Individual Analytical Analysis

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Introduction

This memo presents an analytical evaluation of the alternator used in a human-powered bicycle generator designed to support the Ponderosa High School greenhouse renewable energy system. The overall project aims to enhance an off-grid hybrid system consisting of solar panels, a wind turbine, and supplemental human-powered energy generation.

The focus of this analysis is to determine whether the selected alternator can effectively convert mechanical energy from human pedaling into usable electrical energy. Specifically, this analysis evaluates the relationships between pedal speed, generator rotational speed, voltage output, system efficiency, and mechanical reliability. The results of this analysis directly inform key design decisions, including gear ratio selection, generator suitability, and component durability.

Assumptions

The following assumptions were used to simplify the analysis:

- Pedal cadence is within a typical human range of 70-100 RPM
- Gear ratio is constant and does not vary during operation of the bicycle
- Generator behaves as a linear device with voltage proportional to angular velocity
- Losses (mechanical and electrical) are approximated and grouped into efficiency trends
- Load is assumed to be steady during operation
- Bearings operate under constant radial load

Physical Modeling

The physical modeling of the system focuses on the alternator as the primary energy conversion component, where mechanical energy from the rider is transformed into electrical energy. The alternator is driven by the bicycle drivetrain, which increases rotational speed through a gear ratio to meet the operational requirements of the generator.

The alternator is modeled as an electromechanical device in which the output voltage is directly proportional to its angular velocity. Therefore, the performance of the alternator is governed primarily by its rotational speed, which is dependent on both pedal cadence and gear ratio. This relationship forms the basis for evaluating voltage generation, efficiency and system feasibility.

From a mechanical perspective, the alternator shaft is subjected to rotational loading, which introduces stresses on internal components such as bearings. These loads are influenced by the applied torque from the rider and the resulting generator speed. As rotational speed increases, the alternator experiences higher frictional forces, heat generation, and wear, all of which impact efficiency and component lifespan.

From an electrical standpoint, the alternator is modeled as a system with internal losses, included copper losses (resistive hearing in windings), core losses (magnetic hysteresis and eddy currents), and mechanical losses (friction and air drag). These losses are particularly significant at low rotational speeds, where generated voltage and current are insufficient at low rotational speeds, where generated voltage and current are insufficient to overcome them resulting in reduced efficiency.

The model also considers the interaction between mechanical input and electrical output, where increased electrical loading requires greater torque input from the rider. This coupling is critical in understanding system behavior, as it directly affects rider effort and overall usability.

Overall, the physical model of the alternator integrates:

- Rotational dynamics (RPM and torque)
- Electrical generation behavior (voltage vs angular velocity)
- Loss mechanisms (mechanical and electrical)
- Mechanical reliability (bearing loading and lifespan)

This modeling approach enables a comprehensive evaluation of the alternator’s performance and supports key design decisions related to hear ratio selection, generator suitability, and system efficiency.

