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Development of a Hybrid Solar-Dynamo Powered Charging System

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Abstract: *The extension of Global System for Mobile communication (GSM) to rural and semi-urban dwellers, who are predominantly farmers, is geared towards enhancing economic growth of the rural communities. Unfortunately, majority of these rural and urban communities do not have access to basic electricity supply needed to power mobile phone chargers. An indigenous technology which uses Solar–Dynamo Power that harnesses the energies in sun and bicycle pedals to generate electricity is presented in this paper. In this work, a dynamo mounted on the rear wheel of an adult size bicycle, is actuated through pedaling the bicycle. The dynamo converts the mechanical power generated by the peddler to electrical power. The electric power produced is processed for voltage rectification and voltage regulation to charge a battery which would supply the utilities for mobile phone recharging and illumination. A 2W_{peak} solar powered system was also incorporated into the design as a back up to charge the battery when the bicycle is not pedaled. The speed selection, solar power sizing and the switching mechanism are also presented. The supply circuits (rectification and regulation) and the Switching Control were implemented and simulated via Livewire and Proteus 8.0. The dynamo was modelled at different AC voltages and corresponding frequencies were obtained. The dynamo output voltage for the required regulated output of 5V (DC) and the time required were obtained. A full day test was also carried out to determine selection switch mechanisms between solar and dynamo circuits. The minimum pedaling speed for charging of the battery for the chosen size of the bicycle was also determined.*

Keywords: Dynamo, Solar power, Switching mechanism, Voltage rectification, Voltage regulation

1. INTRODUCTION

The significance of mobile telephony across globe for socio-economic, technological and agricultural development cannot be over emphasized. In Nigeria, more than half of the total population depends on the GSM as the easiest means of communication [1]. This is due to the potential of this technology to create economic opportunities and strengthen social networks in rural areas. Lack of affordable access to relevant information and knowledge services among the rural poor has been a concern to development economists for some time. However, the current fast growing extension of GSM to rural and semi-urban dwellers, who are predominantly farmers, is geared towards enhancing economic growth of the rural communities. Unfortunately, majority of these rural and urban communities do not have access to basic electricity supply needed to power mobile phone chargers.

Therefore, the growing concern over accessibility of grid electricity to the rural and sub-urban dwellers coupled with their lack access to relevant information, knowledge and other essential services which GSM technology can offer creates the need for such a system as Solar–Dynamo Power System that harnesses the energies in sun and bicycle pedals to generate electricity sufficient to charge mobile phone and provide illumination by the bicycle for these sets of people. Pedal power utilizes a foot pedal and a crank system to transfer energy from a human being (energy source). It is a simple piece of technology that has been available for over a century and in the present age; it has been applied in various ways including pedal powered grinders, pedal powered laptops and pedal powered water wells. Some third world development projects currently transform used bicycles into pedal powered tools [2]. The dynamo is actuated through the pedaling of an adult size bicycle and is mounted on the rear wheel of the bicycle. The dynamo converts the mechanical power generated by the peddler to electrical power.

Recently, some of the research efforts in the area of renewable energies are now being tailored towards hybrid approach in the form of Solar–Dynamo Power System. Khemraj *et al.* [3] developed a human powered mobile battery recharger utilizing a voltage doubling circuit. The work involved charging batteries for small (portable) devices while travelling on a bicycle, generating as much electrical power as possible on a stationary pedal generator and powering up electronic devices using the concept of cycle dynamo on stationary mode. Suhalka *et al.* [4] worked on generation of electric power using the bicycle pedal. The output of the dynamo was processed and used to charge Nickel Metal Hydride (NiMH) batteries which in turn are used to power other small power utility devices. Megalingam *et al.* [5] discussed the importance of the use of pedal power to drive water pumps and small-power lighting devices. They extended the principle to power mobile phones, iPods, laptops among others. Method of generating electricity from pedaling a bicycle was described. It involved using bicycle bottle dynamo to generate electric power with detailed analysis of pedal power usage presented which includes pedal powered laptops, refrigerators, washing machine, and other mechanical uses such as rice shredding. Lande and Tukpar [6] showed how to optimally utilize a bicycle by incorporating pedal power with solar power. The importance of renewable energy was extensively discussed wherein solar energy and human pedal power were identified as renewable sources. A human generator was designed and constructed using dynamo and solar panels. The dynamo was used to derive electricity from bicycle riding with the solar panels used to increase the quantity of electricity generated.

Hence, in line with the earlier research attempts conducted on Solar–Dynamo Power System, this work presents an indigenous charging system called Solar-Dynamo Powered Mobile Phone Charger (SDPMPC). Nigeria, like most other countries is hugely blessed with abundant solar energy (sunshine) all the year with an average sun power of 490 W/m^2/day [7]. Solar charged battery systems provide power supply for complete 24 hours a day irrespective of bad weather. The developed charging system in this work uses a bicycle dynamo which converts 6 V_{AC}, 3 W to 5 V_{DC}, 500 mA capable of charging mobile phones.

