

Design of a Flywheel Based Energy Storage and Distribution System for Rural Villages in China

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ABSTRACT

There are 30 million people in remote, rural communities in China without access to electricity. The government of China has initiated an ongoing effort to provide constant, reliable power to these citizens. Renewable energy is being utilized to solve this problem, which necessitates the use of a storage medium for energy, because renewable energies (i.e. wind and/or solar power) are inherently intermittent, variable, and largely unpredictable. By storing excess energy when it is plentiful (for a maximum feasible time of two days) and distributing it to the community in times of scarcity, the intermittent power is effectively leveled and auxiliary power is provided.

A high-inertia flywheel was designed for this application because of its simplicity, ease of maintenance, low cost, and reliability. This design addresses many problems including bearing losses, aerodynamic losses, and distribution losses. The proposed design consists of a six spoke layout with a large outer ring. A flywheel of approximately 152 tons, combined with a grid system and a renewable energy source, will provide constant power for a village of approximately 200 residents with enough energy for up to two days without additional input. The grid system will convert a range of output voltages and frequencies from the output flywheel generator to constant 220 VAC at 50 Hz for consumer use.

LIST OF SYMBOLS

A	Cross-sectional area of the rim (m^2)
A_s	Cross-sectional area of spoke (m^2)
E	Energy (J)
f_1	Intermediate variable
f_2	Intermediate variable
f_3	Intermediate variable
f_4	Intermediate variable
g	Acceleration due to gravity (m/s^2)
I	Second moment of area (m^4)
M_L	Laminar drag moment (Nm)
M_O	Outer edge drag moment (Nm)
M_T	Turbulent drag moment (Nm)
r	Radial distance (m)
r_a	Average radius of rim (m)
r_o	Outer radius (m)
r_{tr}	Transition radius (m)
Re	Reynolds Number
t	Thickness (m)
Z_r	Second modulus of rim (m^3)
2α	Angle between adjacent spokes (rad)
ν	Kinematic viscosity (m^2/s)
ρ	Density (N/m^3)
σ	Stress (Pa)
ω	Angular velocity (rad/s)

INTRODUCTION

Electricity is a utility that a majority of people around the world take for granted. Electricity is usually produced by fossil fuel and nuclear power plants; however renewable energy sources are growing in popularity. In many countries, especially those that have underdeveloped regions, a majority of the population lives in rural areas where major electric grids cannot be practically extended. There are currently 1.6 billion people worldwide to whom electricity is unavailable or unreliable [1].

Currently, China has 30 million people without electricity, mostly spread out between small villages and towns in isolated rural areas [2]. These villages have very little access to technology, and are generally isolated, so the proposed energy storage system must be comprised of parts that can be easily repaired by the local craftsman because mass produced parts will not be available.

In order to remedy this problem, China has envisioned a multi-phase approach that utilizes renewable energy sources, primarily wind and solar power. China has completed the first phase of its rural electrification program, known as *Song Dian Dao Xiang*, which provided electricity to 1,061 townships. The second phase, known as *Son Dian Dao Cun*, began in 2005 to provide electricity to the remaining 30 million people in 20,000 villages in rural, off-grid locales. This electrification program is attempting to accomplish the set goals by installing photovoltaic and wind systems on a per-house-basis for smaller villages (under 50 households) while utilizing complete, large-scale mini-grid systems for larger villages (over 50 households). The most critical problem with such off-grid systems that are powered by renewable energy sources is intermittency which leads to brownouts and blackouts [2].

With this system, power can be unavailable simply because the wind happens to blow at less than average speeds or atmospheric conditions limit the solar energy that can be collected. Inland winds are subject to both seasonal and diurnal variations, which are further complicated by the severe amount of variation between sites even on neighboring hilltops. Because of this variability, it quickly becomes impractical to calculate a storage interval that meets the general requirement of "constant" power; however, a good starting point is two days due to the diurnal nature of wind and solar power.

