Development of Smart Electricity Distribution Algorithm for Multi-Source and Segmented Loads in Buildings

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Abstract

Nigeria has encountered numerous power issues in recent years, including limited and irregular power supply, high power costs, and underdeveloped power facilities, all of which have had major negative consequences on the country's socio-economic development. To improve power availability in buildings and ensure adequate usage efficiency, this paper presents the development of a smart electric power distribution algorithm for multi-source and segmented loads, for implementation on distribution boards. This research aims to develop an algorithm that may be used to support the current building wire infrastructure in Nigeria, allowing for 24/7 reliable power supply and effective management of limited power supply in buildings. It employs a multi-source and segmented load system to provide reliability and energy efficiency measures to balance power supply and demand in buildings. Actual data from offices in the engineering complex of Niger State Polytechnic Zungeru, Nigeria, was used to simulate the developed system in MATLAB Simulink. Results showed that the developed algorithm conserved power by 33.71% compared to the conventional distribution board.

Keywords

Smart distribution board, Smart distribution algorithm, multi-source, segmented load, energy efficiency.

1. Introduction

Our contemporary society has become very dependent on the availability of electric power (National Institute of Open Schooling 2019). The consumption of electrical energy is a part of our daily life in such a depth that we can almost not do without adequate supply of electricity. We constantly need electrical energy for domestic and industrial purposes. A nation's development is measured by the per capita consumption of electrical energy by its citizens (Olugbenga et al. 2013). Energy plays a crucial role in the global economy's expansion and socioeconomic development. The ability to access energy is essential for an economy to grow sustainably, and its absence could have serious ramifications that are harmful to society as a whole (Onyekwena et al. 2017). Industries, agriculture, transportation, and the service sector are important sections of the economy where energy cannot be substituted. Future energy demand is anticipated to rise in response to rising global population, living standards, and fast industrialization (OECD 2012)

However, the supply of electricity constantly faces challenges ranging from generation down to the final consumption (Sambo et al. 2012). The inability to store electricity in its alternating form (a.c) is one of the greatest problems facing the generation and supply of electrical energy (El et al. 2020). It has to be consumed as it is being generated and still, the rate of consumption has consistently exceeded the rate of generation. Also, the world's rapid population increase and industrial growth has made this even a more pressing challenge. The available energy is very limited to sustain the booming world population and this has consequently influenced the high cost of the little available supply.

Substantial amount of effort has been made to address this issue such as; load sharing where power is supplied to a particular area for some time and then switched to another location (Okolobah & Ismail 2013). Also, other sources of electricity have been harnessed such as solar, wind, biomass, etc. However, most of the above alternatives of energy source are dependent on the availability of sun and wind which are not constantly available throughout the day or seasons (Shaner et al. 2018). As a result, the problem of energy scarcity still lingers. Hence, the management and efficient use of the limited available electricity is a matter of urgency and various policies and strategies have been considered in this regard. All these are aimed at reducing the cost of energy consumption. Various energy management systems (EMSs) have been devised and proposed to optimize the energy utilization from the grid.

Energy Management System (EMS) is the process of monitoring, controlling, and conserving energy in an organization/building (Amaral et al. 2013). This is achieved by decongesting the grid, making allowance for alternative energy sources, development of distribution boards that can dynamically switch between power sources and load segmentation. In recent times, a lot of attention is drawn to smart energy management systems (SEMS) because of their potential to autonomously control power consumption without human intervention. Though many works have been carried out on SEMS such as smart grid, smart metering, smart distribution algorithm and various applications of the Internet of Things (IoT) on electric power management as discussed in the literature review section, this work is aimed at improving existing smart distribution algorithms to provide not just reliable power supply but to drastically minimize energy consumption from the grid. We developed a smart electricity distribution algorithm that uses segmented multiple sources and segmented loads to the energy saving efficiency of existing distribution bards, save cost on electric power consumption and forestall the high level of power outages in Nigerian buildings.

The remaining part of this paper is organized as follows. Section 2 investigates some related works on smart energy systems, section 3 discusses the approach used in the design of the proposed smart distribution algorithm, section 4 presents the data gathered for the experiment, section 5 analyzes the results and section 6 concludes the paper.

1.1 Objectives

The objectives of this research work are: to measure and estimate the power consumption of offices in the engineering complex of Niger State Polytechnic Zungeru in Nigeria, to develop an algorithm for the smart electricity distribution system using fuzzy logic, to simulate the algorithm on Matlab and Simulink and to evaluate the performance of the developed algorithm in energy-saving against conventional electricity distribution board.

2. Literature Review

In this section, a variety of research studies on smart energy systems are discussed. Okae *et al.* (2017) for example, developed and executed a building-based smart energy management solution (SEMS). They created a generic algorithm that ensures a steady supply of electricity and efficient power management in buildings. The modeled system with SEMS ensured that the high-priority devices were operational during the occupants' working hours. Similarly, Joshi and Prof. (2017) presented a practical application of the Internet of Things (IoT) for monitoring residential appliances. The developed system was based on wireless sensor networks, which consisted of a current and voltage sensor placed at an electrical load to sense current and voltage, after which the power consumption of electrical appliances was calculated and transmitted wirelessly to an ethernet shield using the Zigbee protocol. Home appliances can be controlled in three ways: manually, automatically, or remotely. The system uses less energy and is inexpensive to operate due to its small size.

