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ANALYSIS OF MICRO HYDRO, PHOTO VOLTAIC, DIESEL GENERATOR WITH BATTERY STORAGE FOR RURAL ELECTRIFICATION

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***Abstract*— The study focuses on addressing the electrification challenges in rural communities, particularly in Essien Udim LGA, Akwa Ibom State, Nigeria, by designing a hybrid micro grid system. The micro grid solution presented integrates renewable energy sources (solar PV and mini-hydro) with diesel generator and battery storage to ensure sustainable and reliable power supply for the case study community. The work employed mathematical modelling, SIMULINK simulation, and genetic algorithm optimization carried out in MATLAB to determine optimal system parameters. A techno-economic analysis was conducted to evaluate the economic feasibility and the cost effectiveness of the micro grid, demonstrating its potential to enhance rural electrification, reduce dependency on fossil fuels and improve economic viability. Key findings reveal a payback period of 0.65 years and a 48% internal rate of return, highlighting the system's economic sustainability. The study contributes to knowledge by optimizing micro grid design and operations offering a scalable solution for rural energy access. For the time of the operation of the energy sources, National grid was to operate from 4am to 8am, solar PV to operate from 8 am to 4pm, the battery cell was to operate from 4pm to 9pm and the diesel plant to operate from 9pm to 12 am, the mini-hydro to operate from 12 am to 4 am; this outcome when implemented will ensure a constant electricity in the community.**

Keywords — Genetic Algorithm (GA), Solar PV, Micro Grid, Renewable Energy Sources , Hydro Power

1. INTRODUCTION

The use of electricity has brought tremendous development across the globe. It is usual to begin the electricity distribution by making it available in the cities since they host both industries and businesses [1,2]. The presence of electricity in these locations allows telecommunication companies, institutions, and firms to function better financially.

On the other hand, agricultural workers have struggled to increase their earnings. In their study, [3] found that rural areas have a greater share of people living in poverty than the people living in urban areas. According to [4,5], the cost of relying on fossil fuels for rural electricity is very high, which leads to minimal returns because of poverty. Also, [6,7] found that approximately 42% of rural settlements have been without power for some years and there is unlikely to be any improvement. The authors found in their work that the solution to improve power supply in affected areas is to either connect from an outside energy source, or use several small power sources without connecting to the national electricity network [8,9].

Accordingly, the focus in this work is to supply the community in Essien Udim with a total of 7.3MW of electricity by combining renewable energy with fossil fuel energy. PV solar panels, a mini-hydro system, and a diesel generator (for fossil power) are used to generate electricity. A storage unit for the batteries is linked to the low-voltage network. The essence of the study is to provide the design and some test case results based on the case study load demand and simulations conducted in SIMULINK and MATLAB software.

2. METHODS

2.1 The Research Material and the Procedure

The major materials for the research were the data collection and the software applications utilized for the simulation of the work, as listed in Table 1.

Table 1: Research Materials

Materials/Applications	Description
Data information sheet	Contains the outcome of the physical inspection carried out in the case study site and the data of the solar energy source, hydro-energy source, diesel plant and battery storage information.
SIMULINK	For modeling of the micro-grid
MATLAB	For computation of the values, data analytics and result presentation and arrangement
Office words	Data arrangement and presentation of the project report.

The research procedure is as presented in Figure 1. The case study site selected for the research is a local community situated in Atan Ikot Okoro, Essien Udim local government area of Akwa Ibom State. The choice of this community was based on the availability of river (which can be used for the mini-dam) and the high rate of sunshine hours especially during the dry season. These available energy resources are necessary for the generation of electricity in solar systems and hydro-dams.

The location of interest has a river with current. Hence, a physical inspection was carried out to determine the current rate and the depth of the river to determine the hydraulic head that is necessary to determine the water volume to be required for the mini-dam. The meteorological information of the location was determined, especially the peak sunshine and sunshine hours, to determine the amount of power that can be generated within the period of the sunshine. The information is necessary to determine the number of solar PV cells required to generate to load demand of the community. The load demand obtained for the case study community were used in sizing the battery bank and the diesel generator. Hence, the power outputs from each generation source of the micro-grid were the independent parameters to the linear model that were utilized as the objective function for the genetic algorithm (GA) optimization technique.

The data utilized, especially the load data, as shown in Table 2 was based on the empirical load profile survey that was carried out within the case study community in Essien Udim. The total load from Table 2 represents the actual load for the modelling of the power system network with value being 7.4036MW. Further information obtained showed that the electricity generated from the national grid lasts for 1.5 hours daily. The estimated timing from the electricity from the national grid was between 3- 4:30pm (based on information obtained from the resident of the community). The design for the power ratings (expected power outputs) of each of the power generation components was based on the total load of the case study site.

Table 2: Load profile of the community

Residential Load		**Commercial load**	
Units (amount)	**Load (kW/hr)/per unit**	**Units (amount)**	**Load (kW/hr) per unit**
High load consumption building (900). **Low load consumption house (400)**	**4.70 (4.23MW)** **2.90 (1.16MW)**	**Churches (19)** **Health center (1)** **Lock up shops (55)** **Wielding stations(3)**	**2.567 (0.049MW)** **0.320** **2.22 (0.1221MW)** **33.5(1.8425MW)**
Total	**5.39MW**	**Total**	**2.0136MW**

