needed:

- Combiner box: with a surge protection
- Mounting equipment: to hold firm the modules on the supporting structure.
- Disconnects

ATS design considerations

It is obvious that the best method for Switching from Solar to Mains during bad weather conditions or in the need of more Power is the *Automatic Mechanism.* This device also known as *ATS* (Automatic Transfer Switch) has the following characteristics:

Reliability: It switches power from Solar and Grid and keep monitoring the sources voltage and measuring the current being drawn.

Protection: It protects the loads against Over/Under voltage and over current.

Efficiency: It uses an external 9VD battery for its operation.

Safety: The device is safe because there is no connection in the circuitry with fluctuating AC source though care must be taken to avoid being shocked at the Relays terminals and Current sensor module.

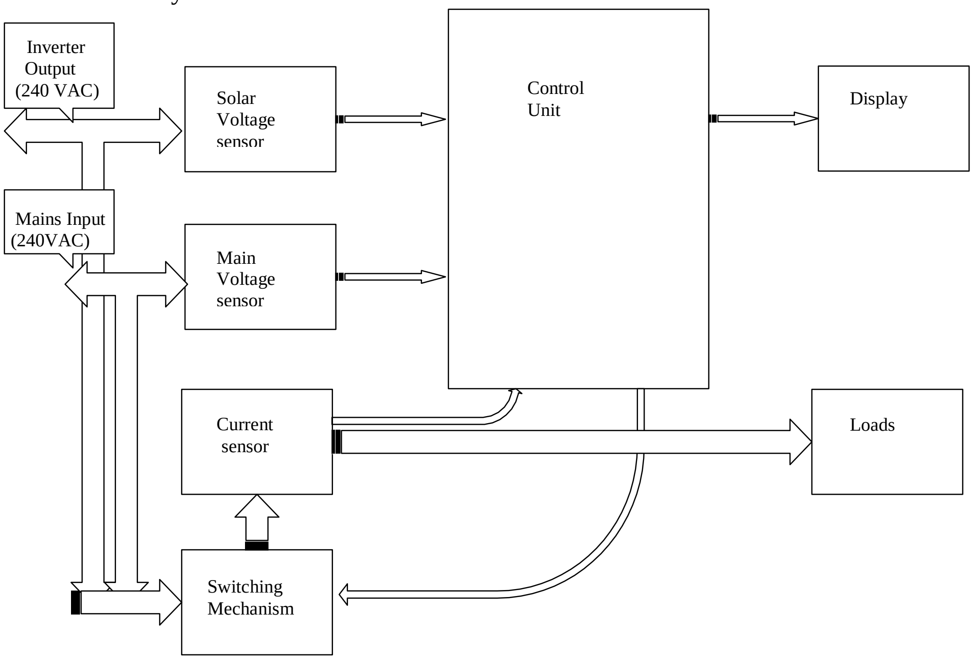
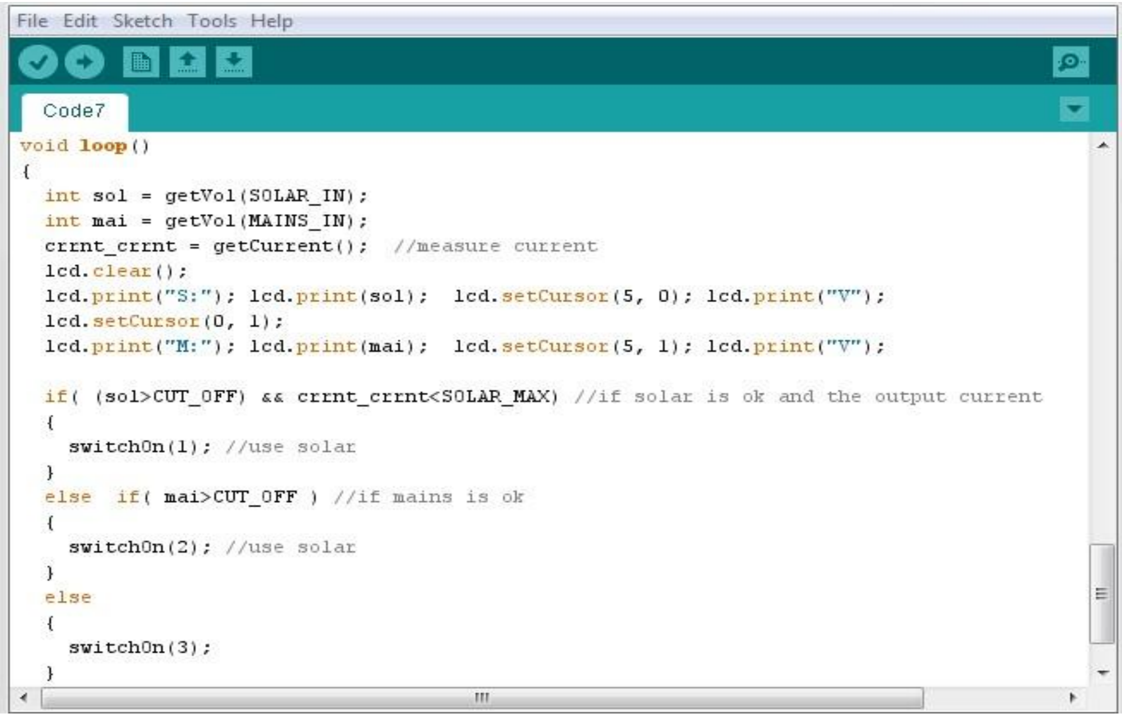