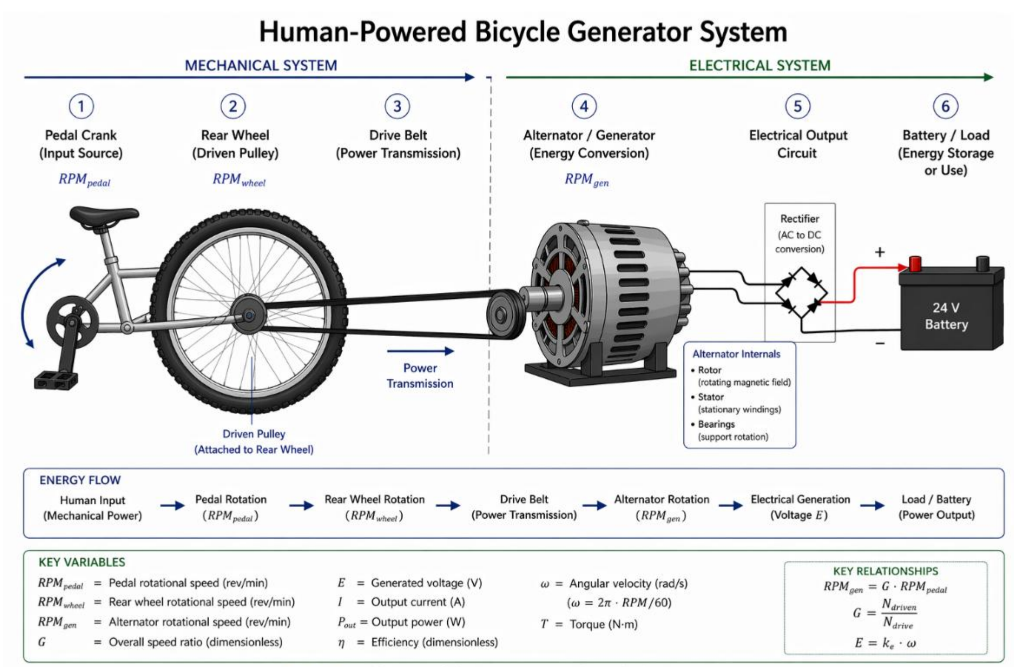

Figure 1. Schematic of the Human-Powered Bicycle Generator System.

Figure 1 provides a schematic representation of the human-powered generator system, identifying the key mechanical and electrical components and illustrating the flow of energy from the rider to the electrical load.

Governing Equations

RPM Matching

$$RPM_{gen} = G \cdot RPM_{pedal}$$

Where:

G= gear ratio
RPM_{pedal}= pedal speed
RPM_{gen}= generator speed

Voltage Generation

$$E = k_e \cdot \omega$$
$$\omega = \frac{2\pi \cdot RPM}{60}$$

Where:

E= generated voltage
k_e= generator constant
ω= angular velocity

Power and Efficiency

$$P_{out} = V \cdot I$$
$$\eta = \frac{P_{out}}{P_{in}}$$

Bearing Life

$$L_{10} = \left(\frac{C}{P}\right)^3$$
$$L_{10h} = \frac{L_{10} \cdot 10^6}{60 \cdot RPM}$$

Where:

C= dynamic load rating
P= equivalent load

MATLAB Modeling

MATLAB was used to mode system performance across varying pedal speeds and gear ratios. The model evaluation:

- Generator RPM vs pedal RPM
- Voltage output vs RPM
- Efficiency trends
- Bearing life vs rotational speed

The model assumes linear generator behavior and incorporates estimated losses.

1. Efficiency vs Pedal RPM

This MATLAB script models the efficiency of the human-powered generator system as a function of pedal speed. The generator RPM is calculated using a fixed gear ratio, and angular velocity is used to determine generated voltage. Electrical output power is computed and compared to an assumed constant human input power to determine system efficiency.

```
clear; clc; close all;


RPM_pedal = linspace(50, 100, 100);   % Human cadence
G = 20;                               % Gear ratio


RPM_gen = G .* RPM_pedal;
omega = 2*pi*RPM_gen/60;


% Generator constants
ke = 0.02;
R = 1.5;
I = 2;


% Voltage and output power
V = ke * omega;
P_out = V .* I;
```

2. Voltage Output vs Pedal RPM (Gear Ratio Comparison)

This script evaluated how voltage output varies with pedal RPM for different gear ratios (G = 10, 20, 30). It calculates generator RPM for each gear ratio and determines voltage using the generator constant.

```
clc; clear; close all;


RPM_pedal = linspace(50, 100, 100);
G_values = [10, 20, 30];


ke = 0.02; % generator constant


figure; hold on;


for i = 1:length(G_values)
    G = G_values(i);

    RPM_gen = G .* RPM_pedal;
    omega = 2*pi*RPM_gen/60;

    V = ke .* omega;

    plot(RPM_pedal, V);
end


xlabel('Pedal RPM');
ylabel('Voltage (V)');
title('Voltage Output vs Pedal RPM');
legend('G = 10','G = 20','G = 30');
grid on;
```