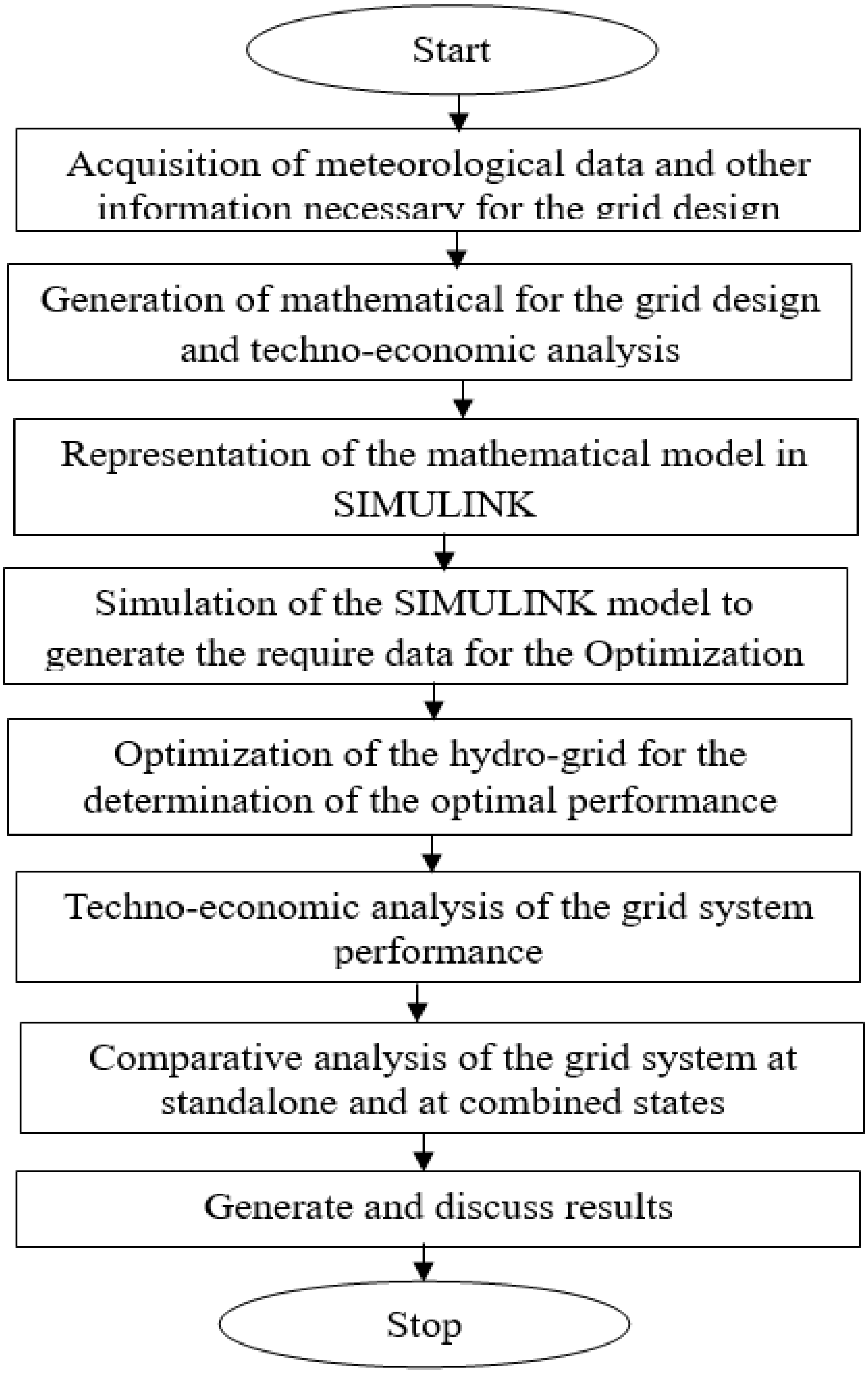

Figure 1: Flow Diagram of the Proposed Research Procedure

2.2 Design of the Energy Source Components of the Micro-Grid

According to the diagram shown in Figure 2, the excess energy generated from the solar PV and the hydro system during their peak time was stored in the battery bank. The type of current from the renewable source and the storage cell was DC, and it was converted to AC by the converter and distributed to the load together with the diesel and the grid that generates AC. When excess power is generated, then the excess power is stored in the battery after it has been converted from the AC to DC.

The solar PV design is as presented in figure 3, since;

$$P_{Load} = P_{PV} \quad (1)$$

Where PLoad and PPV represents the load demand and the power output from the PV. Then it implies that the number of panels required at 570W per rating and the inverter was dependent on the load demand of the existing load of the location with 20% tolerance hence [10,11];

$$P_{PV} = PP_W \times S_P \times E_{fp} \times 20\% \quad (2)$$

Where PPw represents the solar panel wattage (which was 570KW), SP represents the peak sunshine hours and Efp represents the efficiency of the panel (the ability of the power to convert sunlight to electricity which was 72%). Hence, the number of panels Np needed for the design was shown in equation 3 [12, 13].

$$N_p = \frac{P_{PV} \times 20\%}{PP_W \times E_{fp}} \quad (3)$$

Hence the number of panels required was determined to be;

$$N_p = \frac{5.39 \times 10^6 \times 0.2}{570 \times 10^3 \times 0.75} = \frac{1078000}{4275} = 252 \; panels$$

The 252 panels were obtained to generate an equal amount of power with 20% tolerance that will march with the load demand. However, the actual panel is obtained based on the optimization outcome.

The expected design component of the components was depended on the optimization outcome because the first guess to the optimization was shown in equation 3.2. The components' determination from the optimal grid design was the number of solar panels required and the expected operational time to charge the storage cells and send power to the case study at an optimized time. The same amount of load was utilized as the first guess to the determination of the optimized power for the hydropower plant.