Based on a cost analysis conducted by the National Renewable Energy Laboratory (NREL), a village size of 50 households (with a corresponding population of roughly two hundred people) is the minimum cost effective village size for a mini-grid type distribution system. For a village with less than 50 households, it is more efficient for each household to be served by a single-home system, which will serve as the minimum for this study. [3]

A number of studies have been used to determine the minimum power requirements for each household

within these rural villages. Electricite de France, a French electricity provider, determined that the basic consumption needs are 1 kilowatt hour (kWh) per family per day [4]. Applying this basic energy consumption to the minimum village size, a total village household demand of 50 kWh per day is expected.

Various facilities in the communities including medical clinics, schools, and any public works will account for additional energy usage. The United States Agency for International Development (USAID) developed a guide for powering rural health clinics in which the energy consumption of a Category 1 Health Clinic with low energy requirements is defined as being between 5 and 10 kWh per day [5]. A study by the National Renewable Energy Laboratory, a laboratory of the Department of Energy, considered renewable energy to power rural schools in isolated areas which needed 2.75 kWh per day [6]. Including another 2.25 kWh per day for public usage such as water pumps and other such municipal works, the total non-household energy consumption is expected to be about 10 kWh per day. Combining the consumption for household and non-household usage, the total energy consumption per village is expected to be 60 kWh per day. With this baseline figure for energy consumption, the supply and backup required by the storage and leveling system can be established.

The following specifications are applicable:

Implied Design Constraints

- Inexpensive
- Simply constructed
- Easily repairable
- Power must be distributed
- Supply 25 kW to village of 50 households
- Provide energy storage for up to 48 hours

Implied System Benefits

- Potentially provide 30 million people in China with access to constant electricity
- Potentially provide 1.6 billion people globally with access to constant electricity
- Can be used in remote, rural areas
- No required grid connection

SYSTEM OVERVIEW

The flywheel energy storage and distribution system collects wind energy, stores it as rotational energy, and then converts that stored energy to electricity for use by consumers. Wind energy is collected by windmills which generate power via alternating current (AC) generators. The power from the AC generators is used to drive AC motors which provide mechanical input to a horizontally rotating flywheel. Energy is stored in the flywheel as rotational energy and converted to AC power by an outlet AC generator. The power supplied by the outlet AC generator is then rectified and inverted to provide 220 VAC 50 Hz power. The output power is then supplied

through a transformer, transmitted over high voltage lines to minimize transmission losses, and then stepped down by individual transformers on each phase to supply the loads of the consumers.

DISTRIBUTION SYSTEM DESIGN

The design of the distribution system must be analyzed in conjunction with the design of the flywheel to account for electrical losses in the final flywheel design. A number of parameters were considered including the current distribution standards of the country, the electrical demand on the system, and the components that are available to build the system.

China's current distribution standard consists of three phase alternating current at 220 volts with a frequency of 50 hertz [9]. Current electrical standards dictate that distribution lines must rest on poles that are 40 feet tall with at least 10% of that height buried beneath the ground and within maximum spacing of 250 feet. Additionally, the three phase lines are to be spread out

across 8 feet laterally and must be approximately 5 feet above the neutral line [10].

This system is designed to provide power to a village consisting of about 50 homes, a community center or school, and a small medical center. A demand curve was created by considering the appliances that would likely be used in each location and designating the number of hours each appliance would be on per day, as shown in Appendix B.

From this demand curve, the total amount of energy consumed by the village is 60 kWh/day. In addition, it can be seen that a maximum peak power demand of 18 kW is obtained. In order to account for fluctuations, a factor of safety of 1.4 was applied increasing the maximum power demand that must be considered 25.2 kW.

Because the proposed system utilizes a flywheel, the distribution system will require the following components: generator, rectifier, inverter, high voltage transmission lines, transformers, and low voltage distribution lines as well as minor components, such as circuit breakers, switches, etc, as shown in Figure 1.

