Dissertation

On

TOWARDS HUMAN-POWERED LOWER-LIMB EXOSKELETONS

Submitted in partial fulfillment of the requirement for the award of degree of

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Submitted by

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DECLARATION

I hereby declare that work done in this dissertation report entitled, "**Towards Human-Powered Lower-Limb Exoskeletons**" submitted towards partial fulfillment of requirement for award of **Master of Engineering** degree in **CAD/CAM Engineering** in Mechanical Engineering Department of Thapar University, Patiala, is an authentic record of work carried out by me under the supervision and guidance of **Dr. Ashish Singla**, Assistant Professor, Mechanical Engineering Department, Thapar University, Patiala. This matter embodied in this report has not been submitted in part or full to any other university or institute for the award of any degree.

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This is to certify that above declaration made by the student concerned is correct to the best of my knowledge and belief.

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ABSTRACT

Most of the current commercially available exoskeletons use rechargeable Li-Ion batteries, which require frequent charging to meet the operational needs. The battery charging is a serious bottleneck, when the person, wearing the exoskeleton, needs to go for trip outdoors or for extended excursions such as trekking. To reduce the reliance on battery power, more reliable and alternative energy sources are required. In this respect, human-powered products (HPPs) are emerging as useful emergency electric power sources, when regular power supplies are unavailable. Human power is defined as the use of human work for energy generation. The energy is harvested from the user's everyday actions (walking, breathing, body heat, blood pressure, finger motion etc.). Once the power is harvested, it must be stored in a suitable device like capacitors, rechargeable batteries, etc. Being economical and environment friendly, these devices can also act as a boon for under-developed countries, since batteries are expensive and the mains power supply can be unreliable. The energy generation in these devices is broadly based on five methods—*piezoelectric*, *vibrations*, *radio frequency (RF)*, *electrostatic* and *electromagnetic*, and each method produces different amount of electrical energy. All these methods are reviewed in this work; the first four methods produce relatively small amounts of energy, which is inadequate to charge the battery of assistive exoskeletons. Therefore, the focus here is on electromagnetic devices and how this can be used to power assistive exoskeletons. Some human-powered products are also reviewed and the report compares conventional and alternate methods to charge lower-limb exoskeletons used for assisting elderly persons. However, in this thesis objective presented are focused on charging exoskeleton with upper-body motion, the use of a hand-crank generator for this purpose is proposed in this work. A mathematical model is developed to describe the complete process of energy generation and deployment. Further, experimental test-rig is developed to validate the mathematical model. Along with this, the Matlab/Simulink based PID controller is used to suppress the fluctuations in the output of a hand-crank generator.

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τ_c	Torque transmitted to the shaft of HCG
F_t	Applied force
W_t	Total work transmitted to the shaft of HCG
W_{t_Human}	Work done by human limbs
T	Actual torque transmitted
K_T	Generator constant
i_q	Output current from HCG
V_g	Voltage generated
P	Number of field poles
$\emptyset$	Flux produced per pole in Wb (Weber)
N	Rotational speed of armature (rpm)
Z	Total number of armature conductors
A	Number of parallel paths in armature
P_{human}	Power input by human
P_{elec}	Electrical power output
η	Efficiency of HCG
ω	Crank speed (rpm)
K_P	Constant of proportionality
K_D	Constant of differentiability
K_I	Constant of integral
$Z(s)$	Output of controller
$U(s)$	Input to controller

List of Abbreviations

HPP	Human Powered Products
EM	Electromagnetism
AFPM	Axial Flux Permanent Magnet
RFPM	Rotary Flux Permanent Magnet
HPG	Human Powered Generators
HCG	Hand Crank Generators
DOF	Degrees of Freedom
MGR	Merry-Go-Round
AC	Alternate Current
DC	Direct Current
STS	Sit-To-Stand
PID	Proportional-Integral-Differentiable

List of Publications

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3 Saurav Dhand, Ashish Singla, Gurvinder S. Virk, “Towards Human-Powered Lower-Limb Exoskeletons,” (Under Review)

4 Saurav Dhand, Ashish Singla, Gurvinder S. Virk, “Use of Human Effort to Power Lower-Limb Exoskeletons: A Review,” (Under Review)