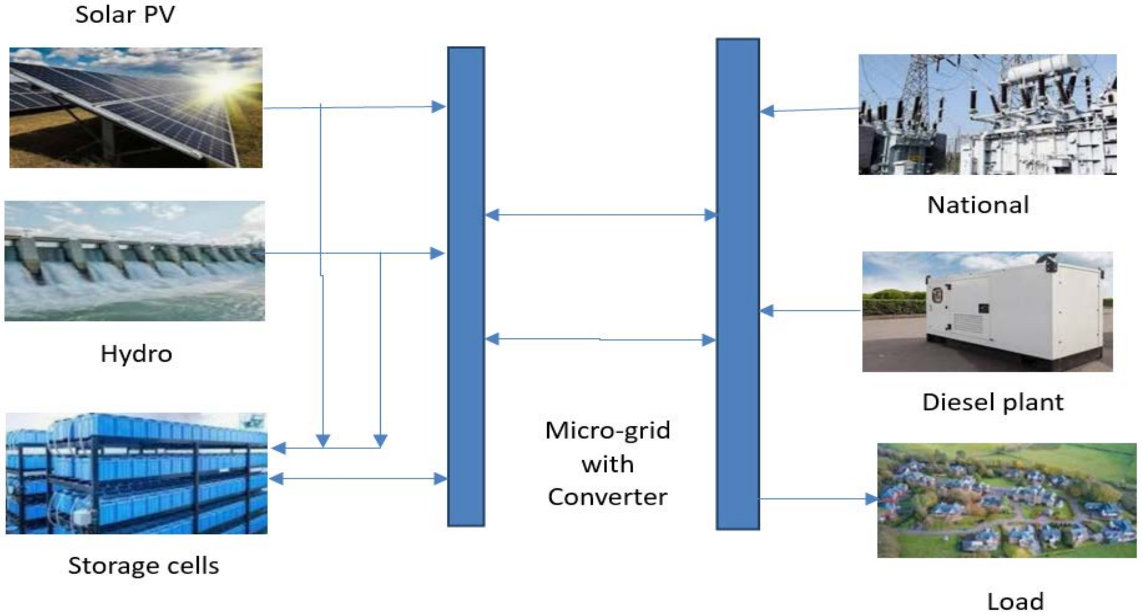

Figure 2: The grid design

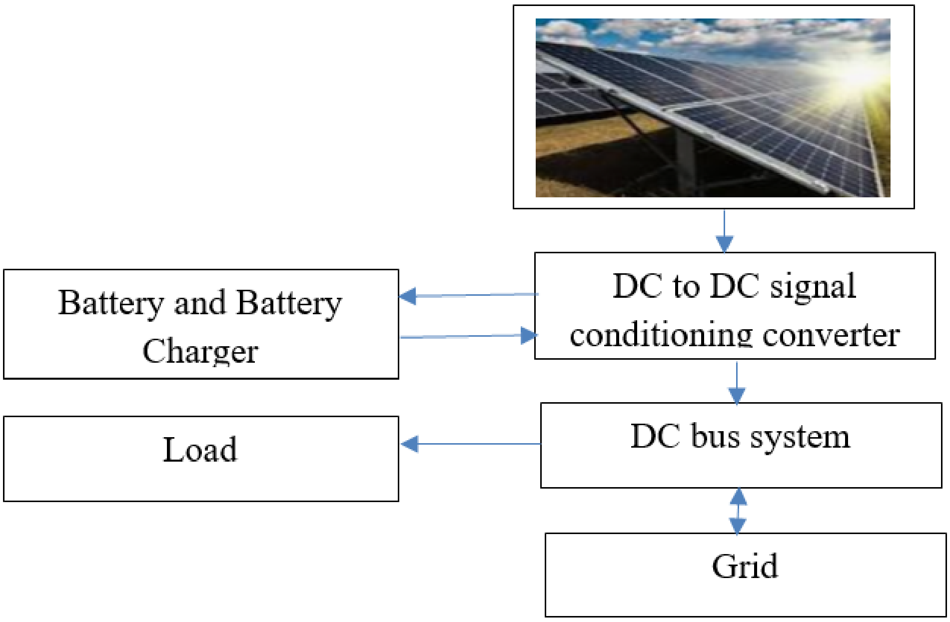

Figure 3: Solar PV design for the micro-grid

The micro- hydro plant design :

The major design components of the hydro plant was the determination of the power output of the hydro plants PHP, the optimal operation time To and the required velocity of the river V and the hydraulic head Hh because [14];

$$P_{HP} = (H_H \times V)\log(T_o) \quad (4)$$

The output and the operational time remain the actual parameters to be deployed for the operational time.

