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Optimal Control of Pv-Wind Hybrid for Rural Electrification

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Abstract:- Many rural dwellers live without electricity due to inadequate generation. The intermittent nature of Standalone Renewable Energy Sources (RESs) is a disadvantage when used as a solution. In light of this, a hybrid of two RESs with a common storage is modeled in the MATLAB/SIMULINK environment. Genetic algorithm approach is used to find the optimal sizes of the RESs while other components are sized based on the peak load of the study area. A power control algorithm is developed and simulated to reduce the reactive power and subsequently increase the active power to meet the load since the rural load is active. The result shows the performance of the system with and without the control at every time instance. This helps in checking the effect of the control in supplying the load.

***Keywords*:-** *hybrid system; renewable energy; genetic algorithm; phase locked loop.*

I. INTRODUCTION

According to statistics, almost one-third of the world's populations do not have access to electricity [1]. Non-electrified rural areas can access electricity either by using standalone system or extending grid transmission lines but grid extension is cost intensive as transmission distance increases. As the current international trend in rural electrification is to utilize renewable energy resources; solar, biomass, wind and micro hydro power systems are seen as alternatives. Hybrid energy system has been seen as an excellent solution for rural electrification [2].

[3] presented a hybrid of photovoltaic (PV) and wind turbine as a small-scale alternative source of electrical energy in an off-grid environment using two individual DC-DC boost converters to control the power flow to the load. [4] designed and constructed a hybrid power system of PV-arrays, wind turbines with battery storage devices and power electronic control devices for residential load. The limitation to this work is that only a single residential load is considered in the design but the approach is techno-economically viable for rural electrification.

In this study, a hybrid of PV-wind power generation system is proposed for rural electrification. The hybrid system is modeled within the MATLAB/SIMULINK environment. A control algorithm is developed and simulated to enhance the active power supplied to meet the active load by reducing the active power.

II. MATERIALS AND METHOD

A. Hybrid Energy System Structure

The hybrid system under study consists of PV and wind turbine. Storage batteries are used to store the power produced by the renewable generation during excess generation. The DC power produced by the battery is converted into AC by the inverter. The structure of the proposed hybrid system is shown in Figure 1.

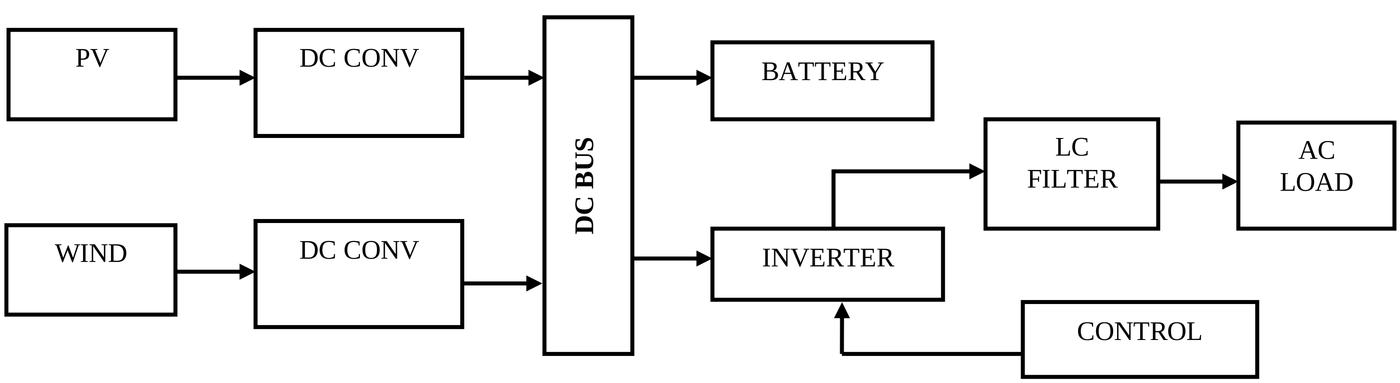

Fig 1:- The Proposed Hybrid System Layout

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➢ *Description of the Study Area*

Ajebamidele village also known as Oko-osi is situated between Ile-on a village in Aramoko and Awo town in Irepodun/Ifelodun local government in Ekiti state. This village is about 6 km from Awo town and 3 km from Ile-on a village. Ajebamidele village is largely surrounded by trees. The village has 17 residential buildings, a church and a block of 6 classrooms primary school as at time of visit. The population of the village is around 120. Farming is the major occupation of all the people living in the area. Electricity is needed in the village majorly for residential applications of which all the loads are active loads. Figure 2 shows the village load profile.