A system based on the Internet of Energy (IoE) was presented by (Hannan *et al.* 2018). The system offers revolutionary possibilities for sustainable building energy management. The author opined that, for sustainable building energy utilization, the existing building energy management system (BEMS) requires upgraded controllers coupled with IoE-based technology. By preventing energy loss and facilitating sustainable energy development, IoE provides sturdy qualities for exchanging power with appropriate energy usage. Ashaj and Erçelebi (2019) on the other hand provided another option for a SEMS for homes and buildings that regulates multiple electrical appliances in real-time. The system combines artificial intelligence (AI) with a low-cost single-board computer to manage light and turn on/off various gadgets by analyzing electricity use, temperature control, and human activity.

A concept of SEMS was proposed by Farzaneh *et al.* (2021), which requires the use of sensors and big data (BD) as well as AI. AI technologies can help reduce energy use by improving control, reliability, and automation. It provides a cyber-physical system that links the cyber world with the physical world, which includes various electric appliances and electronic equipment. It also incorporates sensing devices, controllers, and metering components. Artificial intelligence aids in the optimization of complicated systems' operations by reducing the computing load quickly and efficiently. Meliani *et al*. (2021), introduced the use of EMS to successfully increase the balance between supply and demand while also reducing peak load during unscheduled periods. This is accomplished through the use of clever algorithms and modern control systems to efficiently optimize and schedule load demand.

Etedadi Aliabadi *et al*. (2021) advocated for Home Energy Management System (HEMS) coordination as a means of flattening aggregated load profiles, lowering electricity bills, facilitating energy trading, reducing reverse power flow, managing distributed energy resources, and changing consumer consumption/generation patterns. The method has the potential to reduce electricity expenses by 5% to 30%. The architecture of neighbourhood areas lends itself to coordination strategies based on distributed topology. Gomathy *et al*. (2020) proposed an intelligent energy management system that minimizes peak energy use, moves usage to off-peak hours, and reduces overall energy consumption, especially in smart homes. The use of sensor networks, enables devices to adapt to available power using intelligent monitoring and control algorithms. The HEMS is an Android-based system that allows customers to schedule their appliances.

HEMS based on the whale optimization algorithm (WOA) for scheduling multiple home appliances was proposed by Kaur and Singh (2021). The metaheuristic WOA is providing information on various electrical equipment, such as their power and energy consumption, as well as their configurational characteristics. This information is used by the WOA to schedule the various electrical devices for a set number of iterations. The load demand and cost utilization are defined in terms of the fitness function in each iteration. Prajwal and Gupta (2018) created an EMS that can identify peak times or power shortages and take appropriate action to ensure that consumers are not inconvenienced. The designed system will handle the issue raised to reduce the supply-demand mismatch. The system is made up of two modules: a load forecasting module that forecasts the smart home's next day load, and an energy management module that accepts the inputs needed for a continuous power supply during a power outage while also maximizing energy efficiency.

Esmaeel Nezhad *et al*. (2021) proposed a new model for the self-scheduling problem based on a HEMS, which took into account the presence of solar photovoltaic (PV) panels as well as an air conditioner (AC). The temperature is controlled by an inverter in the air conditioner. The proposed approach is called Time of Use (TOU) for electricity tariffs, with the primary goal of lowering the daily payment. There are certain fixed and variable loads, and to achieve the lowest daily bill, the optimal scheduling of home appliances is treated as a mixed-integer linear programming (MILP) problem. To deal with the unpredictable solar power generation as well as optimally serve the loads during peak hours, the HEMS comprises a PV system integrated with electrical energy storage (EES) system, taking into account the charging and discharging control strategy of the installed EES. In the same vein, Hosseinnezhad and Shafie-khah (2020) suggested a two-stage model of HEMS. An adaptive neuro-fuzzy inference system performs the work, regulating the gaps between anticipated and actual values. The system determines an optimal operation scenario with an appropriate real-time regulation success rate. Under demand response (DR) strategies, the deployed HEMS may maximize the combined scheduling of various household appliances, renewable energy resources, and energy storage.

Arcos-Aviles, Pascual, *et al*. (2021) proposed Fuzzy Logic Control (FLC) based EMS for smoothing the grid power profile of a grid-connected electro-thermal microgrid. When renewable energy sources are integrated into pre-existing grid-connected household appliances, the case study intends to create an EMS to minimize the impact on grid power. The scenario covers a residential microgrid with photovoltaic and wind generators, flat-plate collectors, electric and thermal loads, and electrical and thermal energy storage devices, with no regulated renewable generation or electrical and thermal load demands. The EMS forecasts the microgrid behavior for the 15-minute interval for the 12 hours using a forecast of the electrical and thermal power balance between generation and consumption. Baset *et al*. (2020) presented an energy management strategy for controlling the operation of various components inside a renewable energy system. In a fuel cell (FC)/battery storage (BS)/supercapacitor (SC) system, the battery aids the FC while the load power is high, while the SC works during load transients or fast changes in load. Also, the FLC is at the heart of the management plan. It is utilized to manage the load demand among the many components of the FC/BS/SC system as efficiently as possible.