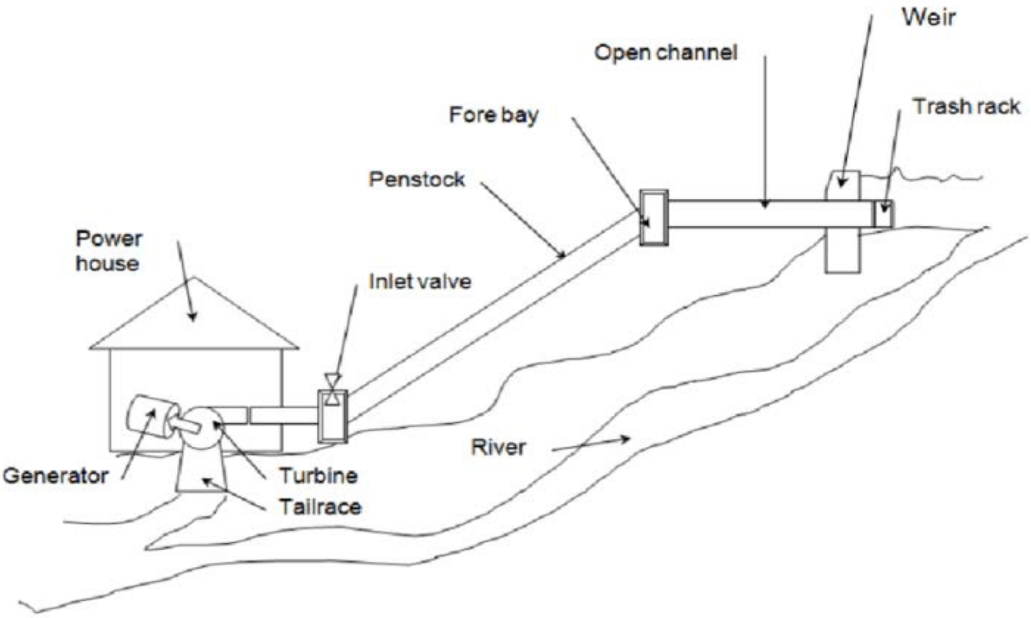

Figure 4: The micro- hydro plant design [15]

From the schematic diagram in Figure 4, it was imperative to determine the hydraulic high and the water velocity of the dam that will satisfy the optimal hydro-system for a satisfactory micro-grid design. The model for HH was shown in equation 5.

$$H_H = \frac{9.81 \times logV^2}{P_{HP}} \quad (5)$$

Hence, the volume of the Dam VD system for the water storage was shown in equation 6.

$$V_D = (P_{HP} \times 10\text{^}6)/(H_H) \quad (6)$$

The length LD, the width WD and the Height HD of the dam were shown in the following equations;

$$H_D = \frac{V_D \times 1.2}{3 \times V} \quad (7)$$

$$L_D = \frac{V_D}{H_D} \times 0.00312 H_H \quad (8)$$

$$W_D = \frac{V_D}{L_D \times H_D} 1.032 \quad (9)$$

The turbine power rating Ptub was shown in equation 10.

$$P_{tub} = 1.2017 H_H \quad (10)$$

Irrespective of the outcome of the optimization, the sizing of the hydro-turbine will not be changed. Hence, the time td it will take to fill the mini-dam was shown in equation 11.

$$t_d = \frac{V_D \times H_D \times P_{tub}}{2.89g} \quad (11)$$

Where g represents the gravitational force (9.81m/s2). The parameters values were significantly affected by the optimization process. The power output of the battery Pbat was shown in equation 12.

$$P_{bat} = P_{Load} \times 0.2 \quad (12)$$

Form the battery, the power was equal to the load demand with a tolerance of 20% and to determine the actual power, the power output from the solar PV and the hydro are utilized in increasing the power of the battery was presented in equation 3.13.

$$P_{bat} = 20\% \times P_{PV} + 30\% \times P_{HP} + P_{NG} \quad (13)$$

Where PNG denotes the national grid rated power output. The number of batteries Nbat required was shown in equation 14.

$$N_{bat} = \frac{P_{bat}}{I_{batt} \times V_{batt}} \quad (14)$$

Where Ibat is used to denote the battery bank rated current while Vbat is used to denote the battery bank rated voltage. The model for the power output of the diesel plant Pdiesel was shown in equation 15.

$$P_{diesel} = 1.2 \times P_{load} \quad (15)$$

The number of diesel generators Ndiesel necessary for the micro-grid was shown in equation 16.

$$N_{diesel} = \frac{P_{diesel}}{P_{rating}} \times 1.065 \quad (16)$$

Where Prating is used to denote the diesel generator rated power output. The diesel generator outcome is implemented in the GA optimization process.

Optimal Design of the Micro-grid

The models for the PV, micro-hydro, battery and Diesel generator with national grid power availability for 1.5 hrs were the objective function for the genetic algorithm optimization (GA).

From the data obtained, the model for each of the power outputs from the energy sources is obtained with the outcome utilized to form the objective function whose schematic model was shown in equation 17.

obj fun (expected grid power and time of operation for each power source)= a0+ $\sum$(Power output from each energy source) + estimated timing of each power sources (17)

Where a_0 represents the coefficient that will be determined using least square method. The initial guesses for the optimal micro-grid power is shown in Table 3.

Table 3: Output Power Coefficient Initial Guess for The Optimization

Parameters	Coefficient values
National grid	1
Solar panels power	1
Solar battery power output	½
Micro hydro power output	½
Diesel plant	2

The value (1) means that the national grid will generate power equal to the total load, ½ implies that solar battery will generate half of the total load and so on. The outcome of the optimization will adjust the guesses to the expected optimized outcome. The constraints to the optimization is based on the operational time of each device and the operating cost which will have a relationship between the power output and the operation time as shown in equation 18.

$Operating\ cost\ (each\ energy\ source) = (system\ installation\ cost)^D + (power\ output \times operating\ time)^x$ (18)

Where D and x where factors utilized based on the type of energy source device modelled. The optimization technique to be utilized is a genetic algorithm optimization process and it is carried out in the optimal tool in MATLAB application.

2.3 The Techno-Economic Analysis

The outcome of the optimization was present, the optimal sizing of each generation device that will ensure continuous power supply in the location of interest is simulated and the performance analyzed. The outcome of the optimization was subjected to techno-economic analysis. The outcome of the techno economic analysis of the micro-grid after optimization is compared to the system before design to determine the performance of the micro-grid design.