2. MATERIALS AND METHOD

Figure 1 shows block diagram of the developed mobile phone charger. The power levels that a human being can produce through pedals depend among others on how strong the rider is and on how long he or she pedals [5]. However, attainment of a desired charging system output is largely dependent on designing a reliable electronic circuit. In this work, the dynamo mounted on the rear wheel of the bicycle, is actuated through the pedaling of an adult size bicycle. The dynamo converts the mechanical power generated by the pedal movement to electrical power. The electric power produced is unregulated and could be ascribed as “raw” asserting that it needs to be processed before being utilized. The processes involved include voltage rectification and voltage regulation to charge a battery which would supply the utilities (mobile phone recharging and illumination). However, a 2 W_{peak} solar powered system is also incorporated into the design as a back up to charge the battery when the bicycle is not pedaled.

2.1 Dynamo Average Power

The average power produced by a dynamo is related to the flux density of the magnetic flux present in the dynamo, the radius of the wound solenoid coil, and the length of the coil within the dynamo. The E.M.F produced by a dynamo depends on the rate of change of the magnetic flux in the solenoid [8]. The magnetic flux (φ_m) in the solenoid with radius r and N number of turns is expressed in equation (1) as:

$$\varphi_m = \pi N B r^2 \cos(\omega t) \quad (1)$$

The peak E.M.F output, E_{peak}, for the magnet is given by equation (2) [8] as:

$$E_{peak} = \pi \omega N B r^2 \quad (2)$$

The peak E.M.F produced is the peak E.M.F amplitude for the alternating current. The corresponding peak current, I_{peak} produced by the dynamo can be found from the magnetic flux (φ_m) and the self-induced inductance, L, of the solenoid, by the relationship expressed by equation (3) [8], where I is the varying current:

$$I = \frac{\varphi_m}{L} \quad (3)$$

By substituting for the magnetic flux with equation (1), and using $L = \frac{\mu_0 N^2 A}{l}$ for a long solenoid [8] where l is the length of the solenoid and μ_0 is the permeability of free space in equation (3), the peak current produced is obtained in equation (4) as:

$$I_{peak} = \frac{BL}{\mu_0 N} \quad (4)$$

Equations (2) and (4), which correspondingly define the peak E.M.F and current produced by the dynamo, can be used to determine the average power produced, P_{av} . This is expressed by equation (5) [8]:

$$P_{av} = \frac{1}{2} E_{peak} I_{peak} = \frac{\pi \omega B^2 r^2 l}{2\mu_0} \quad (5)$$

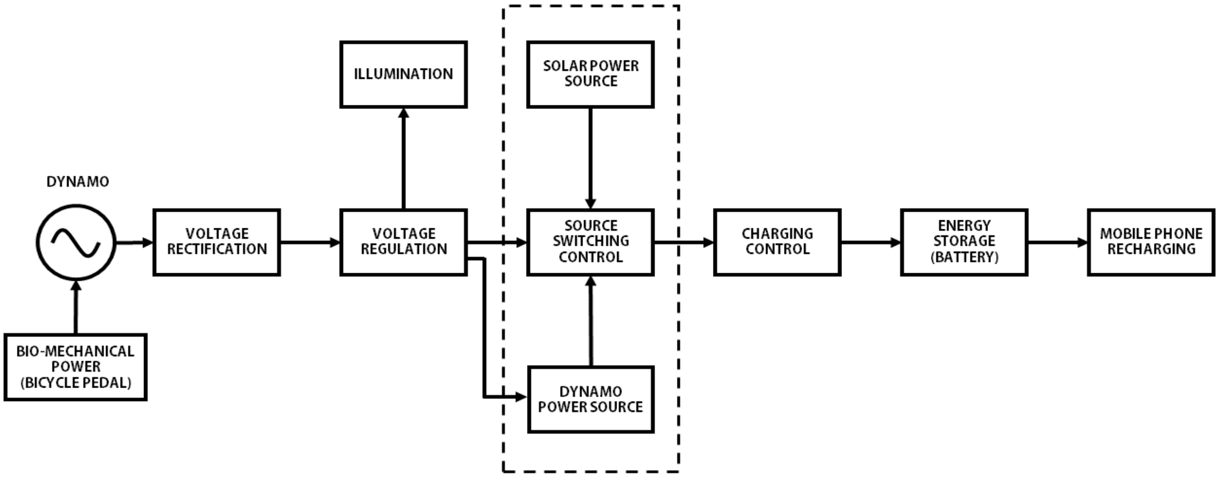


Figure 1: Solar-Dynamo Mobile Phone Charger

2.2 Voltage Rectification

The voltage waveform produced by the dynamo is alternating in nature which is to be rectified to produce Direct Current. The maximum rated voltage of the dynamo as specified in its datasheet is 12V. However, this value is an effective value (that is, the root mean square value). For an alternating sinusoidal signal, the effective value is related to the maximum value by equation (6) given as:

$$V_p = V_{r.m.s}\sqrt{2} \tag{6}$$

Where, V_p in equation (6) is Peak Voltage, $V_{r.m.s}$ is root mean square voltage, and K_f is Peak Factor = $\sqrt{2}$.