5 Saurav Dhand, Ashish Singla, “Production Scheduling Optimization and Sensitivity Analysis,” (Under review)

This page is dedicated to my beloved nephew

Aarav Dhand

Chapter 1

Introduction

1.1 Powering Methods for Exoskeletons

With an emergence in robot technology, it has become a necessity that these robots should also cover medical applications. This opens new area of research that how safe human-patient interactions for various diagnosis, treatment and rehabilitation tasks can be possible. The main sectors of interest currently focus on medical robots for surgery and for rehabilitation. The wearable robot, to assist body for augmentation of load or for rehabilitation purpose, are referred to as exoskeletons. One such commercial available lower-limb exoskeleton, used for rehabilitation purpose, shown in Fig. 1.1, is targeted in this thesis. A review of various exoskeletons is covered in Chapter 2.

Fig. 1.1: Lower-limb exoskeleton [1]

With the increase in the information and communication in every field, be it a medical line, education system, military etc., there has been a continuous increase in use of portable devices like mobile phones, walkie-talkie, and other wireless devices. The major powering source in these devices is rechargeable batteries. Since the life of these rechargeable batteries is around *2-3* hour at full load, frequent charging is required. In case of emergency or situation when there is no source of power, these devices stops working, which can cause problems like miscommunication. Sometimes it can also lead to huge losses. In these emergency situations, human power can be a viable option for powering these devices.

Even though energy harvesting is not a new process, it has always come out as a promising area of research. Self-winding wrist-watch is one such example of energy harvesting, in which electric energy is harvested using the mechanical energy of the user. Energy harvesting involves capturing energy from the surroundings using different transducers like piezoelectric transducer, variable capacitors (electrostatics), inductive generators (electromagnetics) etc. Working principle of all these types of transducers is generally based on different physical phenomenon. Piezoelectric transducers involve straining a piezoelectric material to get voltage output. Thermoelectric generators extract electrical energy from the temperature difference between the human body and the environment. But the voltage output of such transducers is very low. This voltage can be used to power microcontrollers and other low-powered electronics circuits. These transducers will be discussed in detail in this thesis.

Different movements of human body (human walking, arm motion, running etc.) gives as many human power sources. By defining an appropriate motion and location in the human body, a suitable transducer can be selected. In order to design a harvested energy generator, first step is the detection of acceleration and motion of different parts of the body for different activities. The second step consists of obtaining a software model of the generator from the data obtained in the first phase and the electrical circuit of the transducer. The third step consists of the design of a converter and/or storage circuit that has to take into account the output signal of the generator and its impedance. Final step consists of redesigning the generator based on the simulations made in the second phase and the real results obtained by a prototype.

Electricity generation is the process of generating electric power from other sources of primary energy. Electricity is most often generated at a power station by electromechanical generators, primarily driven by heat engines fueled by chemical combustion or nuclear fission but also by other means such as the kinetic energy of flowing water and wind. Other energy sources include solar photovoltaics and geothermal power. Methods used nowadays for generation of electricity includes [2]—hydraulic energy, thermal energy, tidal energy, nuclear energy, solar energy etc. Each method in the above list is used to produce a great amount of Electric power that can be used for power needs of a city or a country. Average production by each method is shown in Table 1.1.

Table 1.1: Source of Electricity (World total year 2008) [3]

	Coal	**Oil**	**Natural Gas**	**Nuclear**	**Renewables**	**other**	**Total**
Average electric power (*TWh*/year)	8,263	1,111	4,301	2,731	3,288	568	20,261
Average electric power (*GW*)	942.6	126.7	490.7	311.6	375.1	64.8	2311.4
Proportion	41%	5%	21%	13%	16%	3%	100%

When the topic of electricity generation comes into mind, one automatically has a perception of generating electricity at large scale e.g. nuclear-power plants. Since the power required for charging the batteries of exoskeleton and other electronics devices is much less than this power, therefore aforesaid methods are beyond the scope of present thesis. Advancements in technology and portable devices have produced a need to generate electric energy at small-scale. Portable devices can be charged on-the-go with solar energy, human power and wind energy as these are non-renewable sources and easily available everywhere. Powering of one such portable device, exoskeleton, has been discussed in this thesis.