The techno-economic parameters necessary to determine the actual design cost of the micro- were: equipment cost, installation cost, managerial cost and operations with maintenance cost of the micro-grid. The equipment cost model utilized was presented in equation 19 as directed in [2].

$$equipment\ cost = cost\ of\ the\ solar\ PV\ system\ components + cost\ of\ the\ micro - hydro\ compoents + cost\ of\ utilizing\ national\ grid + transportation\ cost \quad (19)$$

The cost of transportation was taken as 10% of the solar PV cost. The management cost was 30% of the equipment cost; installation cost was 5% of the equipment cost while operations and maintenance cost 20% of the equipment cost.

3. RESULTS

3.1 Results of the Load Estimation

Smart grid design is mainly based on estimates of the load demand for different times. The plot for the estimated load is shown in Figure 5. The result in Figure 5shows that the load for the case study is 7.51MW. An extra 20% is given as a buffer and this value is used to meet possible demand for more electricity.

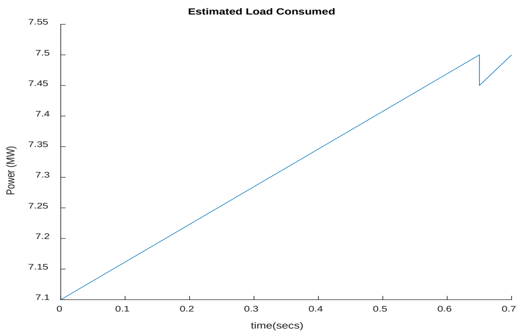

Figure 5: Estimated Load Consumption

3.2 Results of the National Grid Power Generation System

During the simulation, the Nigerian power grid gave 60 amps current signal which was relayed to the micro-grid (Figure 6). The power from the Nigerian grid to the micro-grid design measured 0.25kV (Figure 6). Power was raised from the micro-grid to the right voltage when it was sent to each consumer. The graph in Figure 8 demonstrates how the national grid energy source sends power to the micro-grid. Since the national grid provided enough electricity for the load demand, the micro grid had to include the functionality of the national grid on its own.

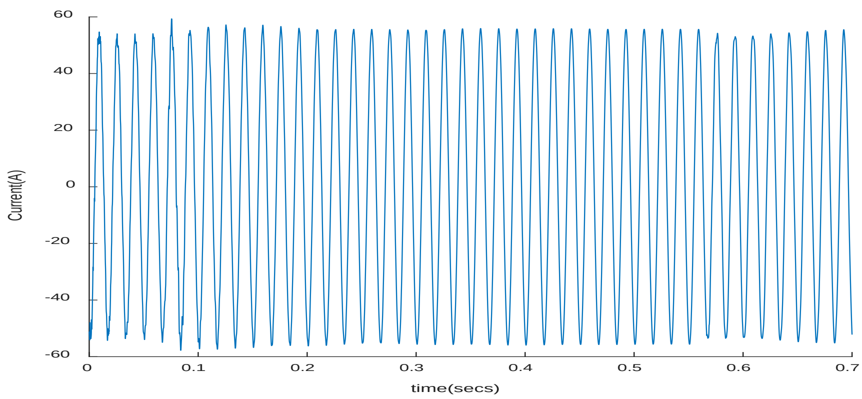

Figure 6: Current signal from the national grid

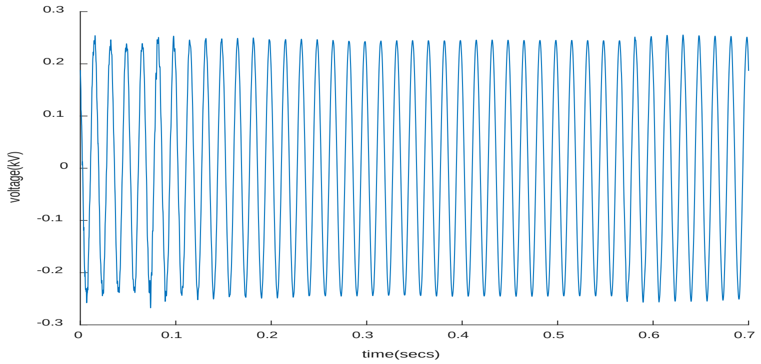

Figure 7 Voltage signal from the national grid

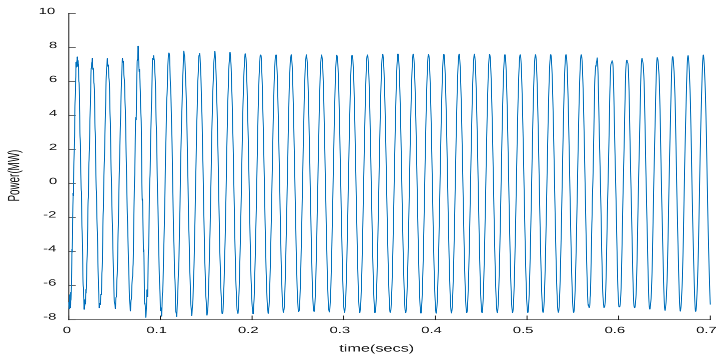

Figure 8: Power output from the national grid

3.3 The Results of the Solar PV

The current signal of the solar PV energy source to the micro-grid is shown in Figure 9 while the voltage signal is shown in Figure 10. The power output of the solar PV energy source to the micro-grid was shown in Figure 11.