For the purpose of this design, a 9V maximum value is selected, therefore, the peak voltage Vp value of the dynamo is calculated as $V_p = 9 \times \sqrt{2} = 12.73$ V.

When the signal with the above peak value characteristic is rectified, the average value or the D.C voltage value obtained with the forward resistances of the diodes considered is given by equation (7) as:

$$V_{DC} = \frac{2}{\pi}(V_p - 2V_\tau) \tag{7}$$

Where V_τ is diode forward resistance.

Therefore, for the circuit in Figure 2a, the average or D.C value produced at its output without filtering or smoothening is calculated as:

$$V_{D.C} = \frac{2}{\pi}(12.73 - 1.2) = 7.34 \text{ V} \tag{8}$$

The ripple factor (γ) of the output voltage is expressed as equation (9):

$$\gamma = \sqrt{\left\{\left(\frac{V_{rms}}{V_{DC}}\right)^2 - 1\right\}} \tag{9}$$

$$\gamma = \sqrt{\left\{\left(\frac{9}{7.34}\right)^2 - 1\right\}} = 0.71$$

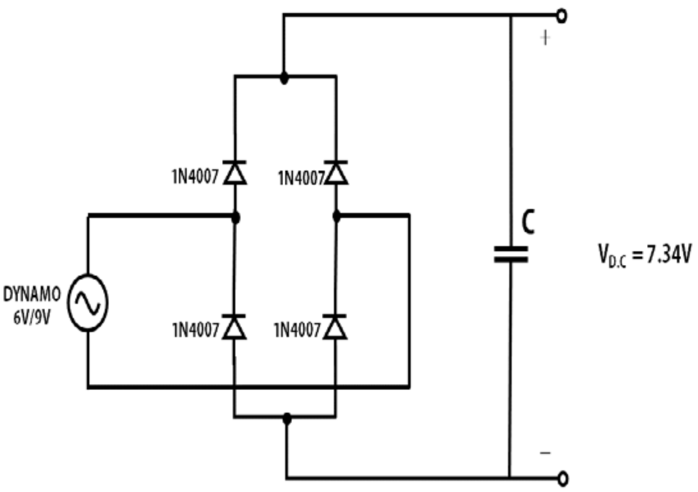
2.2.1 Voltage regulation

The amount the dc voltage changes between the no-load (V_{NL}) and load conditions (V_{FL}) is described by a factor called voltage regulation [9]. Theoretically, voltage regulation is given by equation (10) as:

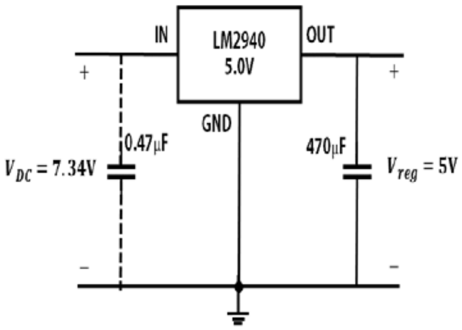
$$\%V.R = \frac{V_{NL} - V_{FL}}{V_{FL}} \times 100\% \tag{10}$$

The LM2940/LM2940C positive voltage regulator features the ability to source 1A of output current with a dropout voltage of typically 0.5V and a maximum of 1V over the entire temperature range of its operation. The 5V variant of the regulator is utilized in this phase of the design. The circuit implementation is taken directly from the typical application presented in the datasheet of the IC. For the output capacitor, the National Semiconductor datasheet [10] for LM2940 specifies that the minimum output capacitance required to maintain stability is 22µF and that the value may be increased without limit (larger values of output capacitance will give improved transient response). Also, the capacitor must be located in closest possible proximity to the IC. The input capacitor is required if regulator is located far from power supply filter.

Since larger values of output capacitance will give improved transient response, the output capacitor selected for the design is 470µF. Figures 2(a) and (b) respectively are the voltage rectification and voltage regulation circuits of the developed system.



(a)



(b)

Figures 2: (a) Voltage rectification (b) Voltage regulation Circuits

2.3 Solar Power System

Solar photovoltaic system or solar power system is one of renewable energy system which uses PV modules to convert sunlight into electricity. The electricity generated can be stored or used directly, fed back into gridline or combined with one or more other electricity generators or more renewable energy source. Solar PV system is very reliable and is a clean source of electricity that can suit a wide range of applications. In the solar powered system design, some important factors are considered and are used progressively to actualize the required design.

