Human Muscle Energy Harvesting: Models and Application for Low Power Loads

Basti Bharath Shenoy, Tonse Laxminidhi, U. Shripathi Acharya
Electronics and Communication Eng.
National Institute of Technology Karnataka
Surathkal, India 575025
ec16f01.bastibharath@nitk.edu.in, laxminidhi_t@nitk.edu.in, shripathi.acharya@nitk.edu.in

Joydeep Mitra
Electrical and Computer Eng.
Michigan State University
East Lansing, MI 48824
mitraj@msu.edu

***Abstract*—This paper presents models for human muscle power which can be harvested and utilized for low power applications. The low power application considered in this paper is the case of off-grid rural electrification, where a person in a rural area uses a bicycle-based human power generating system to charge a battery for the purpose of lighting his home with a few low-wattage LED lamps during periods of necessity. In this regard, two methods to convert energy from human muscle activity into useful electricity by utilizing the commonly available bicycle are proposed and presented with hardware results. The presented hardware results prove that power of the order of 50 W can be successfully generated using these methods. Another important feature is that, the methodology involved in generating useful electricity is carbon-free and power can be generated at any given point of time regardless of location or the associated climatic condition.**

***Index Terms*—Clean power generation, Energy harvesting, Human muscle power model, Rural electrification, Sustainable.**

I. Introduction

The human body is capable of producing a significant amount of energy [1]. Human muscle activity has the potential to generate power which can be used for low power applications. Normal human metabolism produces heat at a metabolic rate of about 80 W [2]. Over an eight hour day for a 48 hour week, a useful norm for a 35-year-old laborer for total power expenditure, including basal metabolism energy, is 0.49 hp (366 W) [3]. Of this total expenditure, approximately 0.1 hp (75 W) is available for useful work [3], [4]. A healthy 20-year-old man can generate about 15% more power than this norm, and a 60-year-old man about 20% less [3]. Well trained cyclists can produce even higher amounts of power output. There are several ways to extract the energy generated by human muscle activity. Walking is one of them, but the power generated is very minimal. A maximum of about 9 W is claimed to be generated [5]. Typically it is even lower [6]. Hand cranking and bicycle pedaling have the capacity to generate higher amounts of power output. The actual amounts of power generated by human muscle activity can be obtained using mathematical models. Harvesting of human muscle energy can be utilized for low power applications in rural electrification, where the power generated can be used for small lighting applications or the like.

Electric grid is not accessible in all rural and remote locations. Access to electricity is considered as a key element in determining quality of life [7]. Energy is required to improve the living environment, and satisfy the needs and aspirations of increasing populations [8]. Almost a fifth of mankind still lacks access to electricity, with around 85% of them living in rural and remote areas [9]. It is often considered a challenging task to connect all remotely located customers onto the electric grid. Hence to meet the electrical energy needs of people who live in these locations, off-grid electricity is a plausible solution. There are several schemes to generate off-grid electricity. The requirement is to adopt schemes which has a lower environmental impact [10] along with being affordable and sustainable over the long run. The requirement is also to use equipments which are easily accessible to the rural population. The electrification systems which are renewable energy based are considered as a suitable option for providing electricity to isolated communities autonomously [11]. Renewable energy systems perfectly fit the context when compared with conventional power generation system, which typically is not environmental friendly. Hence, there is a need to meet the requirement by exploiting alternative energy sources which offer a cleaner and greener solution [12].

Solar and wind are very popular renewable energy sources which are used to generate electricity in areas which are not connected to the electric grid. But the solar photo-voltaic technology relies on weather conditions. During the rainy season or cloudy days, the power generation will be negatively impacted, i.e. the photo-voltaics will not be able to generate the rated power output. This imposes limitations on location [13]. A wind power generation system requires a significant investment along with a substantial amount of space for installation, thereby making it an un-affordable option to individuals [14]. Hence there is necessity for an alternative renewable energy technology which effectively solves the problem posed by seasonal variations and locational disadvantages. This causes the power generation facility to be accessible at any given point of time. The focus is also to make the entire system of power generation affordable to an individual living in a rural or remote location. In this regard, human muscle energy harvesting is being explored and demonstrated as an alternative solution for low power applications in off-grid rural electrification. This can be an effective alternative, especially in rural and remote locations because of its abundance.