Fig. 7 ATS Block diagram

Development tool

The program was written in *C++language* using the user-friendly *Arduino-Integrated Development Environment (IDE)* interface. As such, Arduino not only provides the capacity to boot-loading a microcontroller but also provides comprehensive facilities for programming. It provides source code editor and debugger/compiler. A compiler transforms computer code written in one programming language into another programming language.



```
void loop()
{
  int sol = getVol(SOLAR_IN);
  int mai = getVol(MAINS_IN);
  crrnt_crrnt = getCurrent();  //measure current
  lcd.clear();
  lcd.print("S:"); lcd.print(sol);  lcd.setCursor(5, 0); lcd.print("V");
  lcd.setCursor(0, 1);
  lcd.print("M:"); lcd.print(mai);  lcd.setCursor(5, 1); lcd.print("V");

  if( (sol>CUT_OFF) && crrnt_crrnt<SOLAR_MAX) //if solar is ok and the output current
  {
    switchOn(1); //use solar
  }
  else  if( mai>CUT_OFF ) //if mains is ok
  {
    switchOn(2); //use solar
  }
  else
  {
    switchOn(3);
  }
```

Fig. 8 Arduino IDE: Part of the code

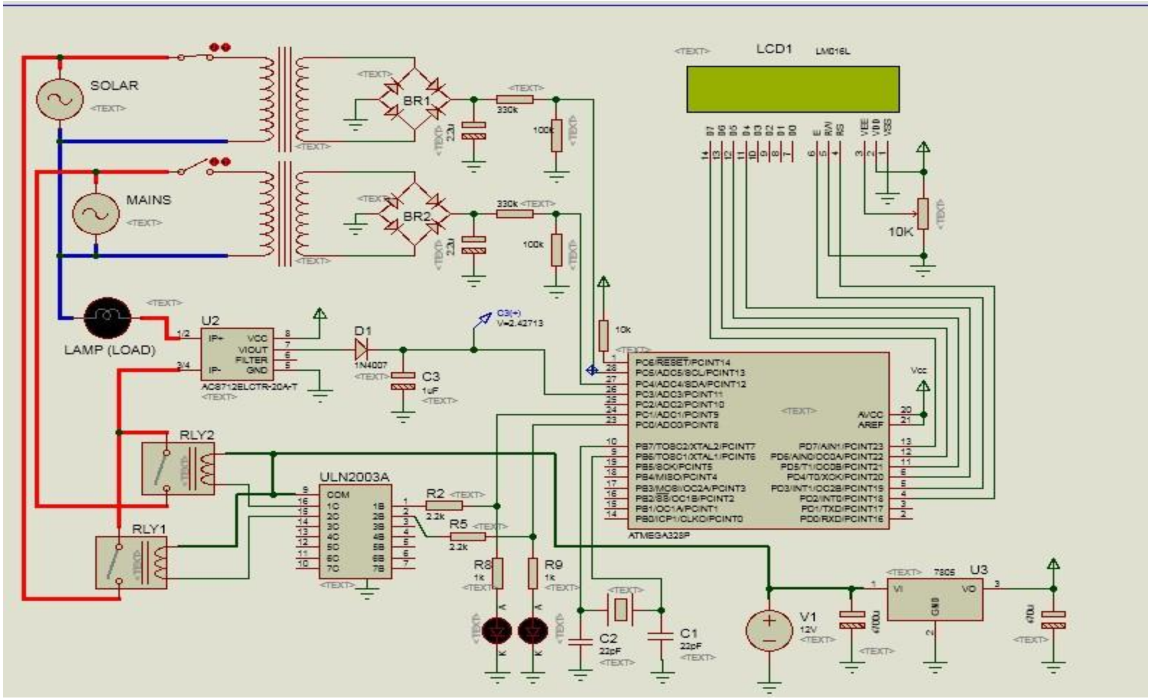


Fig. 9 ATS Circuit Diagram

UMEME tariff

Though the conventional meter can be still found at some households, UMEME has increasingly been focusing on switching its customers from the old-fashioned billing system (postpaid payment) to the prepayment system, commonly known in Uganda as *YAKA.*

This research has focused on the YAKA-prepayment system which is based on the *block rate tariff.*

In a block rate tariff, energy consumed is divided into block and each block has its own specified charge. The charge rates progressively reduce on succeeding blocks of energy.

UMEME prepayment tariff is charged as follows:

- Block A: First 15 units at UGX150.0
- Block B: Proceeding units at UGX520.6 per unit

- Monthly service fee: UGX3,3600
- Value Added Tax (VAT): 18%

Considering the average monthly consumption of a Ugandan household being at 93.6kWh, the cost of energy is:

Block A: 15 Units x UGX150= UGX2250
Block B: 93.6units – 15units = 78.6 units; 78.6 Units x UGX520.6= UGX40, 91916
Total: UGX (2,250 + 40,919.16) = UGX 43,169.16

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Total: UGX (2,250 + 40,919.16) = UGX 43,169.16