Jafari *et al*. (2020) introduced a revolutionary EMS for a home microgrid application with two operating horizons. The microgrid uses photovoltaic, FC, and battery bank energies to provide local loads via a combination of electric and magnetic buses. The suggested microgrid can function in a variety of grid-connected and off-grid modes. A long-term data prediction unit based on 2-D dynamic programming and a short-term fuzzy controller is included in the EMS. The long-term prediction unit is used to estimate the proper variation range for the battery state of charge and FC hydrogen condition. Zand *et al*. (2020) introduced an adaptive fuzzy logic-based energy management technique for a combined power generating system incorporating FC, battery, and an ultracapacitor, The FC serves as the primary energy source, with the battery and ultra-capacitor serving as backup. In comparison to the power tracking control (PTC) technology, it saves fuel usage and better tracks the reference speed.

Arcos-Aviles, Pacheco, *et al*. (2021) proposed EMSs based on off-line trained FLC as an alternative to those based on online optimized mixed-integer linear (or nonlinear) programming to reduce computational effort. Using two nature-inspired methods, particle swarm optimization, and differential evolution, it aims to reduce the power peaks and fluctuations on the power profile exchanged with the utility network. Similarly, Busisiwe *et al*. (2021) suggested a fuzzy logic-based EMS reduce domestic electricity usage by scheduling household appliances according to TOU tariffs. A fuzzy logic electrical energy controller was used to accomplish this. Variable load consumption per hour was used to optimize the process. The fuzzy rules were created to make intelligent decisions based on the time of usage tariff, daily limit remaining, and load consumption. The consumer selected the preferred number of days, and the system computed the daily limit based on the amount of electricity available in the smart meter.

Yasin and Alsayed (2021) proposed an FLC-based power management strategy for managing power flows in a small and local distributed generation system. The main power sources in the stand-alone Micro Grid (MG) are wind and PV generators. A battery storage system (BSS) and a Diesel Generator (DG) with an SC make up the backup system. Through the DC bus, the various energy sources are linked. The proposed management scheme's main goal is to restore the system's power balance. Teo *et al*. (2020) offered a fuzzy logic-based energy-management system (FEMS) for a grid-connected microgrid with renewable energy sources (RESs) and an energy storage system (ESS). The FEMS aims to reduce average peak load (APL) and operating costs by managing the charge and discharge rate of the ESS depending on the ESS's state of charge, the power difference between load and RES, and the electricity market price. The membership functions have a significant impact on the usefulness of fuzzy logic.

Literature has revealed that a lot of work has indeed been done on smart energy management systems. On smart distribution boards, Okae *et al*. (2017) developed a smart distribution algorithm that uses multisource and segmented loads. Their system achieved energy efficiency of 20%-25% compared to traditional distribution boards without a smart algorithm component. However, in their work, multiple sources were not segmented. They were harnessed as a single input to ensure increased power availability. Thus, Switching was only done at the load level. Hence, in this work, the energy sources are segmented like the loads, and the developed smart algorithm feeds the load based on their requirements using the most suitable and cost-efficient source.

3. Methodology

This presents the methodology and procedures of the proposed smart distribution algorithm. Four independent power sources S1, S2, S3, and S4 are defined. S1 is power supplied from the solar, S2 is the grid source, S3 is the battery source, and S4 is supply from the generator. Supply from the solar (S1) has the highest priority because it is cheaper while S4 has the least priority. Moreover, L1, L2, L3, and L4 are segment loads with a wattage rating of W1, W2, W3, and W4, respectively. L1 is the sum of all lighting points and ceiling fan loads, L2 is the sum of all 13 Amp sockets loads, L3 consists of all 15Amp sockets loads, while L4 consists of all security lighting points. In the loading domain, during the day (between 7 am to 6 pm), L1 has the highest priority because it consumes the least amount of power and is the most vital for buildings, while L3 has the lowest priority. At night (between 6 pm to 7 am), L4 is the only priority. The system model is given in Figure 1.