1.2 Problem Statement

Exoskeletons, for assisting elderly people, are limited with their working due to the size and operating time of the battery. In order to provide complete and independent mobility, frequent and portable charging device is required. For stable and affordable charging of exoskeleton battery, a charger is required that can be used at the will, no matter, if there is any grid supply or not. The problem becomes big when the exoskeleton wearer person has to move out of his/her house to a remote area for a couple of days. Under these circumstances, the use of human-power for powering exoskeletons is proposed in this work. A low power lower-limb exoskeleton, mostly used by elder people, has been targeted in this study. Since this exoskeleton is for lower-limbs, energy generated by upper limbs can be used for powering this. The main objectives of this study are:

a) Exploration of various upper-limb powered products e.g. hand-powered, backpack generator etc. for power generation.
b) To calculate of power required by an actuator at one joint (knee, hip or ankle).
c) To calculate the output of proposed hand-crank generator.
d) To develop the mathematical model of power generation process.
e) To investigate the power requirement of exoskeleton.
f) To implement a PID controller in Matlab/Simulink environment to suppress the fluctuations in generator output.

Before claiming the use of human power to charge an exoskeleton, above mentioned objectives needs to be met first. Based on the output of each objective, a solid conclusion is made that whether human-power, specifically hand-crank generators, can be used for powering exoskeletons or not.

1.3 Scope of the Thesis

The scope of this thesis is in the rehabilitation of elderly people. By providing with the facilities like exoskeletons make them feel independent and good as they do not need to be dependent on any family member or domestic help. A lot of research has been conducted worldwide on helping elderly people walking. To make the working of exoskeletons prolong and hassle-free, a feasibility investigation of human-power exoskeleton is discussed in this report. Although the idea discussed in this report is limited to low-power lower-limb exoskeletons, the scope of the application can be extended to upper-limb exoskeletons by adopting appropriate changes for example, a person with lower body disability can generate power using his upper limbs i.e. using HCG. On the other hand, if a person has upper body disability he/she can generate power using lower limbs i.e. using bicycle powered generators. Moreover, the output of this work is not only applicable to exoskeletons, but also to other electronics equipment that require low power for their working e.g. walkie-talkie, radio, mobile phones etc.

1.4 Organization of the Thesis

Based on the work done, this dissertation report is organized into six chapters. Chapter 1 consists of the introduction about thesis topic. In this chapter, an introduction about exoskeletons is given in the starting and then various non-conventional powering methods to charge its battery are discussed with reference to conventional powering techniques. Along with this, need of the research and various issues involved regarding this topic are also discussed with brief literature in problem statement section. In the end of this chapter, the scope of the thesis is also discussed, where various area of application of this study is defined. The significance of this work is also covered under this section.

In Chapter 2, the literature is reviewed extensively for every aspect related to this dissertation topic. Starting with the introduction to existing exoskeletons, their powering methods, limitations associated with the powering method and proposed charging method is discussed with appropriate references to each section. This chapter is further divided into four sections. First section is purely related to classification of exoskeletons and their present powering methods. In second section, the literature about source of powering or powering methods is discussed with limitations associated with each method. Third section gives brief idea about the alternate energy methods that are presently used as various power-sources. Fourth section gives details on the literature present about the proposed charging method i.e. human-powered products. A number of commercially available human-powered products are also discussed in this section.

Chapter 3 discusses the use of human-power to generate electric power using hand-crank generators. This chapter is also divided into four main sections. In first section, general working of the HCG is given in detail. Various principles of working of HCG are discussed with their advantages and limitations. Section two consists of mathematical modeling of the HCG. Basically, in this section the complete power generation process is described using certain assumptions in order to obtain mathematical relation between input and output. In third section, block diagram of the complete power generation process and deployment is discussed. Section four of this chapter gives the rough estimation of the charging time based on the torque requirement at various joints.

The experimentation part is covered in Chapter 4, in which the overview of the HCG and other parts is given in section one. Section two gives the experimental data of input cranking torque and output current. Whereas the relation of output voltage with cranking speed is verified in section three. Based on the above experimental results, various losses associated with each step is calculated and listed in section four. In the end, the efficiency of whole process is also discussed in this chapter.