2.3.1 Power consumption PV Module sizing

The total power and energy consumption of all loads that need to be supplied by the solar PV system is obtained as follows:

Mobile Phone Recharging = 3 W

Assumed number of hours of expected use per day = 3 hours per day

Therefore, Watt-hour rating per day is $(3 \times 3)\ Wh/day = 9\ Wh/day$

Also, LED Power is 3 W

Number of hours of expected use per day is 4 hours per day

Watt-hour rating per day is $(3 \times 2)\ Wh/day = 6\ Wh/day$

Therefore the total watt-hour per day rating for the two applications

$$[6 + 9]\ Wh/day = 15\ Wh/day$$

Now, the energy lost by the system is accounted for when considering the amount of Watt-hour per day needed from the Photovoltaic module. The energy loss is accounted for by multiplying the calculated Watt-hour rating by 1.3 implying an expected 30 percent loss [11]. Hence, the total Watt-hour per day needed from the PV modules is:

$$1.3 \times 15 Wh/day = 19.5 Wh/day$$

Considering the solar light intensity experienced here in South West, Nigeria, the panel generation factor selected for this design is 5 hrs/day [11]. Therefore, the total Watt-peak rating needed for the PV module to operate the appliances is:

$$\frac{19.5}{5} = 3.9\ W_p$$

The selected PV module has a rated Watt-peak output of $2W_p$. Therefore, the number of PV modules required is:

$$\frac{3.9}{2} = 1.95\ PV\ modules$$

This implies that 2 units of the selected rated PV modules should be utilized for the system.

2.3.2 Switching mechanism

To realize switching mechanism, a switching circuit is used. The circuit utilizes a 555 Timer IC which is selected due to its flexibility and reliability. The switching mechanism is designed to utilize the operation of the 555 Timer IC such that the pins 2 and 6 are supplied by the regulated 5V supply from the dynamo. The output at pin 3 is utilized to ensure switching the dynamo power source to the charging controller when the bicycle is pedaled and to switch back to the solar source when the bicycle is not pedaled. The control switching circuit for both the dynamo and solar hybrid sources are shown in Figure 3.

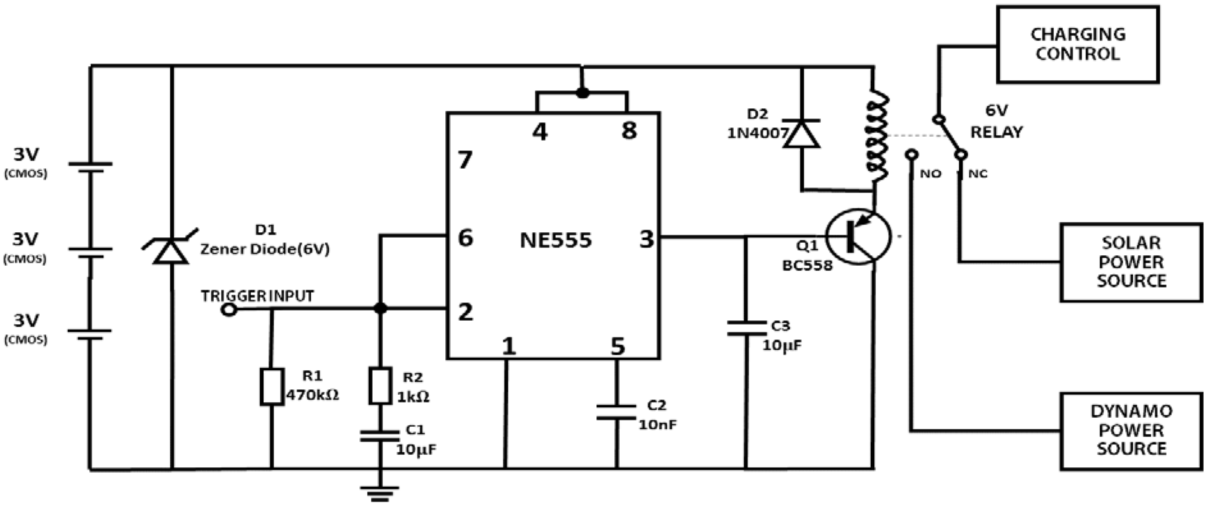


Figure 3: Control Switching Mechanism for Solar-Dynamo Charging System for Mobile Phone

2.3.3 *Mobile phone recharging*

LM2940 is also utilized here just as in the voltage regulation design. However, the 5V variant would be utilized and the input is obtained from the battery, while the 5V output is connected to a Universal Serial Bus (USB) port as shown in Figure 4.

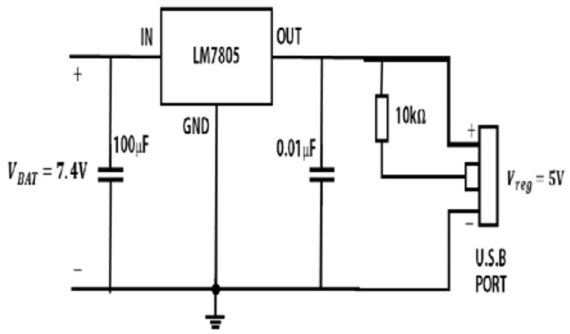


Figure 4: Mobile Phone Recharging Circuit

2.3.4 *Dynamo and pedal speed selection*

Velocity ratio in a motion transmission terminology of a rotational system is simply the ratio of the velocity of the driven part of a machine to the velocity of the rotational part driving it. A bicycle's configuration is such that its pedal transmits motion to the rear wheel, and in the case of the attachment of a bottle dynamo, the pedal transmits motion to the wheel of the dynamo. For a given bicycle, with diameters of rear wheel sprocket, pedal sprocket (d_{ps}), rear wheel (d_r) and dynamo roller (d_d), a velocity ratio can be obtained.