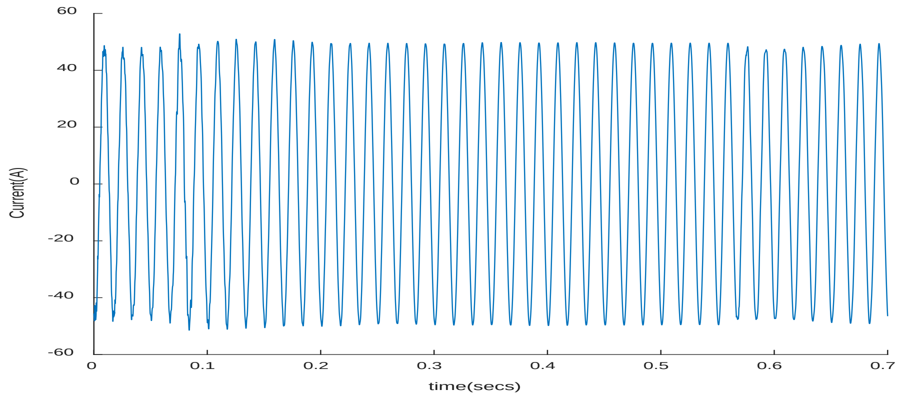

Figure 9: Current signal from the solar PV

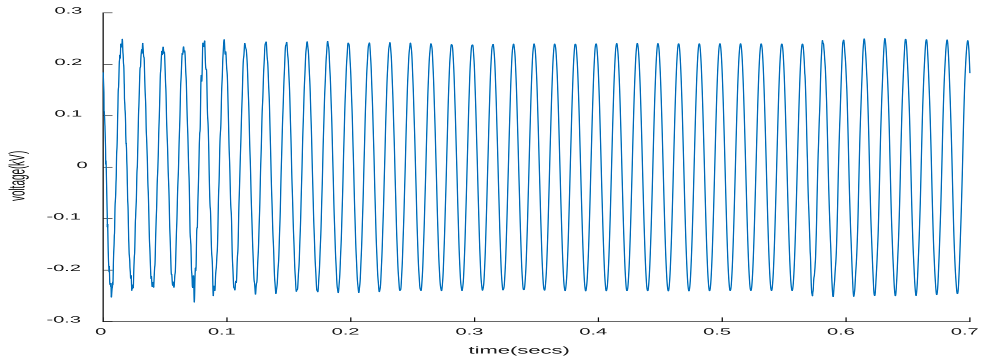

Figure 10: Voltage signal from the solar PV

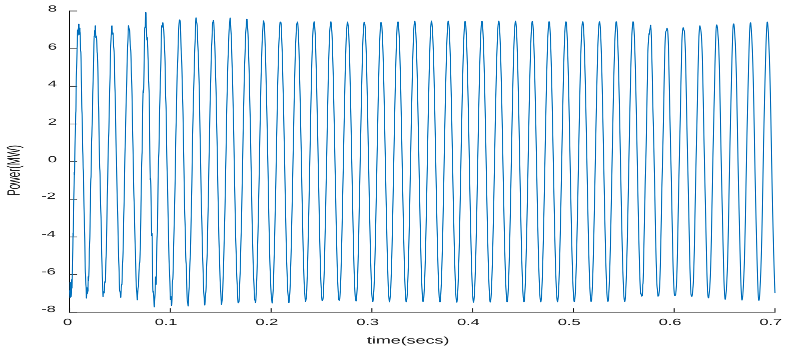

Figure 11: Power output from the solar PV

3.4 The Results of the Diesel Generator

The current signal of Diesel generator energy source to the micro-grid was shown in Figure 12 while the voltage signal is shown in Figure 13. The power output of the Diesel generator energy source to the micro-grid was shown in Figure 14.