The remainder of the paper is structured as follows. Section II discusses about the human muscle power models and also

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gives a basic block diagram of an off-grid Light Emitting Diode (LED) lighting system. Section III presents two methods to generate electricity from human muscle activity during bicycle pedaling along with hardware results. Application of human muscle power for rural electrification with power generation system details and generalized power back up time calculation is discussed in section IV. Finally, section V provides concluding remarks on the work presented.

II. Human Muscle Power Model and Off-Grid Lighting

This section deals with the discussion of human muscle power models and also gives the block diagram describing the various components of an off-grid based lighting system.

A. Muscle Power Models

Human muscle activity can generate power which can be used for doing work. The generated power varies from individual to individual and also across age groups. According to a rule of thumb, power developed by European males can be expressed as a function of age and duration of effort in minutes for work lasting from 4 to about 480 min, assuming that 20 % of the total power output is useful, the function is given in for different age groups as in (1), (2) and (3) [3]:

$$P_{20}(t) = 0.4 - 0.1 \times \log(t) \quad (1)$$

$$P_{35}(t) = 0.35 - 0.09 \times \log(t) \quad (2)$$

$$P_{60}(t) = 0.3 - 0.08 \times \log(t) \quad (3)$$

Where P_{20}, P_{35} and P_{60} represent power outputs expressed in horsepower (hp) for age groups of 20, 35 and 60 respectively and *t* is in minutes. Well trained athletes can produce higher amounts of power, but for short intervals of time.

The useful power production from human beings mainly depend on the contact between muscle mass and mechanism of power transmission. Bicycle pedaling makes use of a large quantity of muscle mass. Hence pedaling, i.e. the use of leg muscles is chosen in this work to convert human muscle power to electricity. For pedaling efforts considering 1 to about 100 minutes, the power output can approximately be expressed as below [3]:

$$P(t) = 0.53 - 0.13 \times \log(t) \quad (4)$$

Again (4) assumes that 20 % of the power output is only useful. Fig. 1 shows a plot of useful power with respect to time for a period of 1 to 100 minutes. The average useful power in hp is found from the area under the curve and its value is calculated as 0.0648 hp. The watt equivalent of the average useful power is 48.32 (1 hp = 745.7 W). If the pedaling is considered for a period of 1 to 16 minutes (effectively 15 minutes of pedaling), the average useful power in hp is again evaluated from the area under curve between 1 and 16 minutes. The value is calculated to be 0.0839 hp. The watt equivalent of the average useful power now is 62.56.

The following observations can be made about human muscle power output from Fig. 1:

- As pedaling time is increased, the useful power delivered by human leg muscles decreases.
- The average useful power when a bicycle is pedaled for 15 minutes is about 48.32 W.
- The average useful power reduces from 62.56 W to 48.32 W when the pedaling time is increased from 15 minutes to 99 minutes.

The reduction in average useful power occurs due to the fact that, as pedaling time advances, the pedaler develops fatigue and finds it harder to pedal.

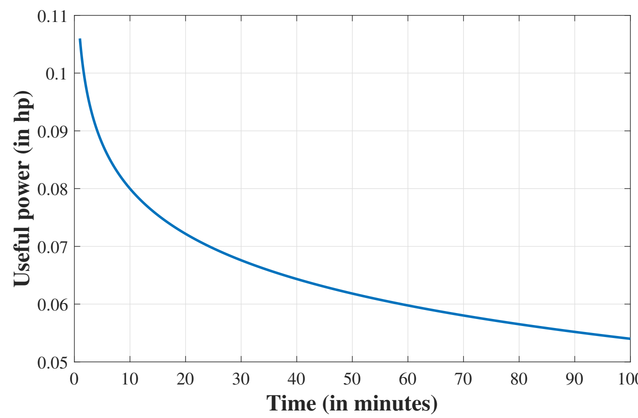

Fig. 1. Plot of useful power in hp for 99 minutes of pedaling

B. Off-Grid based Conventional Lighting System

A conventional off-grid based lighting system with power back up can be represented in a block diagram format as shown in Fig. 2. The energy source can be any form of energy. While it is preferred to be a renewable form, usually it is wind or sunlight. The energy conversion device helps to convert the source of energy into an electrical form. The power converter circuit 1 is required to convert output of the energy conversion device into a form suitable to push useful electrical energy into the energy storage device. The energy storage block is typically a battery. After the energy storage block (i.e. the battery) accumulates enough energy, it is connected to the power converter circuit 2, which is typically a LED driver. This circuit powers up the LED lamp, which can be used for lighting in remote areas. The power converter circuit 1 is essentially a battery charger. The LED driver and battery charger are chosen based on LED specification, battery specification and system specifications.