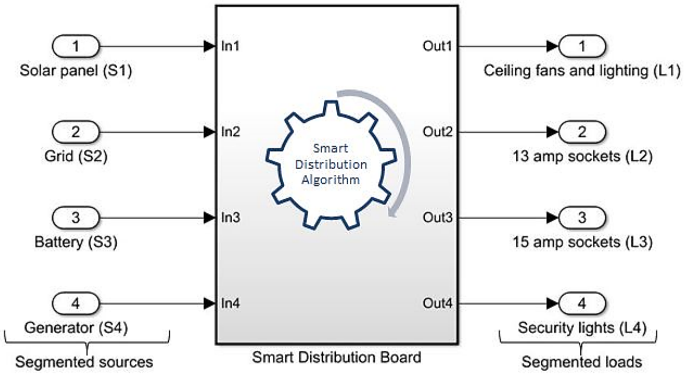


Figure 1. Smart distribution board model

3.1 Smart Distribution Board Algorithm

The pseudocode of the smart distribution algorithm and the flowchart (see Figure 2) are discussed in this subsection

Pseudocode of smart distribution algorithm

```
$Input(W1, W2, W3, W4)$
$Estimate(W_{s1}, W_{s2}, W_{s3}, W_{s4})$
$If\,(7am \le time \ge 6pm)$
    $Activates(fuzzy - controller)$
$Else(L1, L2, L3 = 0)$
    $if\,(W_{s2} > W_{L4})$
    $Display(S2 \rightarrow L4)$
    $Elseif\,(W_{s3} > W_{L4})$
    $Display(S3 \rightarrow L4)$
    $Elseif\,(W_{s4} > W_{L4})$
    $Display(S4 \rightarrow L4)$
    $Endif$
$Endif$
```

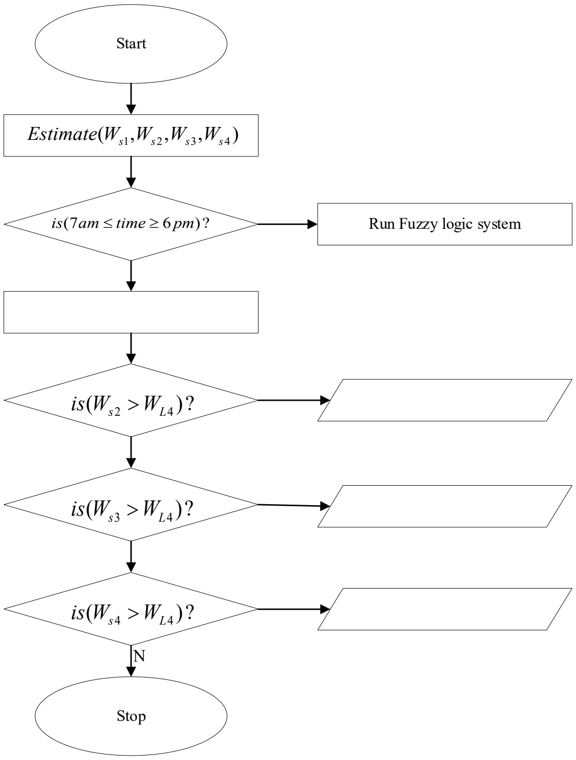


Figure 2. Flowchart of smart distribution algorithm

From the pseudocode and flowchart, the distribution algorithm turns off all loads at night time and selects a suitable source to power the security lighting points starting from S2 to S4. S1 is ignored at night time due to the unavailability of sunlight. During the daytime, the algorithm activates the fuzzy logic system to decide which load(s) should be powered and the appropriate source(s) to use. The proceeding section discusses the fuzzy logic system employed and its various components.

3.2 Fuzzy Logic System

The Mandani Fuzzy Inference System (FIS) was used in the fuzzy logic system to map sources to loads dynamically. The Mandani FIS was used because of its simplicity in design and high level of accuracy. The model of the Fuzzy logic system was designed in Matlab and presented in Figure 3.

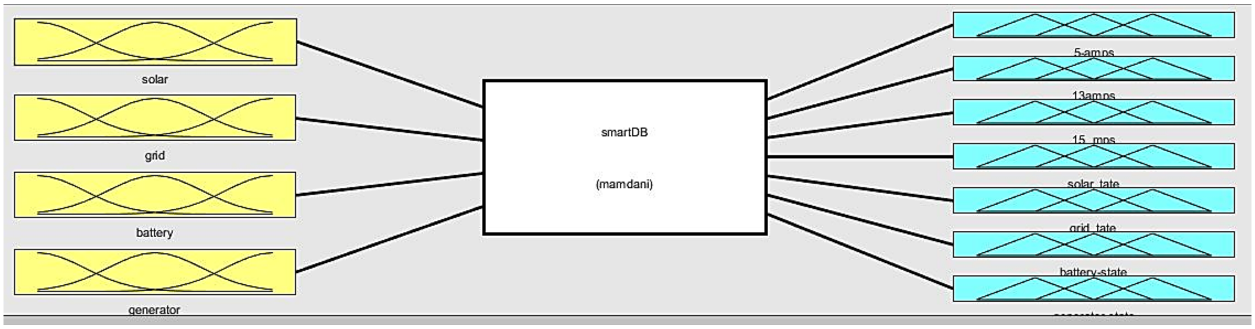


Figure 3. Fuzzy Logic System Model

The FIS is composed of four (4) inputs which are the four (4) independent sources considered in the study, that is, solar panel (S1), grid (S2) battery (S3) and generator (S4). A triangular membership function was used in the fuzzification of the inputs because of its high computational efficiency as shown in Figure 4. The states of each input are: ‘off’, ‘low’, ‘medium’ or ‘high’. Where ‘off’ means that the specified source is turned down. ‘low’ on the other hand means the source can only serve L1. ‘medium’ indicates that the source can only serve L1 and L2 while ‘high’ means that the source can server L1, L2 and L3.