In applying the velocity ratio concept, and supposing N_{rs} Speed of the rear wheel sprocket (r.p.m), N_{ps} is Speed of the pedal sprocket (r.p.m), N_r is Speed of the rear wheel (r.p.m), N_d is Speed of the dynamo roller. (r.p.m), then the velocity ratio of the pedal sprocket and the rear wheel sprocket is obtained by equation (11) as:

$$\frac{N_{rs}}{N_{ps}} = \frac{d_{ps}}{d_{rs}} \tag{11}$$

The velocity ratio of the rear wheel and dynamo roller is obtained by equation (12) as:

$$\frac{N_d}{N_r} = \frac{d_r}{d_d} \tag{12}$$

The product of equations (11) and (12) yields equation (13):

$$\frac{N_{rs}}{N_{ps}} \times \frac{N_d}{N_r} = \frac{d_{ps}}{d_{rs}} \times \frac{d_r}{d_d} \tag{13}$$

But the rear wheel sprocket and the rear wheel are mounted on the same shaft; they therefore have identical velocities as expressed by equation (14) and therefore equation (13) reduces to equation (15):

$$N_{rs} = N_r \tag{14}$$

$$\frac{N_d}{N_{ps}} = \frac{d_{ps}}{d_{rs}} \times \frac{d_r}{d_d} \tag{15}$$

The above expression in (15) yields the velocity ratio of the pedal sprocket and the dynamo. Rearranging further, we obtain dynamo speed expressed in equation (16):

$$N_d = \frac{d_{ps}}{d_{rs}} \cdot \frac{d_r}{d_d} \cdot N_{ps} \tag{16}$$

Equation (16) gives the speed of the dynamo in r.p.m when other physical parameters are known.

2.3.5 *Illumination*

The illumination utilizes High-power LEDs (Figure 5) for its implementation. They are light emitting diodes with a high rated current. The normal LED power rating is generally 0.1W and its operating current about 20mA, but high power LEDs possess power rating of about 1W, 2W, or even tens of watts and operating current ranging from tens of mA to several hundred mA. They consume low amount of power, do not heat up easily, possess long life, respond fast and have optimum directivity and are popularly used in general lighting.

Figure 5: 1W white High-power LED

The power LED is driven by the LM317 adjustable output, positive voltage regulator IC and is capable of supplying in excess of 1.5A over an output voltage range of 1.2V to 37V. This device can also be used to make a programmable output regulator, or by connecting a fixed resistor between the adjustment and output, the LM317 can be used as a precision current regulator [12]. The illumination circuit is shown in Figure 6.

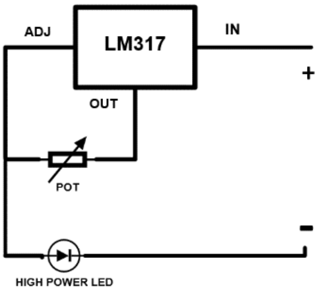


Figure 6: Illumination Circuit

The LM317 is a three terminal floating regulator. In operation, the LM317 develops and maintains a nominal voltage reference (V_{ref}) between its output and adjustment terminals. The regulated output voltage produced by the LM317 is given by equation (17) [12]:

$$V_{out} = V_{ref}\left(1 + \frac{R_2}{R_1}\right) + I_{Adj}R_2 \qquad (17)$$

3. RESULTS AND DISCUSSION

3.1 System Assembly

The designed circuits were assembled on a veroboard and packaged in plastic cases. The rectification and regulation circuits were assembled as in Figure 7 and switching circuit shown in Figure 8. The developed Solar-Dynamo system is presented in Figure 9.