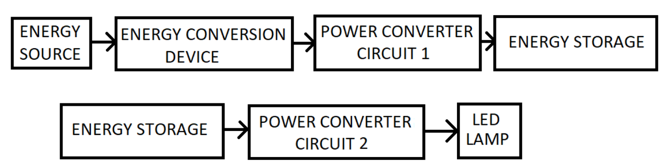

Fig. 2. Block diagram of an off-grid based conventional lighting system

III. HUMAN MUSCLE GENERATED POWER CONVERSION METHODOLOGY

Human muscle activity has the ability to generate useful power [3], which can then be utilized for low power applications. Because of the effective contact between leg muscles and power transmission mechanism, bicycle pedaling is used in this work. This section mainly deals with two methods to convert human muscle activity into useful electricity using the commonly available bicycle.

A. Method 1: Car Alternator based

The block diagram of this methodology is shown in Fig. 3. The bicycle rear wheel is coupled with the car alternator shaft using a friction based drive. The alternator converts mechanical energy into an electrical form, which in-turn is used to charge the battery through a battery charger circuit. The battery charger circuit is chosen such that it has a current limiting functionality. This is done to make sure that charging current does not exceed the recommended value. Power rating of the car alternator used is 500 W (14.4 V at 35 A) and the RPM rating is 2000 to 10000. The alternator is electrically wired up in a car as shown in Fig. 4. Similar configuration is used for the alternator. The manual switch plays a critical role in making the system function appropriately.

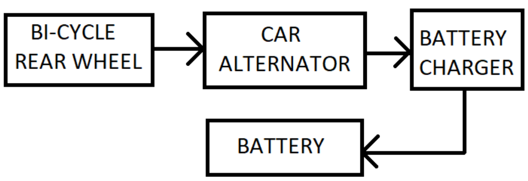

Fig. 3. Block diagram: Method 1

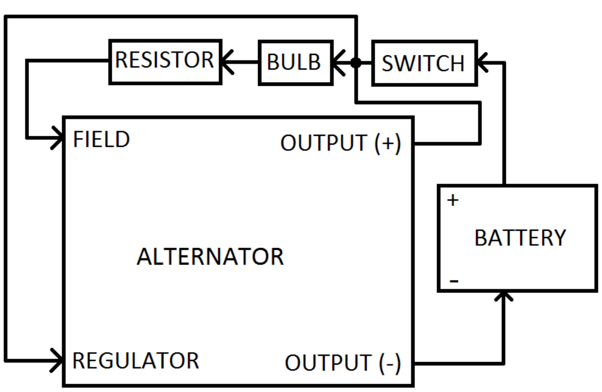

Fig. 4. Alternator electrical connections in car

The implementation is simple, but there are a few associated disadvantages. Firstly, it requires a dedicated battery for implementation. Secondly, the car alternator is bulky, making it harder to pedal the bicycle. Finally, the drive mechanism is friction based, which is quite lossy.

Table I gives the measured power outputs after implementing method 1. It can be observed that power of the order of about 60 W can be generated using the above method, when bicycle is pedaled.

TABLE I
POWER OUTPUT OF METHOD 1 FOR VARIOUS RESISTIVE LOADS WHEN BICYCLE IS PEDALED

Load resistance (Ω)	Measured output voltage (V)	Measured load current (A)	Power output (W)
4.7	12.47	2.33	29.05
4.7 ‖ 4.7	11.38	4.15	47.23
4.7 ‖ 4.7 ‖ 4.7	10.63	5.59	59.42

B. Method 2: Permanent Magnet Direct Current (PMDC) Generator based

The block diagram of this methodology is shown in Fig. 5. The bicycle rear wheel is coupled with the PMDC generator shaft using belt based or friction based driving mechanism. The PMDC generator converts mechanical energy into the electrical form which is given to the battery charger circuit, which in-turn charges the battery. The battery charger should have a current limiting functionality along with voltage regulation, so that charging current does not exceed the recommended value. PMDC generator used for the implementation has a rated power of 50 W (12 V at 5.2 A). The RPM rating is 1500. The implementation of belt based and friction based drives are discussed next.