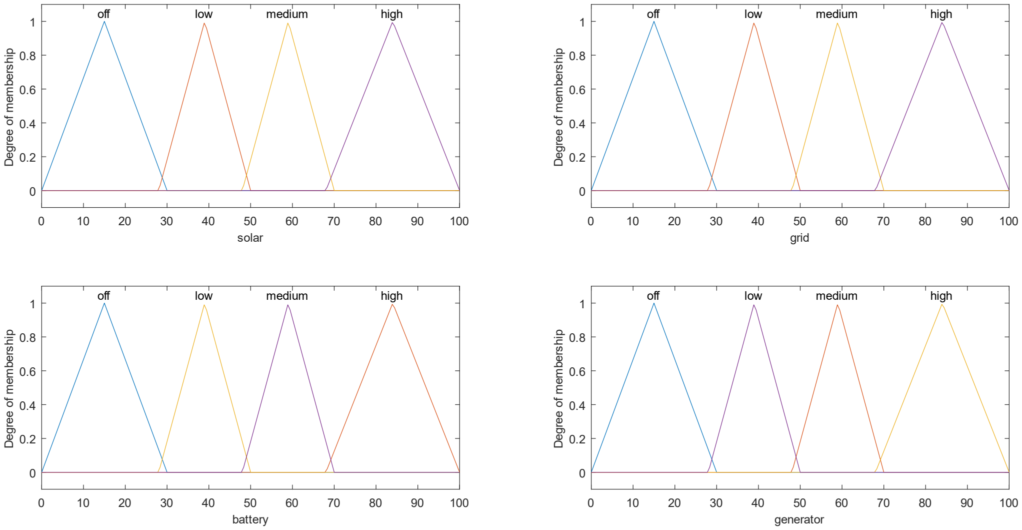


Figure 4. Input membership functions

The output variables of the FIS are 5 amps (L1), 13 amps (L2), 15 amps(L3) loads and the states of the four sources. In the defuzzification process, a triangular membership function was used with a centroid function. Centroid function was preferred over other defuzzification techniques because of its low computational complexity. Figure 5 and Figure 6 show the membership functions of the output variables. The state of the output variables for the loads is either ‘off’ or ‘on’ while that of the source is either ‘active’ or ‘idle’. ‘off’ means that the load is turned off, ‘on’ indicates that the load is being served’, ‘active’ means that the source is serving a load while ‘idle’ indicates that the source is ‘on’ but not serving any load or the source is turned off.