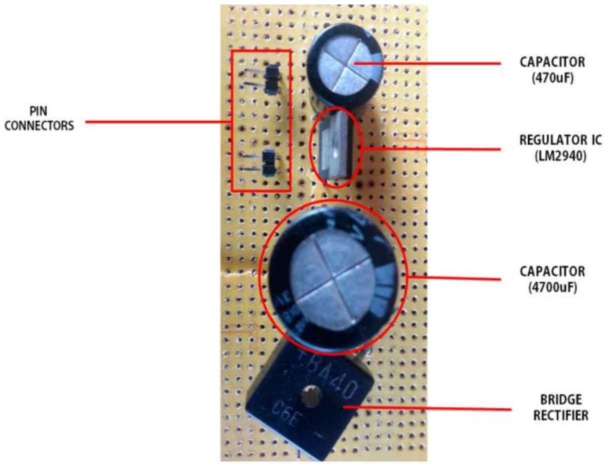


Figure 7: Rectification and regulation circuit

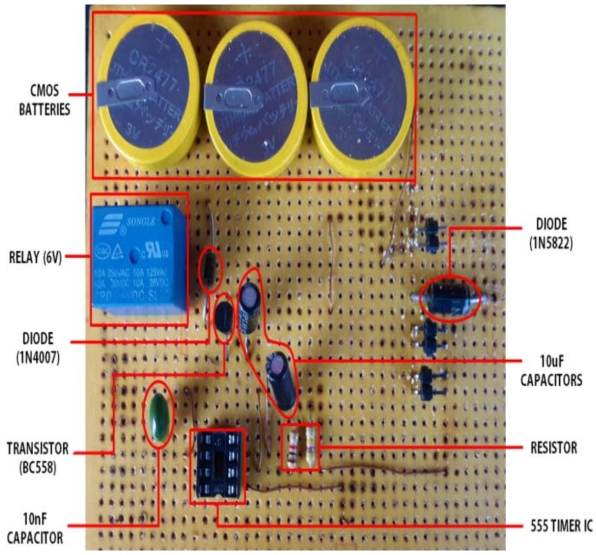


Figure 8: Switching mechanism circuit implementation

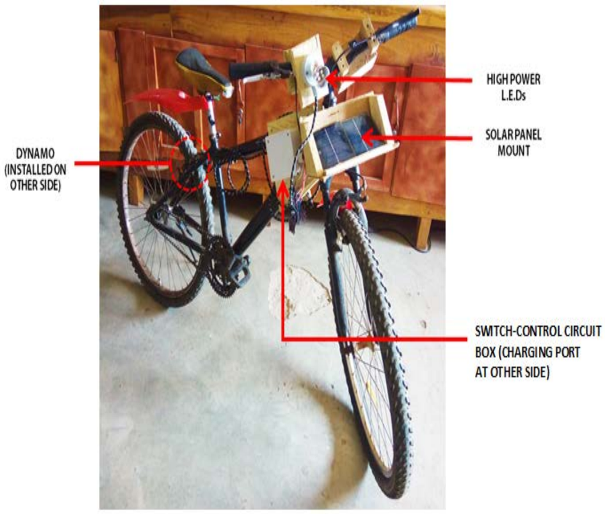


Figure 9: Dynamo and Solar Powered System

3.2 Simulation and Testing

The supply circuits (rectification and regulation) and switching control were implemented via Livewire and Proteus

8.0. The simulation to evaluate the speed and output voltage of the dynamo was implemented and the obtained graphical results presented as indicated in the following sections.

3.2.1 The output voltage with speed changes

The obtained voltage of the dynamo system with selected pedal speeds are presented in Table 1, and the corresponding regulated DC charging voltage from the produced system AC voltage were simulated against time and graphically shown at the designated frequencies and varying time intervals in Figures 10 to 15.

Table 1: Dynamo output characteristics at selected speed

Speed (m/s)	Output Voltage (V)	Frequency ($f = V/0.018\Pi$ Hz)
5	2.45	88.42
15	5.78	265.26
30	7.23	530.52