The meteorological wind and solar data adapted to design the hybrid for this off-grid area is a year data taken from Obafemi Awolowo University Ile-Ife, Osun State, Nigeria. The average values of the data were calculated for each day in a year and these are shown in Table.

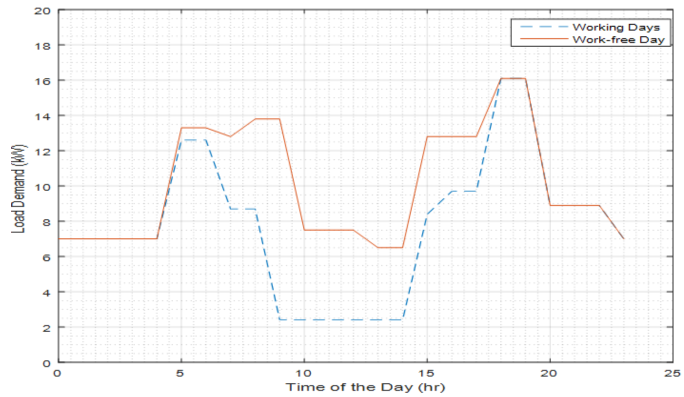

Fig 2:- Ajebamidele Load Profile for both Working Days and Work-free Day

Time (hr)	Wind Speed (m/s)	Irradiance (W/m²)	Temp (°C)	Time (hr)	Wind Speed (m/s)	Irradiance (W/m²)	Temp (°C)
01.00	2.92	2.36	24.20	13.00	6.59	631.86	29.55
02.00	2.32	2.31	23.27	14.00	6.10	635.81	30.84
03.00	2.05	2.96	22.96	15.00	5.94	525.06	31.58
04.00	1.02	4.34	22.92	16.00	5.43	473.16	32.30
05.00	1.49	3.01	22.73	17.00	5.48	258.46	31.48
06.00	1.36	3.36	22.90	18.00	6.08	87.64	29.20
07.00	1.97	1.83	22.89	19.00	3.24	17.81	26.57
08.00	2.01	44.75	23.14	20.00	3.05	8.66	25.66
09.00	3.97	160.23	24.39	21.00	2.46	8.06	24.91
10.00	4.37	234.53	25.45	22.00	2.24	3.78	24.65
11.00	5.23	398.68	26.68	23.00	2.37	6.85	24.35
12.00	5.86	553.75	28.17	24.00	2.75	4.48	24.17

Table 1: Wind and Solar Data

➢ *Optimal Sizing of the System Components*

The sizes of the hybrid components determine the cost and reliability of the system. The system should not be oversized to avoid high cost and must not be undersized to maintain the reliability of the system. To determine the optimal sizes of the components from an economic viewpoint, levelized cost of electricity (LCOE) was used. The optimization problem for the hybrid involves the minimization of the total cost C_T subject to constraint. The objective function to be minimized is given as equation (1) and the constraint as equation (2).

Minimize

$$C_T = C_w P_w + C_{pv} P_{pv} \quad (1)$$

Subject to constraint

$$P_w + P_{pv} = P_{L(\max)} \quad (2)$$

Where C_w is the cost of wind turbine per Kw, C_{pv} is the cost of PV system per kW, P_w is the power rating of the wind turbine in kW, P_{pv} is the power rating of the PV system in kW and $P_{L(max)}$ is the peak load taken as 17 kW.

To solve the optimization problem, genetic algorithm (GA) code under MATLAB software is utilized and a MATLAB Code is written to compute the values of the objective function.

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- *Modeling of Wind Energy System*

From the result of the optimization, the size of the wind energy system is obtained to be 8 kW and this gives the power rating of the system. Four pieces of 2 kW dc wind turbine manufactured by Pacific tool company was used in this work. A dc wind turbine was used to eliminate the cost of ac–dc rectifier and also reducing the complexity of the system design. The rated power (P_r) of the wind turbine is given as equation (3).

$$P_r = \frac{1}{2} C_p \rho A v^3 \tag{3}$$

Where C_p is the performance coefficient, ρ is air density, A is swept area and v is the rated wind speed.
The coefficient of performance C_p, of the wind turbine can be calculated from equation (3) as

$$C_p = \frac{2 \times 2000}{1.25 \times 8.04 \times 11^3} = 0.3$$

The output voltage of the wind turbine system is obtained from the steady state dynamic model equations for a permanent magnet dc generator driven by a wind turbine given as [4]:

$$V = k.w \tag{4}$$

Where V is the voltage output, k is the voltage coefficient and w is the rotational speed.
The blade tip speed ratio of the wind turbine is calculated using equation (5) to be 6.4.