To get a regulated and fluctuation free output from the HCG, a proposed rectifier and control method is discussed in Matlab/Simulation environment in Chapter 5. Details on the PID controller and thyristor bridge rectifier is discussed in first two sections of this chapter. The results of simulation using Simulink are shown in third section.

Finally, conclusions are drawn from the analytical and experimental techniques in Chapter 6 along with the possible future directions.

Chapter 2

Literature Review

2.1 Introduction

With the invention of electrical motor, there has been a great revolution in the operation, working, and application of electrical equipment. It has greatly influenced the production also as it has facilitated to produce in mass, accelerated, time saving and sometimes enabled us to travel in longer distance. The continuous evolution in equipment design, operation and size is shown in Fig. 2.1. It can be noticed that all the classical equipment have been modernized to run on electricity with electrical motors most of the times. Employing electric motor in devices also helps in better performance during operation. Moreover it has also seen that modernization leads to the process to be efficient on time scale. Since the motor requires a battery for operation when it is installed in a portable device, the demand of passive mechanism for energy harvesting has been increased continuously.

Fig. 2.1: Modernization of various equipment

The main focus of this section is to review the existing exoskeletons, their powering methods and sources, and also review of proposed human-powered products suitable for exoskeletons.

2.2 Exoskeletons

Exoskeletons are the integration of human and robotic machines. It is basically an assistive device that is used for either load augmentation or rehabilitation of person with disability as shown in Fig. 2.2. Load augmentation ability means enhancing the capability of an able-bodied person to carry heavy loads for longer period than usual. Therefore the fatigue of carrying heavy loads can be considerably reduced. These types of exoskeletons are mostly used for military operations, to carry heavy weapons on the back of soldiers.

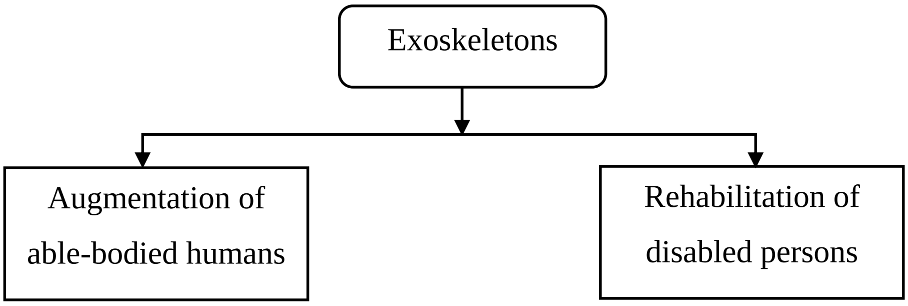


Fig. 2.2: Exoskeletons and its types

On the other hand, exoskeletons are also used for gait assistance for disabled persons to enable them perform his/her daily activities like bladder and bowel functions without the any domestic help. Clearly exoskeletons have some added advantages over the conventional wheel chairs. The exoskeleton wearer can go to one place to other without taking help from others. Table 2.1 categorize different types of exoskeletons and their developers according to the purpose they have made for. Before 1960, exoskeletons were appeared in science fictions and some of the early patents. In late 1960's, United States and former Yugoslavia started parallel working in this field. The focus of the groups in United State was basically to develop the exoskeletons for augmentation of the abled-bodied persons in order to assist military operations, whereas later started working in the field of development of active orthosis devices for rehabilitation of disabled persons [1].

Later on, many authors have developed different concepts on exoskeletons in their literatures. Further, the exoskeletons have been classified on the basis of mobility, as shown in Fig. 2.3. There are basically two types of exoskeletons— *portable and non-portable*. Portable category is also known as Mobile exoskeletons as it provides freedom to the wearer to go anywhere. Whereas for non-portable exoskeletons, there is a limit in the mobility due to excessive power requirements, which results in the use of direct power supplies. Therefore these exoskeletons are tied with wires to the powering source, hence limiting their work space. These classifications are discussed with the help of commercially available exoskeletons as their examples.