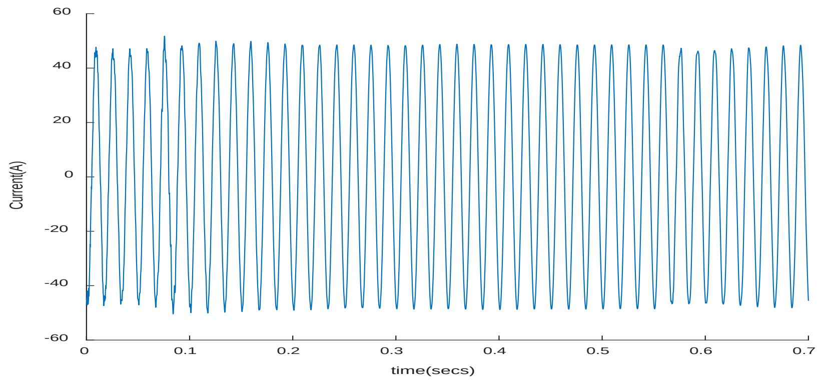

Figure 12: Current signal from the Diesel generator

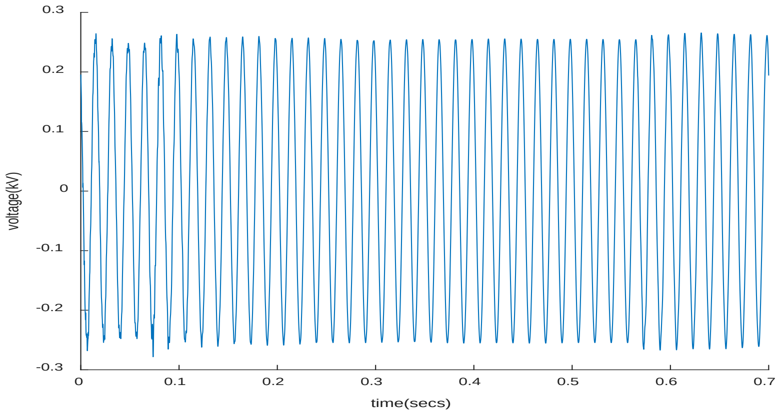

Figure 13: Voltage signal from the Diesel generator

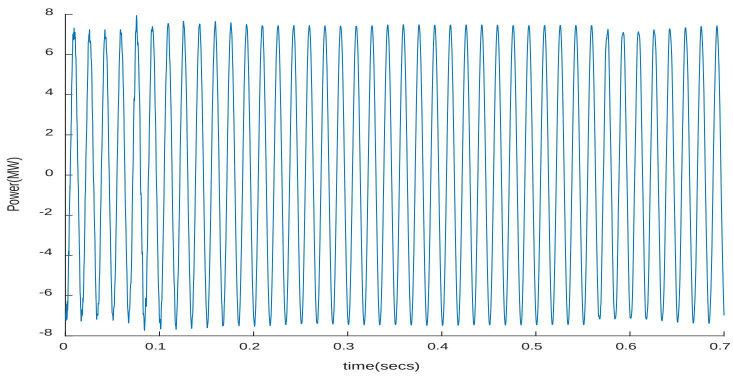

Figure 14: Power output from the Diesel generator

3.5 The Results of the Micro-Hydro generator

The current signal of micro-hydro generator energy source to the micro-grid was shown in Figure 15 while the voltage signal is shown in Figure 16. The power output of the micro-hydro generator energy source to the micro-grid was shown in Figure 17.

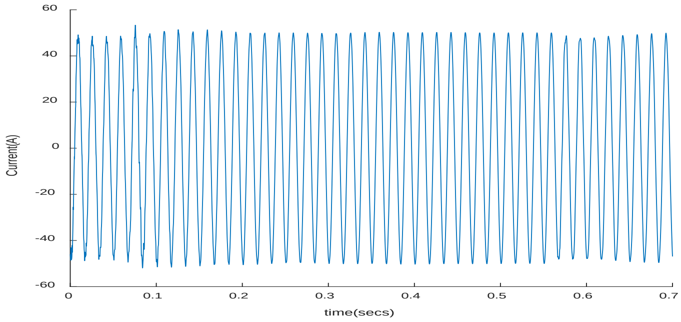

Figure 15: Current signal from the micro-hydro generator

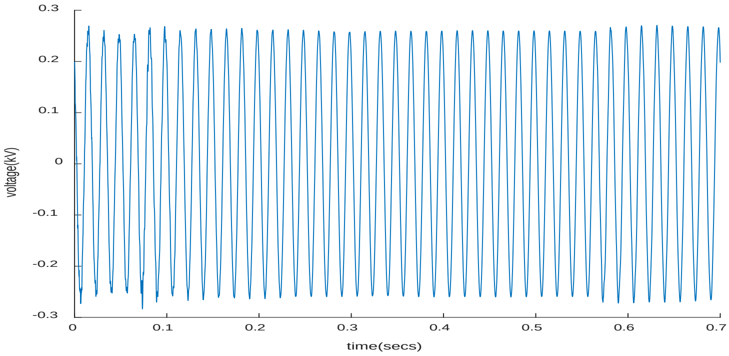

Figure 16: Voltage signal from the micro-hydro generator

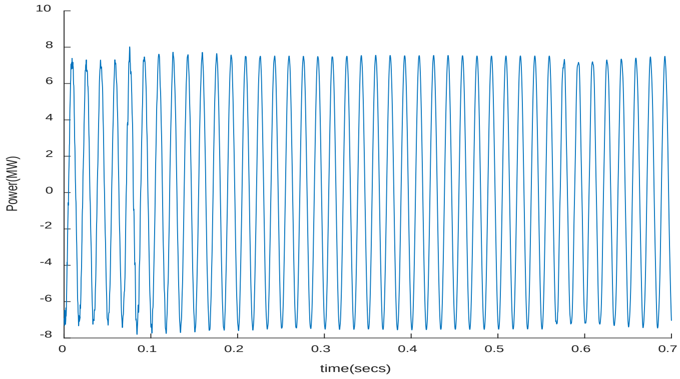

Figure 17: Power output from the micro-hydro generator

3.5 The Results of the Battery Bank

The current signal of battery energy source to the micro-grid was shown in Figure 18 while the voltage signal is shown in Figure 19. The power output of the battery energy source to the micro-grid was shown in figure 20.