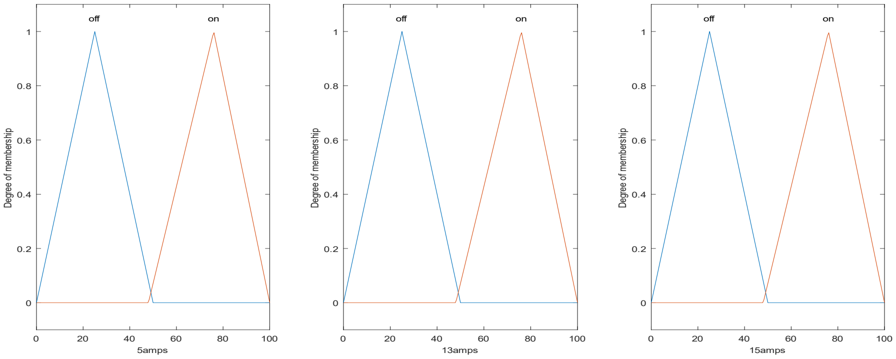


Figure 5. Output membership function of the loads

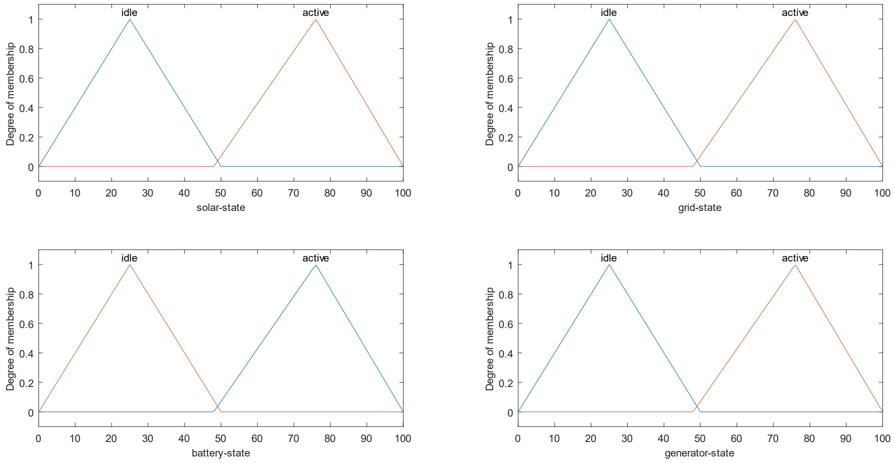
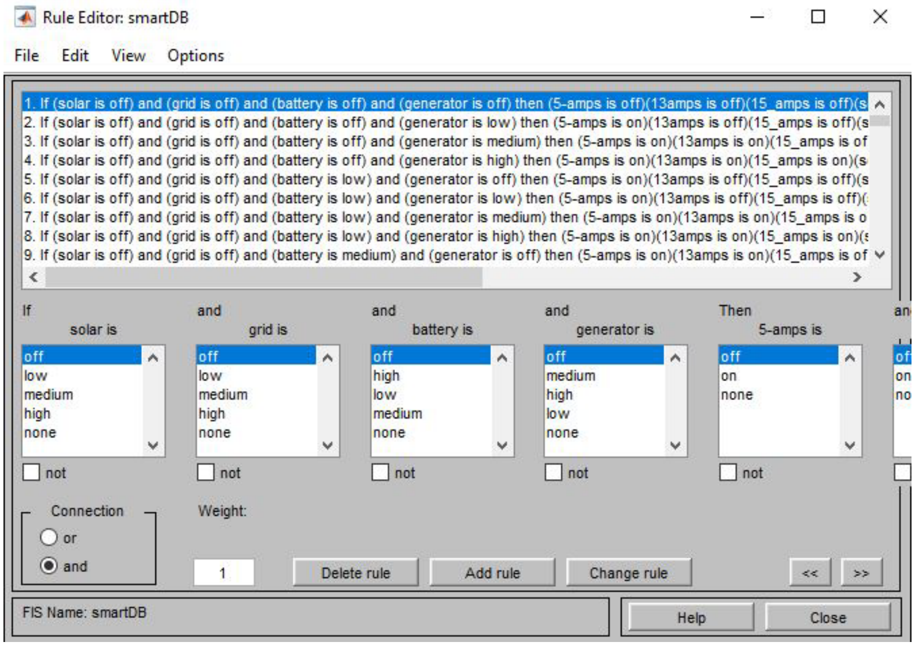


Figure 6. Output membership function of the sources

In the FIS, a total of 256 rules were used to determine the output as shown in Figure 7.



```
1. If (solar is off) and (grid is off) and (battery is off) and (generator is off) then (5-amps is off)(13amps is off)(15_amps is off)(s
2. If (solar is off) and (grid is off) and (battery is off) and (generator is low) then (5-amps is on)(13amps is off)(15_amps is off)(s
3. If (solar is off) and (grid is off) and (battery is off) and (generator is medium) then (5-amps is on)(13amps is on)(15_amps is of
4. If (solar is off) and (grid is off) and (battery is off) and (generator is high) then (5-amps is on)(13amps is on)(15_amps is on)(s
5. If (solar is off) and (grid is off) and (battery is low) and (generator is off) then (5-amps is on)(13amps is off)(15_amps is off)(s
6. If (solar is off) and (grid is off) and (battery is low) and (generator is low) then (5-amps is on)(13amps is off)(15_amps is off)(
7. If (solar is off) and (grid is off) and (battery is low) and (generator is medium) then (5-amps is on)(13amps is on)(15_amps is o
8. If (solar is off) and (grid is off) and (battery is low) and (generator is high) then (5-amps is on)(13amps is on)(15_amps is on)(
9. If (solar is off) and (grid is off) and (battery is medium) and (generator is off) then (5-amps is on)(13amps is on)(15_amps is of
```

Connection
○ or
● and

Weight: 1

FIS Name: smartDB

Figure 7. Fuzzy logic rules

As shown in Figure 7, rule 1 turns all loads off while rule 2 serves only L1 using S4. Rule 3 on the other hand, serves only L1 and L2 using S4 while rule 4 serves L1, L2 and L3 using S4. This continued until all possible combinations between the sources and loads were satisfied.

4. Data Collection

In this section, the power requirement of loads in the engineering complex of Niger State Polytechnic, Zungeru Nigeria was measured and presented in Table 1.

Table 1. Power requirement of loads in engineering complex, Niger state polytechnic Zungeru

SN	Load points	Average number of appliances	Wattage per device (Watts)	Total wattage (Watts)
1	Lighting points (5Amp)	352	40	14,080
2	Ceiling fans (5Amp)	321	60	19,260
3	13 Amp. socket outlet	447	600	26,680
4	15 Amp. Socket outlet	74	1500	111,000
5	Security lighting point	129	40	5,160

Before being fed into the algorithm, the measured values were normalized and transformed into a percentage. When the power output of a source input or output is less than 35 kW, it is represented in the algorithm by a value between 0 and 30. In this case, no output is sent to the load. However, it indicates 30-50 on the algorithm when it is between 35 kW and 65kW. Only the 5 Amp loads will be powered in this situation. Similarly, it represents 50-70 when the source input or output is between 65 kW and 175 kW. This signifies that the source is limited to 5 Amp and 13 Amp loads. When the input or output exceeds 175 kW, the algorithm interprets it as 70-100, implying that the source can supply all 5 Amp, 13 Amp, and 15 Amp loads.