3. Bearing Life Calculation

This script calculates the bearing life (L10 life) for a given set of operating conditions, including dynamic loading rating, applied load, and generator RPM.

```
clc; clear; close all;


% GIVEN VALUES (example)
C = 3000;    % Dynamic load rating (N)
```

```
P = 500;     % Equivalent load (N)
p = 3;       % Ball bearing exponent
RPM = 2000;  % Generator speed


% L10 life (million revolutions)
L10 = (C / P)^p;


% Convert to hours
L10_hours = (L10 * 1e6) / (60 * RPM);


% Display results
fprintf('L10 Life: %.2f million revolutions\n', L10);
fprintf('L10 Life: %.2f hours\n', L10_hours);
```

4. Bearing Life vs. Gear Ratio

This script evaluated how bearing life changes as a function of gear ratio, assuming a constant pedal RPM. As gear ratio increases, generator RPM increases, which affects bearing lifespan.

```
clc; clear; close all;


% Pedal RPM (constant rider input)
RPM_pedal = 80;


% Gear ratio range
G = linspace(5, 40, 100);


% Bearing parameters
C = 3000;   % N
P = 500;    % N
p = 3;


% Calculate generator RPM
RPM_gen = G .* RPM_pedal;


% L10 life (million rev)
L10 = (C / P)^p;
```

```
% Convert to hours
L10_hours = (L10 * 1e6) ./ (60 .* RPM_gen);


% Plot
figure;
plot(G, L10_hours);
xlabel('Gear Ratio');
ylabel('Bearing Life (hours)');
title('Bearing Life vs Gear Ratio');
grid on;
```

Results

1. Efficiency vs Pedal RPM

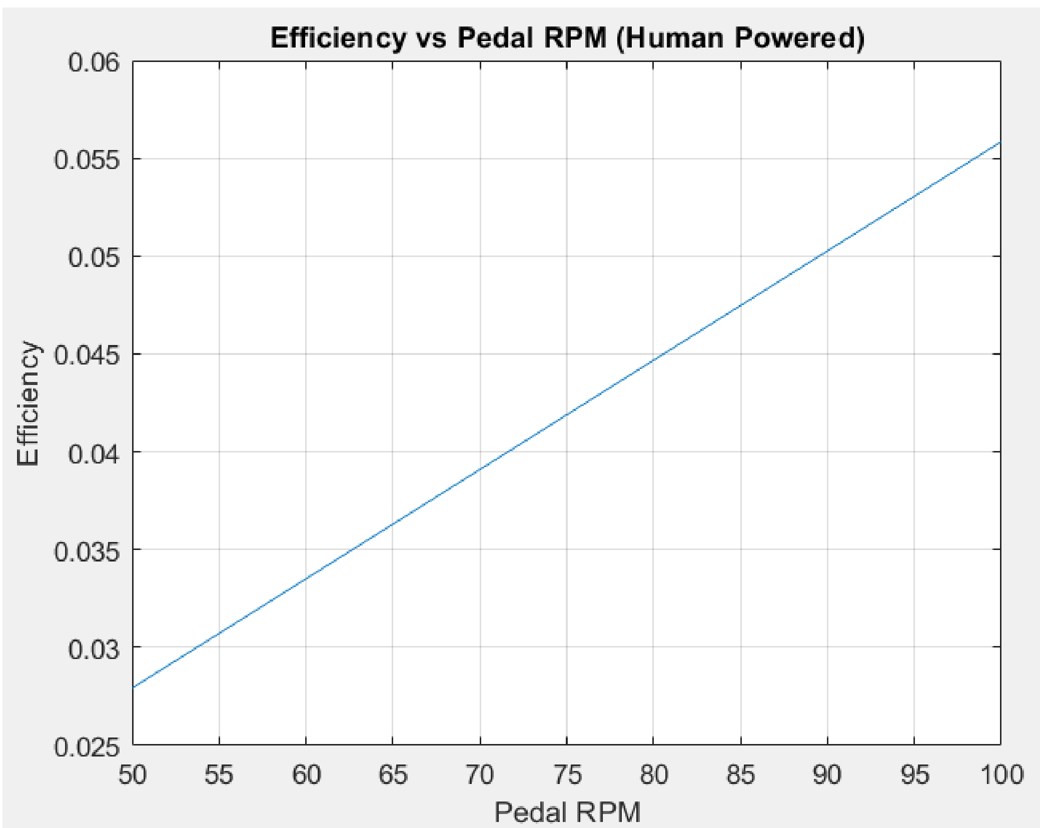

Figure 2. Efficiency vs Pedal RPM

The results show that efficiency increases with pedal RPM. At lower pedal speeds (50-60RPM), efficiency is relatively low because the generated voltage and power output are small compared to the constant input power. As pedal speed increases toward 80-100 RPM, efficiency improves significantly.