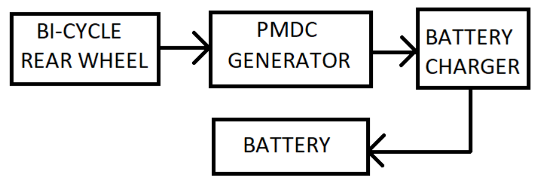

Fig. 5. Block diagram: Method 2

1) Belt based Drive: The rear wheel of the bicycle, the rim in this case is mechanically coupled to the shaft of PMDC generator using a link belt.

Table II shows the power outputs after implementing method 2 with link belt based drive mechanism. It can be observed that power of the order of 50 W can be generated using the above method, when the bicycle is pedaled. The power output can further be increased by using a PMDC generator of higher power rating. This method uses a better approach when compared to a lossy friction based drive mechanism used in method 1, in-turn making it easier for the bicycle pedaler. The major drawback associated with this method is that, the bicycle should be used as a stand-alone equipment. This increases the system cost making the overall system more expensive.

2) Friction based Drive: In this method, the rear wheel of the bicycle is coupled to PMDC generator shaft by using friction based drive mechanism. Here the larger bicycle rear wheel is mechanically coupled with the smaller wheel

TABLE II
POWER OUTPUT OF METHOD 2 (LINK BELT BASED) FOR VARIOUS RESISTIVE LOADS WHEN BICYCLE IS PEDALED

Load resistance (Ω)	Measured output voltage (V)	Measured load current (A)	Power output (W)
4.7	12.61	2.32	29.25
4.7 ‖ 4.7	11.21	3.95	44.28
4.7 ‖ 4.7 ‖ 4.7	10.72	5.31	56.92

connected to the PMDC generator shaft. The difference in wheel diameters replicate a gear mechanism, increasing the speed of rotation of PMDC generator shaft in comparison with the bicycle rear wheel. Table III gives the measured power outputs after implementing method 2 with friction based drive mechanism. It can be observed that power of the order of 50 W can be generated using the above method, when the bicycle is pedaled. The power output can further be increased by using a PMDC generator of higher power rating.

TABLE III
POWER OUTPUT OF METHOD 2 (FRICTION BASED DRIVE) FOR VARIOUS RESISTIVE LOADS WHEN BICYCLE IS PEDALED

Load resistance (Ω)	Measured voltage (V)	Measured load current (A)	Power output output (W)
30	30.76	0.96	29.53
20	30.42	1.37	41.67
6.6	19.98	2.59	51.75

This method effectively addresses the major drawback posed by the link belt based approach. The following advantages are associated with this system:

- The bicycle used here need not be a stand-alone equipment. It can be plugged into the charging platform for power generation when required and later can be used for transportation, i.e., making the bicycle multi-purpose.
- The charging platform can be hooked to the bicycle rear wheel within a few seconds, making it easier for the user to assemble the system.

The charging platform in this case can also be shared by several households in rural and remote locations, thereby further reducing the overall system cost.

IV. HUMAN MUSCLE POWER FOR RURAL ELECTRIFICATION: LOW POWER APPLICATIONS

This section deals with the practicality discussion of human muscle power as a possible alternative for off-grid rural electrification, for low power applications. The power generation system (using Method 2 discussed in section III) details for low power lighting application, along with power back-up time calculation for DC LED bulb are also presented.

A. Human Muscle Power Practicality Discussion

Human power is best suited for applications that require small amounts of power, that benefit from portability or exist in remote locations, and that need to be available on demand and that are relatively inexpensive [15]. Hence human muscle power is a viable option for off-grid rural electrification, i.e. for low power applications in rural areas such as lighting a home with few low-wattage LED bulbs during periods of necessity. As an energy source, the advantage associated with human muscle energy is that, it is available in abundance. The muscle power models discussed in section II also prove that, it is possible to generate an average power of about 48 W, if the pedaling effort is sustained for 15 minutes. This order of power generation is suitable for low power applications in areas which are not connected to the electric grid. The method of power generation is also eco-friendly and sustainable. Also, human muscle power is well-suited to those who want a healthy body and a healthy environment [15].