$$\lambda = \frac{wR}{v} \tag{5}$$

The rotational speed can be expressed in terms of wind speed as in equation (6) from equation (5).

$$w = \frac{6.4v}{1.6} = 4v \tag{6}$$

Hence, the wind turbine output voltage at different wind speeds can be expressed as equation (7)

$$V = 6.82 \times 4v = 27.28\ v \tag{7}$$

- *Photovoltaic System Modeling*

From the optimization result, the rating of the solar panel was given as 9 kW i.e. $P_{pv\text{-}rated}$ = 9 kW but it is impossible to get this rating from one single panel. Hence, 36 pieces of 250W solar panel manufactured by Trina solar company are used in this work to maintain the system voltage.

The output voltage V of the photovoltaic system is modeled using equation (8).

$$V = N_s \left[\frac{AkT}{q}\right] In \left(\frac{I_{ph} - I + I_0}{I_0}\right) \tag{8}$$

Where N_s is the number of series-connected panels, q is the electronic charge, k is the boltzmann's constant, A is the diode ideality factor, I_o is the cell reverse saturation current and I_{ph} is cell photocurrent.

- *Battery Modeling*

The battery is sized so that it would be able to independently serve the load. Hence, the total capacity C_B of the battery to be used in the hybrid system is calculated from equation (9) [6].

$$C_B = \frac{E_L\ S_D}{v_B\ DOD_{max}} \tag{9}$$

Where E_L is the load, S_D is the battery autonomy taken as 1 day [1], V_B is the battery voltage and DOD_{max} is maximum depth of discharge of battery taken as 80 %. The selected battery rating is 12V, 450Ah. The peak demand 16.1kW ≈ 17kW was used as E_L. The total capacity of the battery is calculated as 21.6 kWh. Many batteries are connected in series and parallel to meet the demand.

Number of batteries to be connected in parallel N_{BP} is obtained as 4 from equation (10).

$$N_{BP} = \frac{\text{Total battery capacity}}{\text{Nominal battery capacity}} \tag{10}$$

Number of batteries to be connected in series N_{BS}

$$N_{BS} = \frac{\text{System dc voltage}}{\text{Battery nominal voltage}} \tag{11}$$

The system dc voltage value is taken to be 650 V. The series connected batteries are 55 batteries. Therefore, total number of batteries required in the battery bank N_B is obtained as 220 batteries.

- *DC-DC Converter Modeling*

The sizes of the dc-dc converters are chosen based on the optimization results for the RESs. A 10 kW dc-dc converter is selected for wind turbine system which has a rating of 8 kW and an approximately 12 kW dc-dc converter is chosen for the PV system which has a rating of 9 kW. The dc-dc boost converters are controlled to yield constant output DC voltage level V_o with a negligible power loss at by varying the duty ratio D_R from 0 to 1, in response to varying voltages V produced by either of wind turbine or photovoltaic systems.

The converter is modeled using equation (12) [7].

$$V_o = \frac{1}{1-D_R} V_i \qquad (12)$$

➢ *Modeling of LC filter*

The inductance L of the LC filter is found using equation (13) [8].

$$L = \frac{V_{dc}}{8 f_s \, i_{ripple}} \qquad (13)$$

Where V_{dc} is the constant dc voltage 650 V, f_s is the switching frequency 0.5 kHz, i_{ripple} is the ripple current which is taken as 15 % of the rated current i.e. 15 % of 77.3 A = 11.595A.
The capacitance C of the filter is found to be 595.2 µF using equation (14).

$$C = \frac{1}{(2\pi f_o)^2 L} \qquad (14)$$

Where f_o is the cut-off frequency taken as 45 Hz and L is the inductance of the filter.

➢ *Modeling of the inverter control system*

The inverter is used to convert the constant dc voltage into AC. The inverter size is taken to be 125% of the peak demand 22kW. The inverter is controlled using phase locked loop so that maximum usable power is available to the villagers at all time. The control algorithm is highlighted below.

1. The inverter output currents I_{abc} (t) and voltages V_{abc} (t) are measured.
2. The three phase inverter outputs are transformed to d-q components.
3. The active power P and the reactive power Q are calculated.
4. Set the reference active and reactive power (P_{ref} & Q_{ref}).
5. Find the reference d-axis and q-axis currents (I_{dref} & I_{qref}) by comparing P & Q with P_{ref} & Q_{ref}.
6. The reference d-q components are transformed to reference three phase currents.