2. Voltage Output vs Pedal RPM (Gear Ratio Comparison)

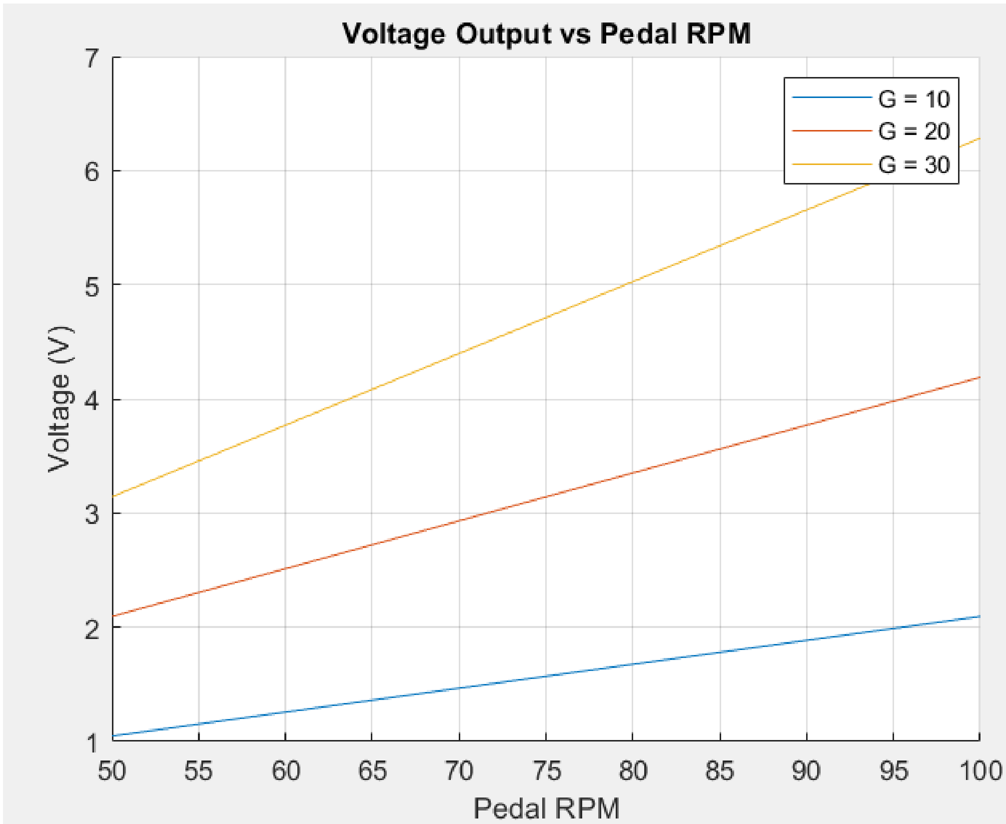

Figure 3. Voltage Output vs Pedal RPM

The results show a linear relationship between pedal RPM and voltage output for all gear ratios. Higher gear ratios produce significantly higher voltage at the same pedal speed.

- G = 10: Low voltage output
- G = 20: Moderate voltage output
- G = 30: Highest voltage output

However, even at higher gear ratios, voltage may still be below desired system levels at realistic pedal speeds.

3. Bearing Life Calculation

L10 Life: 216.00 million revolutions

L10 Life: 1800.00 hours

The calculated bearing life provides an estimate of how long the bearing will last under the specified conditions.

- The life in million revolutions remains constant for a given load

- The life in hours depends on RPM

At 2000 RPM, the bearing life is reduced compared to lower speeds due to faster accumulation of cycles.