B. Power Generation System for Low Power Lighting Application in Rural Areas

The entire system can be represented in a block diagram form as shown in Fig. 6. The 12 V DC LED bulb is chosen,

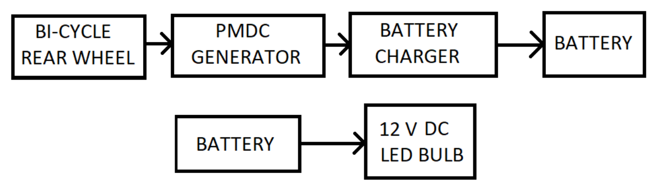

Fig. 6. Power generation system block diagram

such that it has a driver of its own. Hence, once the battery is charged, it's output is directly connected to the LED bulb. Battery charger is a high efficiency DC-DC buck-boost converter which matches the system specifications. The choice of buck-boost converter is due to the fact that, while the system gets started, the PMDC output voltage will be lower than that required to charge the battery. The buck-boost converter can be replaced by a buck-converter if, an electronic switch is added between the PMDC generator and battery charger. The electronic switch to be used connects the PMDC generator output to the battery charger only when sufficient voltage is built up at the output of PMDC, which can be used to charge the battery.

C. System Specifications

The system specifications are given in Table IV. It takes into account the overall system, also including the DC LED bulb specification. Since the application targets low power loads, LED wattage is considered in between 1-3 W. The output voltage of PMDC generator, output voltage limit of power processing circuit required, average output current limit of power processing circuit and power conversion efficiency are the critical system specifications required in making the proper choice for battery charger circuit.

TABLE IV
SYSTEM SPECIFICATIONS

Output voltage of PMDC: 0-35 V
Maximum output power of Battery Charger: 50 W
Output voltage limit of Power Processing Circuit required: 13.2 V
Average output current limit of Power Processing Circuit: 3.8 A
Source of energy for charging the battery: Human muscle energy
Battery charger circuit: High efficiency DC-DC buck-boost converter
Energy storage device: Battery (12V, 9 Ah VRLA battery)
DC LED bulb wattage: 1-3 W
DC LED bulb operating voltage: 12 V

D. Bicycle with Charging Platform

The snapshot of the bicycle with charging platform is shown in Fig. 7. Method 2, with friction based drive is used here to convert human muscle energy into electricity due to its associated advantages. The choice of Method 2 is based on the fact that, the bicycle needs to be used for its regular purpose apart from acting as a mode for energy conversion. This reduces the overall system cost. The charging platform can be shared by a few rural households, further helping to reduce the overall system cost.

Fig. 7. Bicycle with charging platform

E. Calculation of Power Back Up Time

Let us consider that the bicycle is being pedaled for T minutes, the 12 V DC LED bulb back up time as $T_{back-up}$ and LED wattage as W watts. The average value of useful power can be calculated using muscle power model given in (4). This value is represented as P_{Muscle}. Let the mechanical to electrical power conversion efficiency (including bicycle and PMDC generator) be η_1, battery charger power conversion efficiency (including charger and battery internal resistance) be represented by η_2 and the DC LED bulb power conversion efficiency be η_3. The total amount of useful energy delivered to the battery can be given as:

$$E_{battery} = P_{battery} \times T \quad (5)$$

The equation for average power delivered to the battery can be given as:

$$P_{battery} = P_{Muscle} \times \eta_1 \times \eta_2 \quad (6)$$

On the other hand, the DC LED bulb requires an average power given by:

$$P_{LED} = W \times \eta_3^{-1} \quad (7)$$

Hence from (5), (6), and (7), the DC LED bulb power back up time can be calculated as:

$$T_{back-up} = P_{Muscle} \times \eta_1 \times \eta_2 \times \eta_3 \times W^{-1} \times T \quad (8)$$

V. CONCLUSION

Human muscle power models are discussed and analyzed. Human muscle energy, as an alternative energy source is proved to be suitable for low power applications such as lighting few low wattage LED lamps and other low power applications pertaining to off-grid rural electrification. The power generation is validated by using hardware results of power generated using an assembly consisting of bicycle, PMDC generator and charging platform. Hardware results also prove that power of the order of 50 W can be generated from human muscle power using bicycle pedaling. The usual bicycle with minor modification is proved to be useful and cost-effective mode to convert human muscle energy into electricity because, it is the commonly used mode of transportation in remote and rural areas. Generalized power back up time calculation for a typical lighting application has been derived for the proposed power generation system. The proposed method of power generation is also environmental friendly, sustainable over the long run and suited for those who want a healthy body. The power generation system also caters to seasonal and locational disadvantages, making it accessible at any given place and point of time.

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