5. Results and Discussion

This section explains and summarizes the findings of the Matlab simulation. Figure 8 shows that when solar, grid, and battery are high (that is >70%) and generator is off (that is <30%), the algorithm serves all the loads using only solar source while others are kept idle.

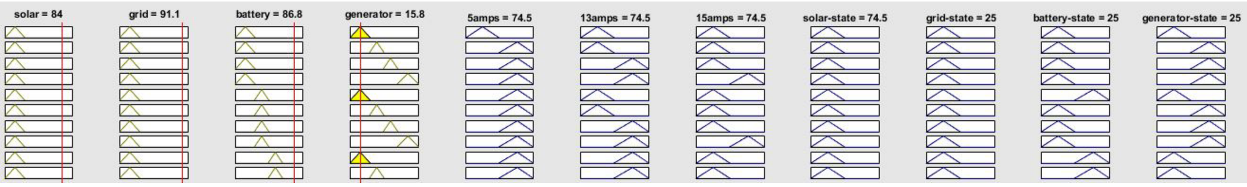


Figure 8. Simulation result 1

Similarly, in figure 9, the solar source is medium (50%-70%), the grid and battery are high (>70%) while the generator is off (<30%). In this scenario, solar powers the 5 Amp and 13Amp loads while the 15 Amp loads are powered by the grid.

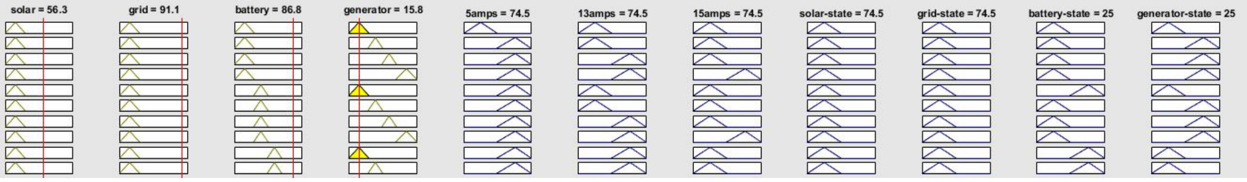


Figure 9. Simulation result 2

More so, when the solar source is low (30%-50%), the grid is medium, the battery is low and the generator is off, only 5 Amp and 13Amp loads are served by the algorithm. The 5Amp loads are served by solar while the 13 Amp loads are served by the grid as shown in Figure 10.

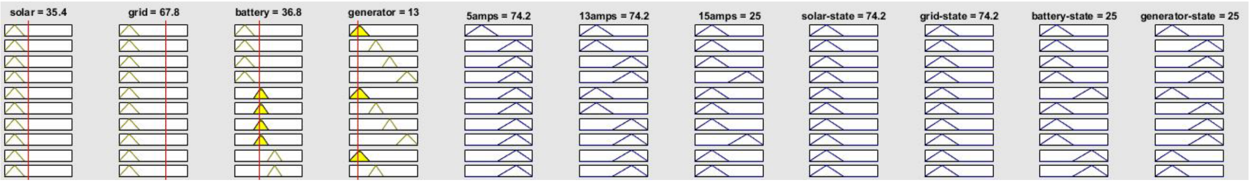


Figure 10. Simulation result 3

Figure 11 depicts the inputs from the four (4) sources throughout a seven-day research period. Except for the generator source, which was off during the research period, all of the sources were high on day 1. The grid and battery were both high on Day 2, while solar was medium. On Day 3, solar and battery power were low, while the grid was medium.

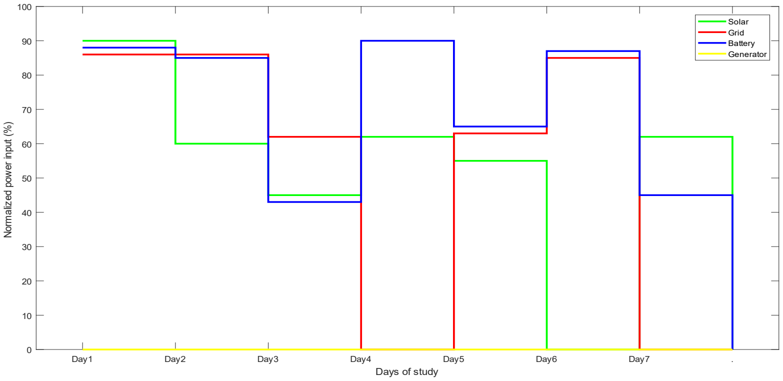


Figure 11. Source input states

Based on the source inputs presented in Figure 11, the output of the Conventional Distribution Board (CDB) is presented in Figure 12. Results showed that on day 1, CDB was switched to solar source because all the sources except the generator were high and solar is the cheapest. However, on day 2, only the grid and battery were high. The CDB was switched to grid because it is cheaper. This continued until day 7. The plot (Figure 10) shows that the CDB takes the cheapest source that can drive the most loads.