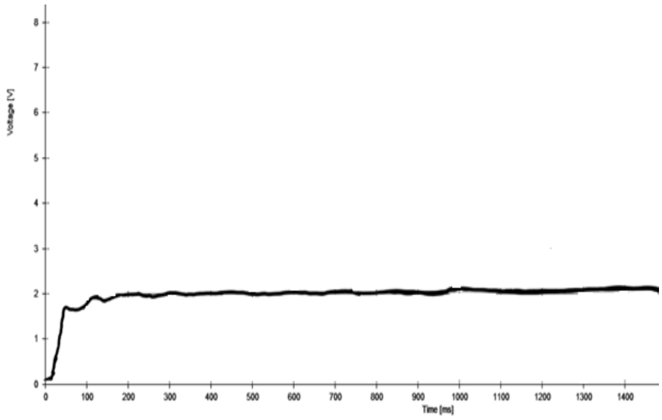


Figure 10: Graph of V_{DC} when V_{AC} is 2.45V and dynamo frequency is 88.42Hz

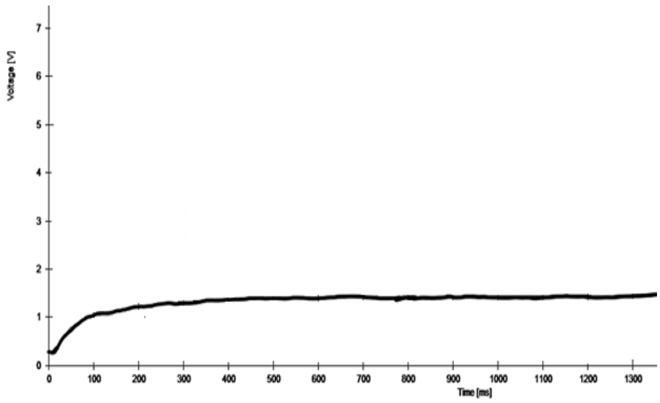


Figure 11: Graph of V_{reg} when V_{AC} is 2.45V and dynamo frequency is 88.42Hz

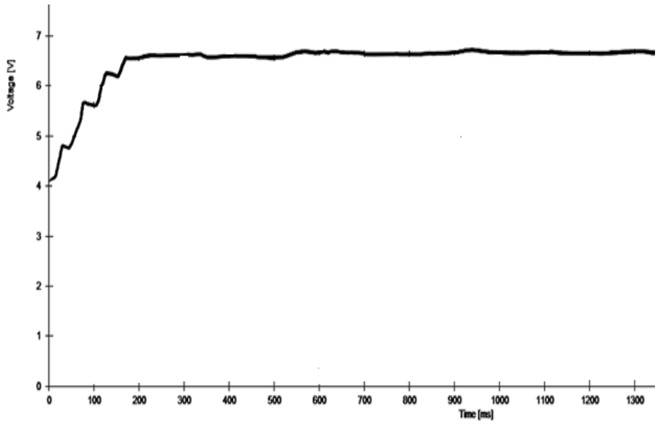


Figure 12: Graph of V_{DC} when V_{AC} is 5.78V and dynamo frequency is 265.26Hz

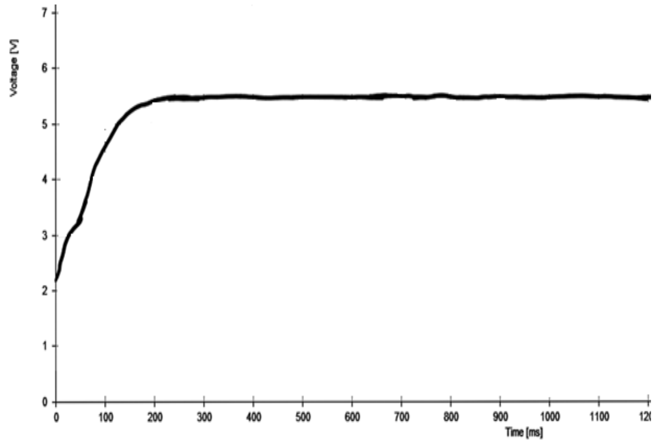


Figure 13: Graph of V_{reg} when V_{AC} is 5.78V and dynamo frequency is 265.26Hz

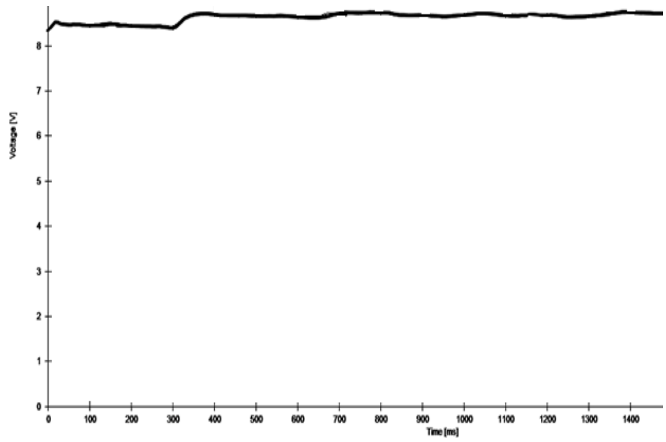


Figure 14: Graph of V_{DC} when V_{AC} is 7.23V and dynamo frequency is 530.52Hz

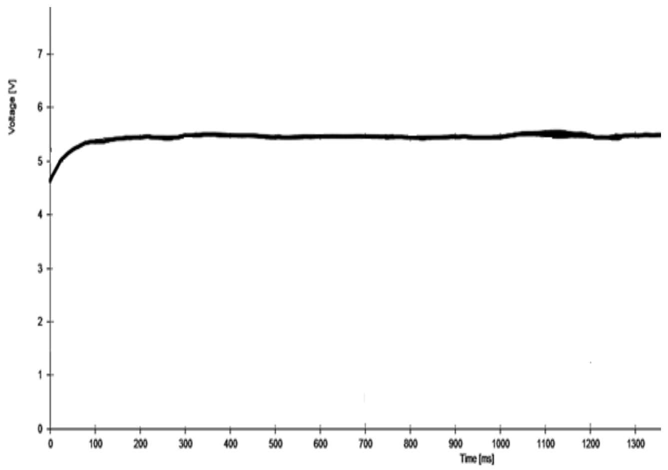


Figure 15: Graph of V_{reg} when V_{AC} is 7.23V and dynamo frequency is 530.52Hz

Considering the above Figures 10 to 15, when the voltage output from the dynamo (V_{AC}) is 2.45V, V_{reg} (DC) which is responsible for charging the power storage is 1.5V which is not sufficient to kick start charging. At a dynamo output (V_{AC}) of 5.78V, $V_{reg\ (DC)}$ stabilized at 5.3V after about 250ms, which indicates that at this value of V_{AC}, the battery pack can begin to charge. A further increase in the speed of rotation of the dynamo to a point where V_{AC} is 7.23V, V_{reg} (DC) stabilized at 5.3V in less than 10ms which is an acceptable voltage level for charging the battery pack.