The three phase AC and currents produced by the inverter are shown in equation (15).

$$x_a(t) = X_a \cos \omega t$$
$$x_b(t) = X_b cos(\omega t - 120^o) \qquad (15)$$
$$x_c(t) = X_c \cos(\omega t + 120^o)$$

where x denotes current or voltage.
The 3-phase outputs of the inverter are transformed into d & q components as shown equation (16) [9].

$$V_d = V_a \cos wt + V_b \cos(wt - 120^0) + V_c \cos(wt + 120^0)$$
$$V_q = -[V_a \, sin wt + V_b \sin(wt - 120^0) + V_c \sin(wt + 120^0)]$$
$$I_d = I_a \cos wt + I_b \cos(wt - 120^0) + I_c \cos(wt + 120^0)$$
$$I_q = -[I_a \, sin wt + I_b \sin(wt - 120^0) + I_c \sin(wt + 120^0)]$$
$$(16)$$

The active and reactive powers supplied to the load are calculated using equation (17).

$$P = \frac{3}{2}\left[V_q I_q + V_d I_d\right]$$
$$Q = \frac{3}{2}\left[V_q I_d - V_d I_q\right] \qquad (17)$$

A voltage oriented phase locked loop is used in this study for the control of d and q-axes current components and this makes the q-axis voltage to be zero. Hence, equation (17) becomes (18).

$$P = \frac{3}{2} V_d I_d$$
$$Q = -\frac{3}{2} V_d I_q \qquad (18)$$

The reference values for I_d and I_q are found respectively using equation (19) (Rahman, 2014).

$$I_{dref} = \frac{2}{3} V_d [P_{ref} - P] G(s)$$
$$I_{qref} = \frac{2}{3} V_d [Q - Q_{ref}] G(s) \qquad (19)$$

There G(s) is the transfer function of the PID controller whose parameters K_p, K_i and K_d are set as 180, 3200 & 0.1 respectively [10]. The time derivative constant is found to be 0.000556s. The d-q reference current is converted to 3-phase reference current using Park's and Clarke's transformations and the phase locked loop internally generated the angle required in the transformation.
The effectiveness of the control *Eff* at each hour of the day is calculated using equation (20).

$$Eff = \frac{P_a - P}{P_b} \times 100\% \qquad (20)$$

Where P_a is the active power with control and P_b is the active power without the control. The hybrid system was simulated for both week days and work-free day. The time of simulation was set as 2.4 with each 0.1 equals to 1 hr.

III. RESULTS AND DISCUSSION

The hybrid systems' components were interconnected together with the inverter to control the real and reactive power delivered to the load. Different voltage outputs of the wind turbine and photovoltaic system with respect to the varying input were boosted to 650VDC which was the input of the inverter. It must be noted that the aim of the control is to ensure maximum usable power delivery to the load. The result showed the effect of the control in supplying the load by increasing the active power while reducing the reactive power. This change was evident without change in apparent power. The result of the simulation is shown in Figures 3-6. During weekdays, there was an increase of 24 % in the active power delivered to the peak load at 6.00 pm and 7.00 pm which made it possible for the load to be satisfied. During work-free day i.e. Sunday, there was an increase of 24 %, 58 %, 73 % and 18 % in the active power at 7.00 am, 11.00 am, 12.00 pm and 3.00 pm respectively. In terms of cost, the PV-wind hybrid system saved about ₦ 56,351,500 when compared with grid extension to the village.