4. Bearing Life vs. Gear Ratio

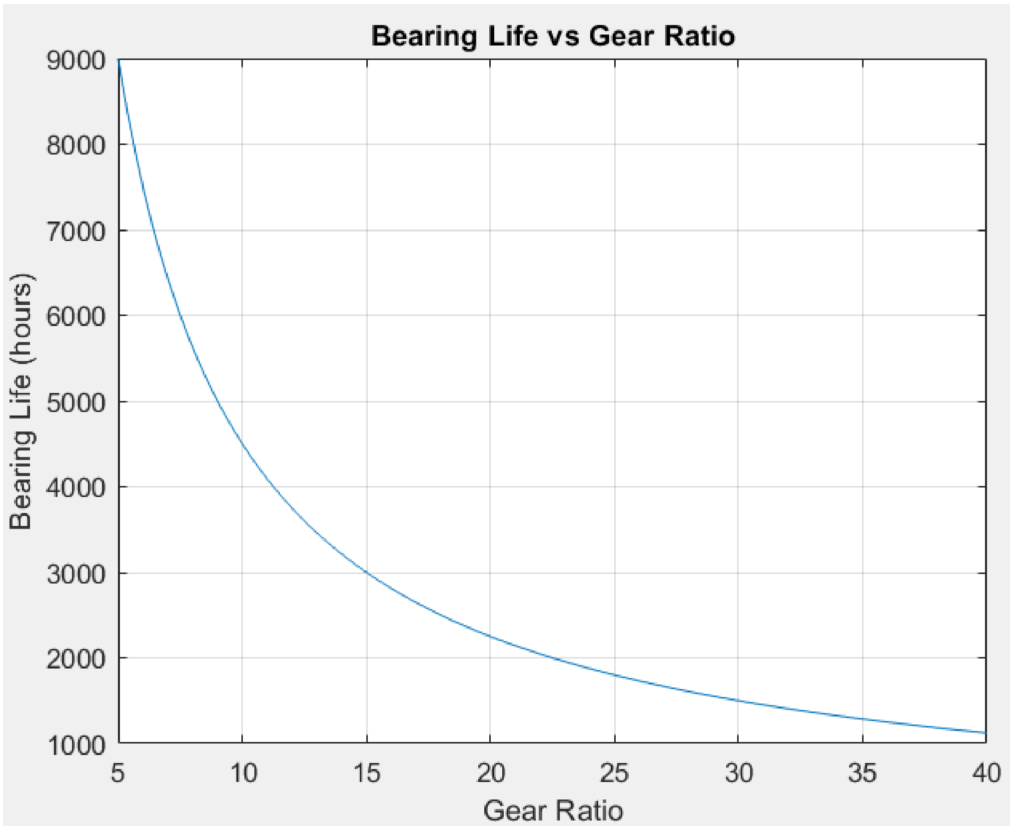

Figure 4. Bearing Life vs Gear Ratio

The results show that bearing life decreases as gear ratio increases. This occurs because higher gear ratios increase generator RPM, leading to fast accumulation of fatigue cycles.

- Low gear ratio → lower RPM → longer life
- High gear ratio → higher RPM → shorter life

Design Impact

This analysis directly influenced several key design decisions:

- Selection of gear ratio (20–30 range)
- Identification of need for higher voltage generator or system modification
- Inclusion of dual bearings for improved lifespan

- Consideration of mechanical limits to avoid premature failure

Discussion

The analysis reveals a fundamental trade-off between:

- Electrical performance (higher RPM, higher voltage)
- Mechanical reliability (bearing life, wear)

Additionally, human limitations constrain achievable input power and speed. Therefore, the system must be designed to operate efficiently within a realistic pedaling range.

Conclusion

The alternator analysis demonstrates that while the system is capable of generating electrical energy, the current configuration is limited by low voltage output at practical pedaling speeds. Gear ratio optimization improves performance but introduces mechanical challenges. Future work will focus on generator selection, system optimization, and experimental validation to ensure the design meets performance and reliability requirements.

References

[1] S. J. Chapman, *Electrical Machinery Fundamentals*, McGraw-Hill, 2011.
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[3] R. G. Budynas and J. K. Nisbett, *Shigley’s Mechanical Engineering Design*, McGraw-Hill, 2008.