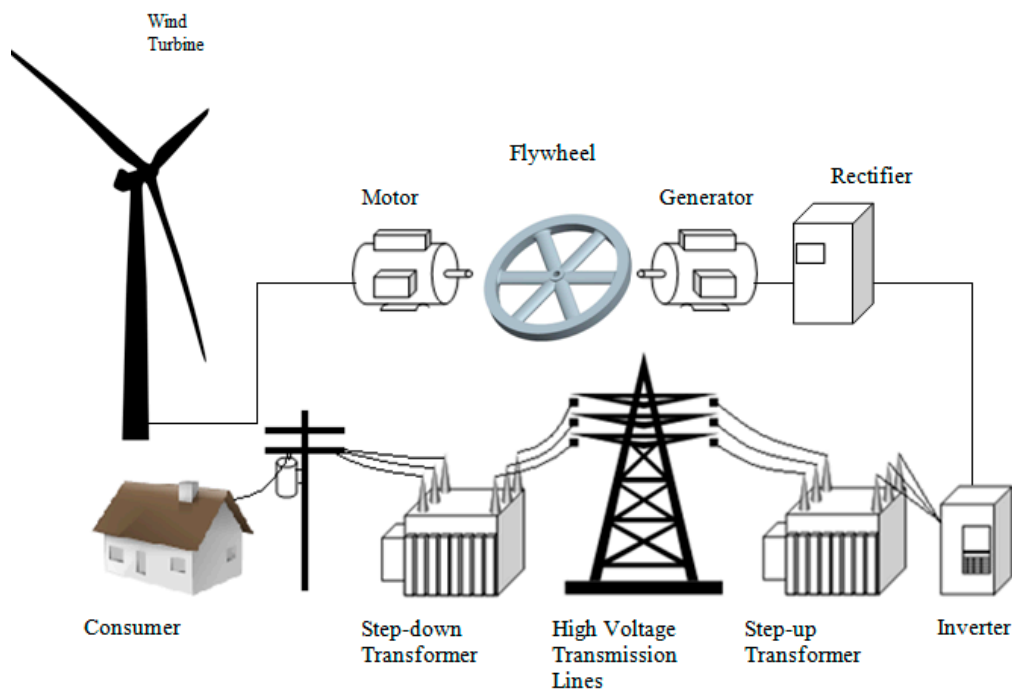


Figure 1: Flowchart illustrating entire system.

An AC synchronous generator was selected over a DC generator due to its cost, maintainability, and ability to regulate output voltage. The speed of the flywheel will constantly change with time. Hence, the voltage and frequency of the generator output will vary. However, the desired output from the generator is 220 VAC at 50 hertz to supply consumer loads.

In order to remedy this problem, a variable frequency drive was used to both rectify the generator output to DC and then invert it back to AC at 50 hertz. The drive transformed inconsistent generator output into a signal

with constant frequency. Based on commercial component performance, the process is assumed to have an efficiency of 87%.

Once the electricity is in its desired state, it must be transmitted to the village. Because it is expected that the wind turbine and flywheel will likely be 2 to 3 kilometers away from the village, high voltage transmission lines will be required to increase the efficiency of the system. Figure 2 illustrates the efficiency and cost break points between high and low voltage power transmission options. It is beneficial for any distance beyond 1400

meters to utilize high voltage transmission lines due to the substantial power losses experienced in low voltage transmission.

The cost difference of the two options must also be considered. From Figure 2, it can be seen that the

largest cost difference between the two transmission options is about \$30,000 while the break point for cost occurs at about 1,600 meters. Initial higher cost is justified by the efficiency gained when utilizing high voltage transmission lines.