3.2.2 Source switching control block testing

The source switching block test was performed such that the signal generator was used to trigger the circuit with DC voltage levels varying from 0V to 5V. The supplied 5V voltage, the designed output value from the regulation phase is expected to trigger the source switching control. The test result shown in Table 2 indicated that the voltage output of at least 4.5V from the regulation phase is necessary to ensure triggering of the switching circuit when the dynamo is being utilized effectively.

Table 2: Trigger state at various voltage levels

Voltage Level (V)	Switch State
0	Not Triggered
1	Not Triggered
2	Not Triggered
3	Not Triggered
4	Not Triggered
4.5	Triggered
5	Triggered

3.2.3 Period of the day testing for Dynamo-Solar charging

The workability of Dynamo-Solar charge was tested at various time of the day with varying pedal speed. The hourly time ranges considered include: early hour (6-8.30am), late morning (11-11.30am), high noon (1.30-2.30pm) and late noon (4-5.30pm). The observed output voltages in each period were recorded in Tables 3- 7. The early morning hours shows very low output voltages of 0.621V to 0.923V from the solar source; implying that at these hours, the battery pack can only be charged by the dynamo. At a pedaling speed of 40 r.p.m, the battery pack begins to charge with the dynamo as its source. The late morning hours show similar results; the output from the solar cell has increased considerably, but not sufficient to kick start the charging of the battery pack.

The pedaling speed at which charging began was the same for all the testing hours. However, the capability of the solar cell used to charge batteries both at the early hour and late evening is low.

Table 3: Early morning hours test results for the switch selection

S/N	Pedaling Speed (rpm)	V_{dynamo} (V)	V_{solar} (V)	Battery Charging Condition	Charging Voltage Source
1	20	3.29	0.621	Not Charging	No Source
2	40	4.68	0.623	Charging	Dynamo
3	60	4.88	0.622	Charging	Dynamo
4	80	5.49	0.887	Charging	Dynamo
5	100	6.88	0.923	Charging	Dynamo

Table 4: Late morning hour test results for the switch selection

S/N	Pedaling Speed (rpm)	V_{dynamo} (V)	V_{solar} (V)	Battery Charging Condition	Charging Voltage Source
1	20	3.27	3.45	Not Charging	No Source
2	40	4.62	3.42	Charging	Dynamo
3	60	4.91	3.50	Charging	Dynamo
4	80	5.54	3.47	Charging	Dynamo
5	100	6.81	3.44	Charging	Dynamo

Table 5: High Noon test results for the switch selection

S/N	Pedaling Speed (rpm)	V_{dynamo} (V)	V_{solar} (V)	Battery Charging Condition	Charging Voltage Source
1	20	3.31	5.78	Charging	Solar
2	40	4.66	5.81	Charging	Dynamo
3	60	4.84	5.86	Charging	Dynamo
4	80	5.56	5.78	Charging	Dynamo
5	100	6.86	5.79	Charging	Dynamo

Table 6: Evening hours test for switch selection

S/N	Pedaling Speed (rpm)	V_{dynamo} (V)	V_{solar} (V)	Battery Charging Condition	Charging Voltage Source
1	20	3.33	4.96	Charging	Solar
2	40	4.67	5.01	Charging	Dynamo
3	60	4.89	4.99	Charging	Dynamo
4	80	5.49	4.97	Charging	Dynamo
5	100	6.82	4.91	Charging	Dynamo

Table 7: Night hours test results for the switch selection

S/N	Pedaling Speed (rpm)	V_{dynamo} (V)	V_{solar} (V)	Battery Charging Condition	Charging Voltage Source
1	20	3.39	0.789	Not Charging	No Source
2	40	4.70	0.623	Charging	Dynamo
3	60	4.83	0.622	Charging	Dynamo
4	80	5.44	0.567	Charging	Dynamo
5	100	6.79	0.467	Charging	Dynamo

4. CONCLUSION

Information is vital in the development of any nation. The ongoing rural GSM installations in Nigeria are steps in the right direction. However, the supply of electric energy to power the GSM facilities are generally very poor. This necessitates the need for alternative means of electric power supply. A dynamo-solar powered system has been developed in this work to harness biomechanical energy from pedal motion, and solar power from the sun for continuous charging of a battery pack in rural communities. The battery pack when charged would be used to recharge the mobile phones when the bicycle is not pedaled and provide also necessary illumination to the bicycle at night when riding.

Having assembled system circuits, Software implementation via Livewire and Proteus 8.0 software were carried out and the dynamo modeled at 2.45 V, 5.78 V and 7.23 V (AC) under varying frequencies of 88.42 Hz, 265.26 Hz and 530.52 Hz. It was observed that at a dynamo output voltage of 5.78 V, the required regulated output of 5 V (DC) was obtained after about 250 ms; but at dynamo output voltages lower than 5.78 V (AC) the required 5 V (DC) could not be obtained. A full day tests were also carried out to determine selection of switch mechanisms between solar and dynamo circuits. Charging of the battery pack is possible at pedaling speed of 40 rpm and above for the chosen wheel size of the bicycle.

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