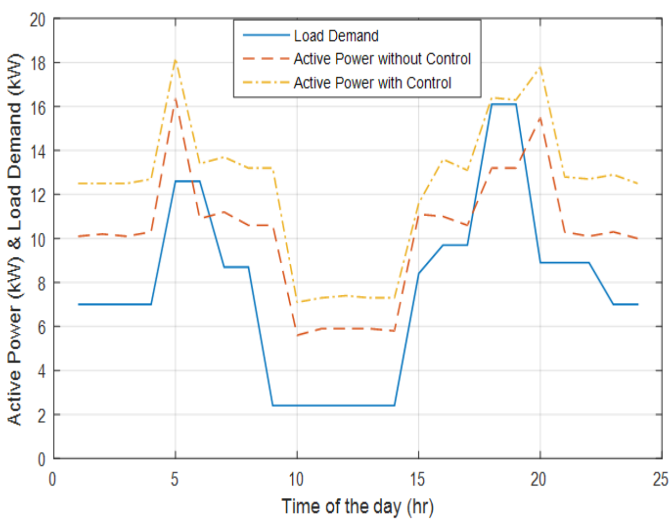

Fig 3:- Active Power & Load Demand Variation for Weekdays

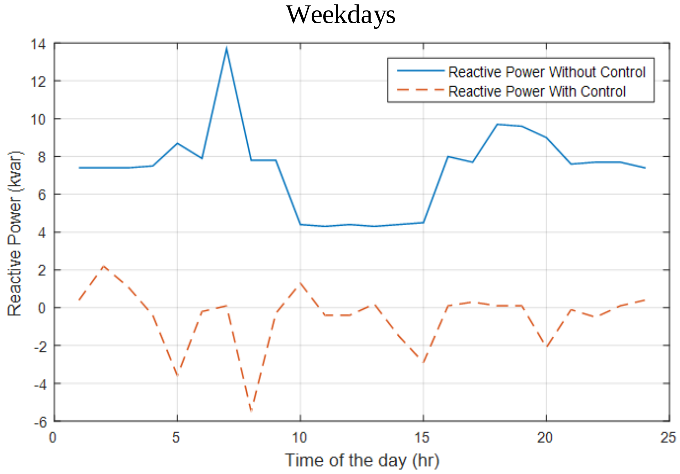

Fig 4:- Reactive Power Variation for Weekdays

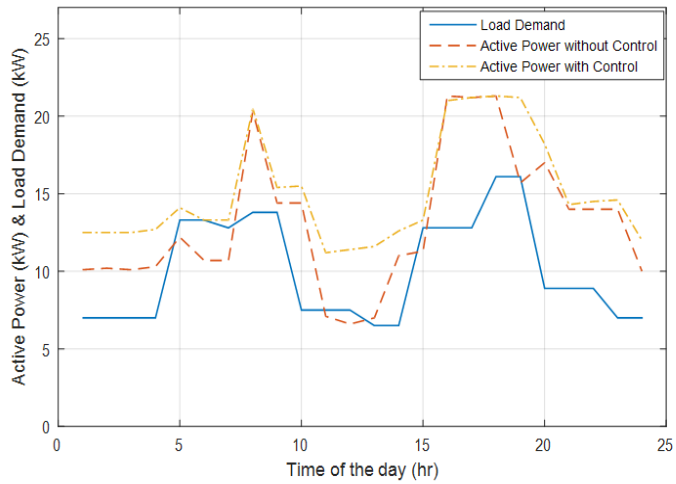

Fig 5:- Active Power & Load Demand Variation for Work-free Day

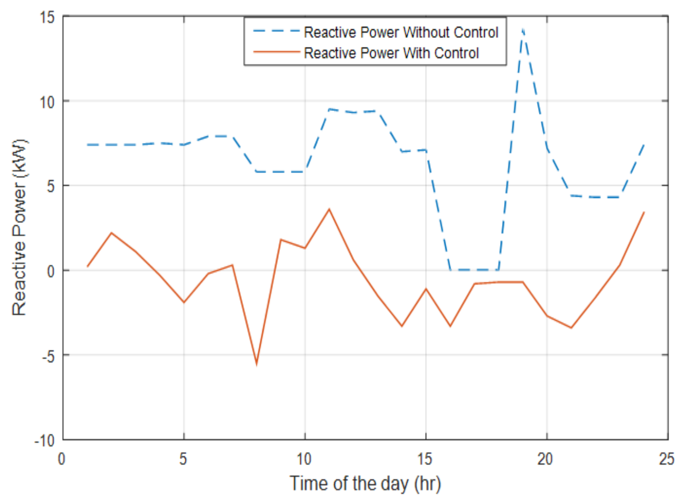

Fig 6:- Reactive Power Variation for Work-free Day

IV. CONCLUSION

The hybrid of two RESs namely: photovoltaic and wind turbine with common battery storage was modelled in the MATLAB/SIMULINK environment. The dc-dc converters were used to obtain a constant voltage at the input of the inverter. An inverter was used to convert the DC power to 3-phase AC and the control was achieved using phase locked loop (PLL). The active power delivered at any time instance is much more than the normal real power that ought to be delivered as the reactive power has been reduced to the nearest minimum due to the control. All the loads were satisfied both during weekdays and work-free day.

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