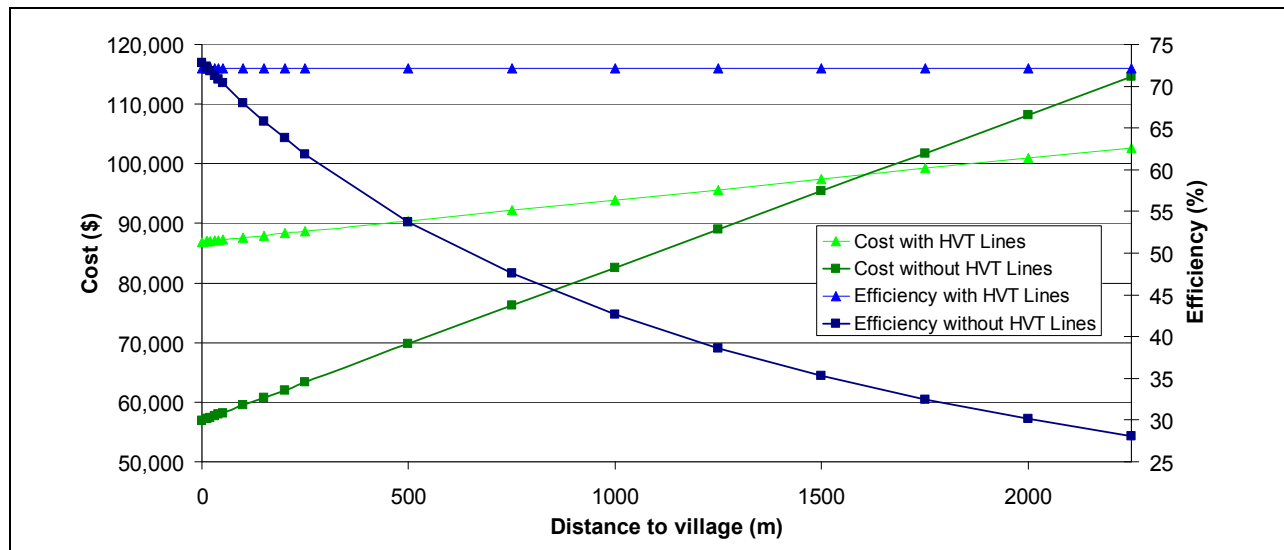


Figure 2: Efficiency and cost comparison between high and low voltage power transmission.

For this system it was determined that 7.2 kV is an appropriate voltage due to the short distance of the high voltage lines. Additionally, the transmission lines should be made of AAC2 (all aluminum conductor) wire. Using this type of wire at the specified voltage, the transmission lines will have a total loss of approximately 102 watts.

In order to boost the voltage from the generator output to this specified voltage, a three phase delta-wye connected configuration step-up transformer is required. In addition, three single phase step-down transformers are required to drop the voltage back down to the desired 220 volts before it can be distributed to the village residents. A standard transformer efficiency of 95% was considered for calculations.

In order to conserve materials, a single phase will be supplied to a series of homes in the village. This implies that the village will be divided into three sectors and each sector will get electricity from one of the three phases of the power supply. Including the efficiencies of the components of the distribution system and the specified values of voltages and frequency, it was found that the generator must be able to supply 37.6 kW at peak demand and the flywheel must be able to store 77.4 kWh per day.

FLYWHEEL DESIGN CONSIDERATIONS

After determining the energy storage requirement of 77.4 kWh per day, a detailed examination of flywheel based inertial energy storage systems was completed. Through numerous iterations, a flywheel consisting of six spokes, a central hub, and an outer ring, as shown in Figure 3, is the optimum design as it allows for the largest inertia to mass ratio. This is desired because the

energy stored in a rotating disc is proportional to the moment of inertia multiplied by the square of the angular velocity. In addition, the weight of the flywheel directly affects the frictional losses. Thus, a flywheel with a large moment of inertia and small mass will be able to store the most amount of energy while minimizing frictional losses.

Since a non-industrialized region is targeted, the situation requires the use of widely available high yield strength steel, such as the American Iron and Steel Institute (AISI) 4340. Angular velocity also limits the design, since the material stresses increase as the angular velocity increases. For this situation, a steel flywheel spinning at approximately 500 rpm will be sufficient to store the energy required (approximately 156 kWh).

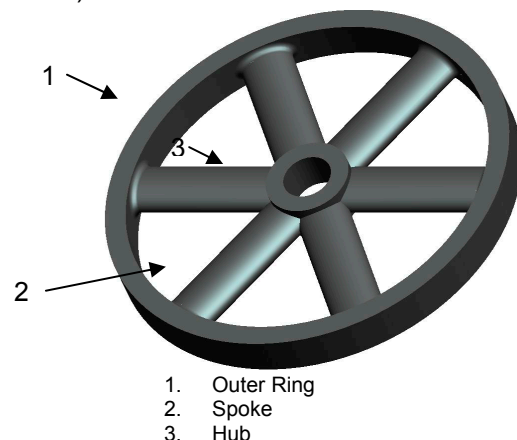


Figure 3: Flywheel and components.