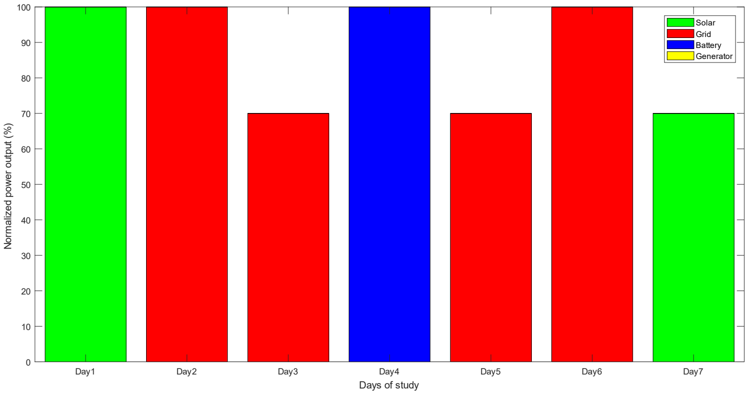


Figure 12. Output of conventional distribution board (CDB)

The Smart Distribution Board (SDB) on the other hand acts differently. Thought on the first day of the study, solar was selected as the preferred source to serve all the loads like the CDB (see Figure 13), on day 2, solar served the 5 Amp and 13 Amp loads while the 15 Amp loads were served by the grid. This is because solar is in a medium state, thus, it is capable of driving both 5 Amp and 13 Amp loads. Instead of using the grid to drive the entire loads because the grid is in high state as the CDB would do, the SDA assigned the 5 Amp and 13 Amp loads to solar and use the grid to power only the 15 Amp loads. Thus, power is saved on the grid. Similarly, on day 3, solar served the 5Amp loads while the grid served the 13 Amp loads. The system operated in like manner until day 7. The SDB when compared with the CDB saves an ample amount of energy because its sources and loads are segmented and the algorithm maps a suitable source to a suitable load dynamically.

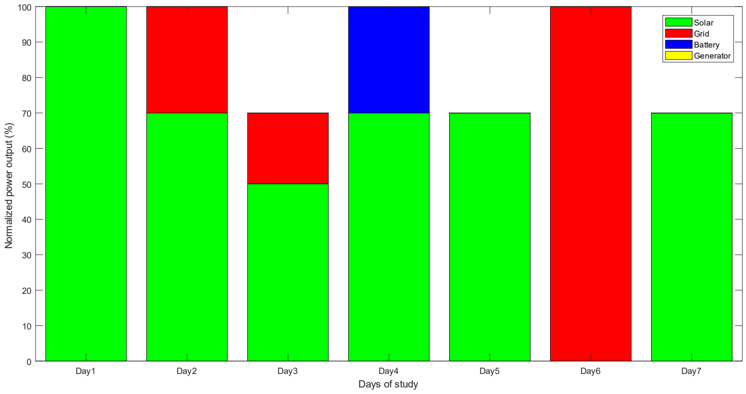


Figure 13. Output of Smart Distribution Algorithm (SDB)

5.1 Energy Saving Efficiency

This section examines the Smart Distribution Algorithm's (SDA) energy-saving efficiency across the research period. Table 2 shows the daily power consumption on the grid and battery by the SDA as compared to the CDB.

Table 2. Power consumption on the grid and battery

SN	Day 1	Day 2	Day 3	Day 4	Day 5	Day 6	Day 7
CDB (KW)	0	171.02	60.02	171.02	60.02	171.02	0
SDA (KW)	0	111.00	26.68	111.00	0	171.02	0

From Table 2, the total power consumption on the grid and battery by the CDB is 633.10 kW while the SDA consumed 419.70kW. This implies that the power saved by the SDA during the study period is 213.40kW. Thus, the energy saving efficiency is 33.71% according to equation (1)

$$\eta = \frac{E_{CDB} - E_{SDB}}{E_{CDB}} \tag{1}$$

where η is the energy saving efficiency of the SDA, E_{CDB} and E_{SDB} are the energies consumed by the CDB and SDB respectively.

6. Conclusion

In this paper, a smart distribution algorithm (SDA) was developed that can run on distribution boards with segmented multiple power sources and segmented loads in buildings. The SDA makes conventional distribution board (CDB) smart by dynamically assigning different sources to different loads in buildings based on demand. Simulation results showed that compared to CDBs that do not run the algorithm, smart distribution boards (SDB) that run the developed algorithm are capable of conserving power by 33.71%. More so, the energy saving efficiency of the developed SDB outweighs that of Okae *et al.* (2017) which operates on combined multiple sources with segmented loads and has a maximum energy saving capacity of 25%. This shows that segmenting both sources and loads simplifies a distribution board and allows for more dynamic power distribution and control. Furthermore, deploying the algorithm on CDB is simple as it only requires basic electrical reconfiguration and installation of electronic components such as a microcontroller unit (MCU) upon which the algorithm runs and a system of relays for switching.

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