4. RESULTS AND DISCUSSIONS

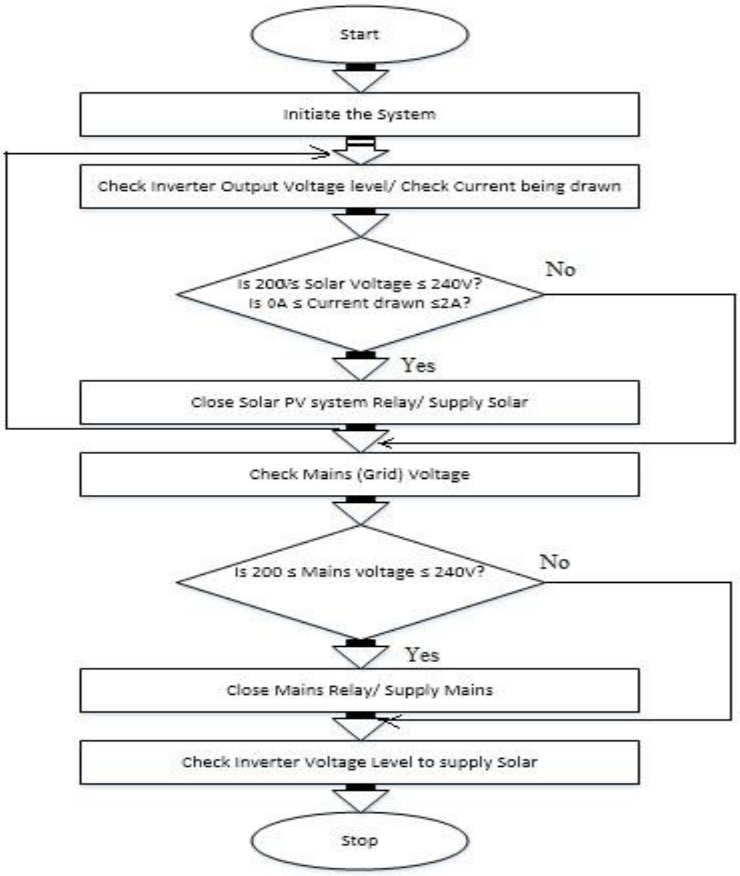

Fig. 10 Flow Chart of the Project

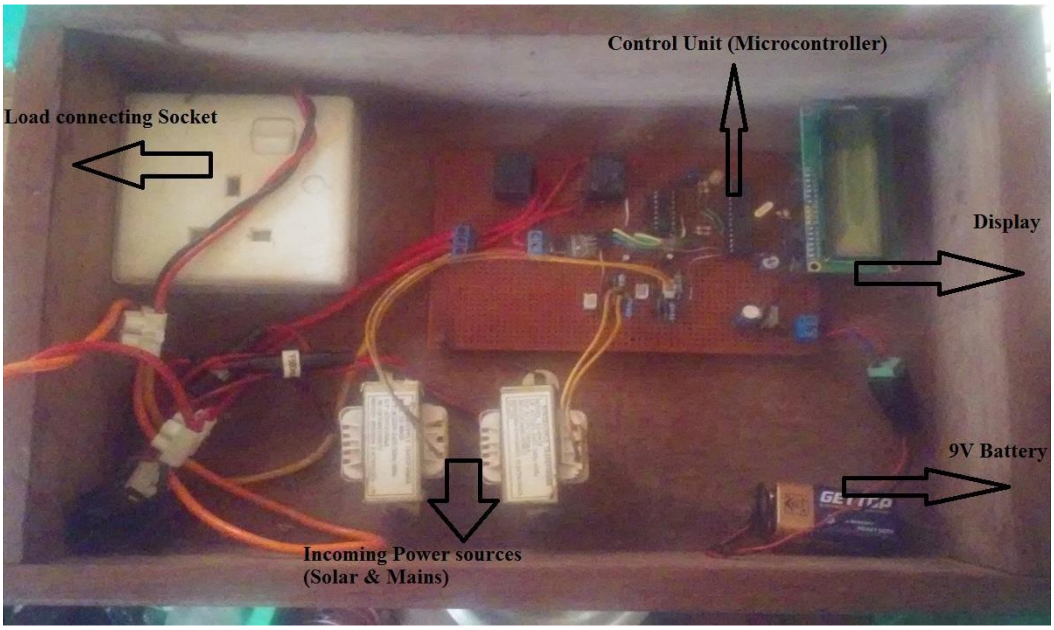

Fig. 11 ATS Complete Circuit Operation

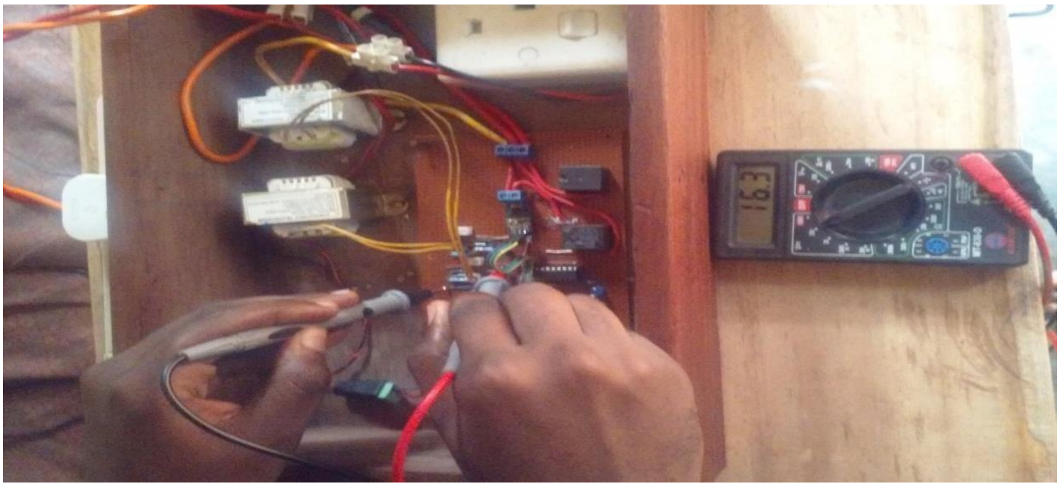

Fig. 11 Laboratory Construction and Testing

Design concept

Eastern and Central African households, especially Ugandans and Congolese do not purchase Solar PV system that fits their loads requirements. They face challenges when it is cloudy i.e. no enough solar irradiance to power Panels, Solar PV system goes off leaving the entire household without electricity, in darkness. And also, sometimes they want to use high power consumption appliances such as Iron, but cannot because their installed capacity is less than the loads at that specific moment.

The ATS device enables PV solar system owners to be powered by the Mains (UMEME) for a specific amount of time.

This system requires the following in order to be effective:

- A solar PV system
- Mains Power from a Utility (UMEME)

It is based on the *"Open transition"* operation. The Open transition refers to breaking the connection of the primary source before connecting to the secondary. Therefore, a time-delay is involved in this operation. For this project, a delay of 300ms.

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