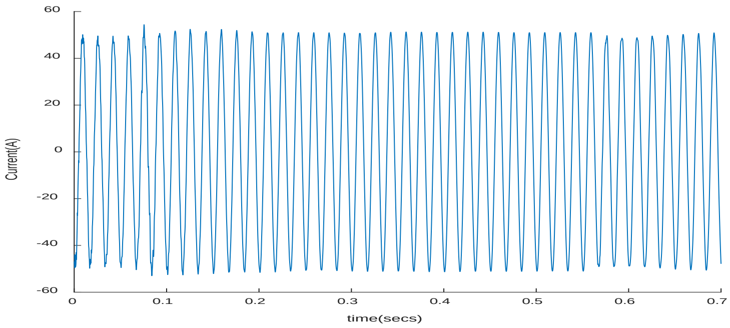

Figure18: Current signal from the battery

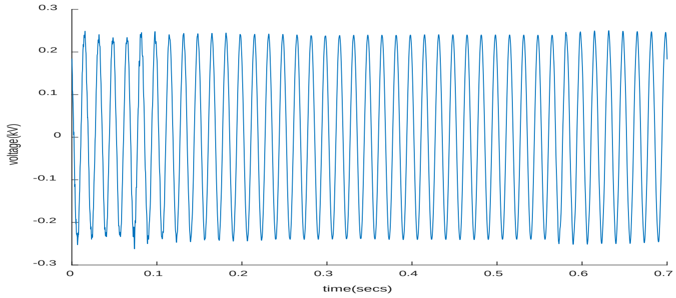

Figure 19: Voltage signal from the battery

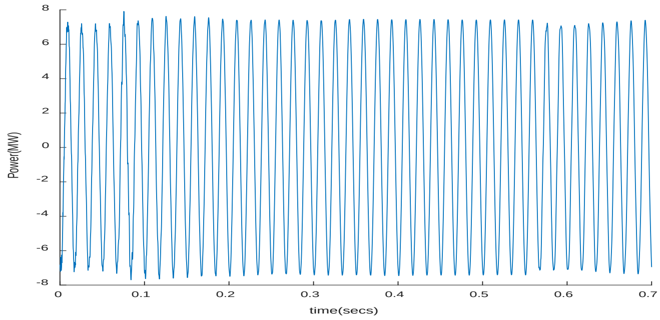

Figure 20: Power output from the battery

3.5 The Results of the Optimization

The summary of the result of the optimized power sizing of the micro grid energy sources is shown in Table 4. The optimal time for the operation of the micro-grid was shown in Figure 21.

Table 4: Power Sizing of the Energy Source Elements of the Micro-grid

Source elements	Initial guess (before optimization)	After optimization
National	1	1
grid	1	1
Solar PV	½	1
Battery	½	½
Micro-	2	1.5
hydro		
Diesel		

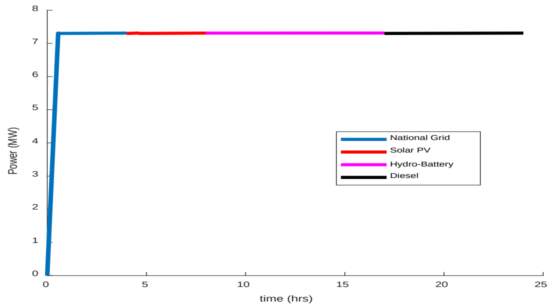

Figure 21: Optimal Operational Time of the Source Elements of the Micro-Grid

3.6 Discussion of the Results

The plot for the estimated load was shown in Figure 5. It was observed that the load varied between 7.1MW to 7.5MW. This can be attributed to load control practices by some of the residential and commercial consumers (especially the commercial consumers that switches off their electricity gadgets after the day's operations).

The current and voltage signals as well as the power output from the national grid was shown in Figure 6, Figure 7 and Figure 8 respectively. The current signal of the national grid was 58A, the voltage signal was 0.248 kV and the power output from the national grid was 7.67MW. The power output from the national grid system was slightly higher than the estimated load which met the required designed for the micro-grid.

The current and voltage signals as well as the power output from the solar panels was shown in Figure 9, Figure 10 and Figure 11 respectively. The current signal of the PV system was 47A, the voltage signal was 0.242kV and the power output from the solar PV was 7.31MW. The power output from the solar PV system was the same as the estimated load which met the required designed for the micro-grid. This implies that the solar PV was designed to have the same power output as the load consumed.

The current and voltage signals as well as the power output from the diesel plant was shown in Figure 12, Figure 13 and Figure 14 respectively. The current signal of the diesel plant was 43A, the voltage signal was 0.262kV and the power output from the diesel plant was 7.36MW. The power output from the diesel plant was slightly higher than the estimated load which met the required designed for the micro-grid.

The current and voltage signals as well as the power output from the micro-hydro plant was shown in Figure 15, Figure 16 and Figure 17 respectively. The current signal of the micro-hydro plant was 45A, the voltage signal was 0.255kV and the power output from the micro-hydro plant was 7.44MW. The power output from the micro-hydro plant was slightly higher than the estimated load which met the required design for the micro-grid.

The current and voltage signals as well as the power output from the battery was shown in Figure 18, Figure 19 and Figure 20 respectively. The current signal of the battery was 47.4A, the voltage signal was 0.227kV and the power output from the battery was 7.61MW. The power output from the micro-hydro plant was slightly higher than the estimated load which met the required design for the micro-grid.

The micro grid design based on the guessed and the optimal power sizing was shown in Table 4. The diesel was reduced from 2 of the load rating to 1.5 so as to be able to charge the batteries while in operation and the battery sizing was increased from 0.5 to 1. The purpose of the increment was to allow the battery operations to operate with more time in the night. The optimal time of operation for each of the energy sources was shown in Figure 21.

For the time of the operation of the energy sources, National grid was to operate from 4am to 8am, solar PV to operate from 8 am to 4pm, the battery cell was to operate from 4pm to 9pm and the diesel plant to operate from 9pm to 12 am, the mini-hydro to operate from 12 am to 4 am this outcome when implemented will ensure a constant electricity in the community.

4. CONCLUSION

The design and optimization of the micro-grid with energy sources from national grid, solar PV, battery, micro-hydro plant and the diesel plant. prior to the optimization process, the initial guess design was for solar PV and national grid power output to be equal to the load demand of 7.31MW, battery and the micro-hydro to be 50% of the load demand and diesel plant to be twice the load demand to ensure that the battery was charged from solar PV, micro-hydro and diesel plant. However, the outcome of the optimization showed that each of the solar PV, national grid and the battery storage system, the micro-hydro plant was optimized to operate 50% of the load and hence was supported by the battery and diesel operations was reduced to 150% of the load. The outcome of the economic analysis showed that the outcome was economically viable.

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