Table 2.1: Different types of exoskeletons

To augment the abilities of able-bodied humans		**To rehabilitate disabled person**	
Exoskeleton Model	**Developer**	**Exoskeleton Model**	**Developer**
BLEEX	DARPA exoskeleton programs	Hybrid Assistive Leg-3 [4]	University of Tsukuba, Japan
Sarcos [5]	DARPA exoskeleton programs	Power Assist Suits [6]	Kanagawa Institute of Technology, Japan
MIT Exoskeleton [5]	MIT	RoboKnee [7]	Yobotics
Enabling Technologies [5]	DARPA exoskeleton programs	CHRIS [8]	Hiroshima University

Further, Fig. 2.4 discuss the charging/powering methods. Most common exoskeletons, their powering source and powering method is given in Table 2.2. Some examples of both the categories, in detail, are discussed below:

2.2.1 Portable Exoskeletons

a) Berkeley Lower Extremity EXoskeleton (BLEEX): This exoskeleton was one of the outcomes of the DARPA program named Exoskeletons for Human Performance Augmentation (EHPA). It carries power source in form of a battery to power the actuators at different joints as shown in Fig. 2.4(e). BLEEX comprises of seven degrees of freedom (DOFs), where three DOFs are at hip joint, one at knee and three at ankle. Due to high DOFs, the power consumption of BLEEX is very high. Approximately *1.3 kW* of power is consumed by hydraulic actuators, various electronics and control systems [9, 10]. Therefore, it falls under the category of high-powered portable exoskeletons using rechargeable batteries, which can be charged using direct AC power supply.

b) Sarcos: DARPA program has also worked on making a full body exoskeleton named Sarcos shown in Fig. 2.4(c). Unlike BLEEX's linear hydraulic actuators, Sarcos has rotary hydraulic actuators. This exoskeleton is much efficient than BLEEX [5]. Walking speed of wearer of this exoskeleton is *1.6 m/s* carrying around *70 kg* of load.

c) Hybrid Assistive Leg (HAL-3): It is a Japanese exoskeleton designed and made by University of Tsukuba, Japan. It weighs around *21 kg*. Main motive behind invention of this exoskeleton is for rehabilitation of disabled persons. HAL can operate continuously for *160 minutes* [4]. Due to the use of number of sensors, the power requirement of the HAL-3 is high therefore it falls under the category of high power exoskeletons. HAL augments joint torques at the hip, knee, and ankle with *100 V* AC supply as shown in Fig. 2.4(a).

d) **Power Assist Suits**: Presented by Kanagawa Institute of Technology, Japan, this exoskeleton provides a nurse caring for a patient or disabled person. Power assist suits has got pneumatic actuators in it as shown in Fig. 2.4(b). Weight of the complete unit is approximately *13.4 kg*. It has got various pressure sensors, mini-computer, solenoid valves, compressed air storage tank etc. for its operation.

e) **RoboKnee**: Developed by Yobotics, INC., RoboKnee provides assistance to knee joint for climbing the stairs or in simple walking in case of disabled person [7] as shown in Fig. 2.4(d). Very few information about RoboKnee is available in literature. *13.4 kg* [6]. It has got various pressure sensors, mini-computer, solenoid valves, compressed air storage tank etc. for its operation.

(a) (b) (c) (d) (e) (f)

Fig. 2.4: Various exoskeletons— (a) HAL-3, (b) Power Assist Suit, (c) Sarcos, (d) RoboKnee, (e) BLEEX, (f) WAD

f) **Walking Assist Device (WAD, Honda)**: WAD is a low power, light weight walking assist exoskeleton manufactured by Honda shown in Fig. 2.4(f). It weighs around *6.5 kg*. It is compact in size. Technology used in WAD is similar to that of ASIMO [11]. Its Li-ion battery can last for two hours after full charging [1].

g) **HandSOME (Hand Spring Operated Movement Enhancer)**: It is a passive, lightweight hand rehabilitation device to assist stroke patient’s hand with the help of series of elastic cords. It has two variants having *0.128 kg* and *0.22 kg* [12]. For grasping the object the four bar linkage mechanism is used for fingers and thumb. HandSOME generally allows full range of motion.

h) **Wearable Agri Robot**: Despite mechanization in agriculture, most of the work needs to be done by hand. In order to assist farmers in planting and harvesting works

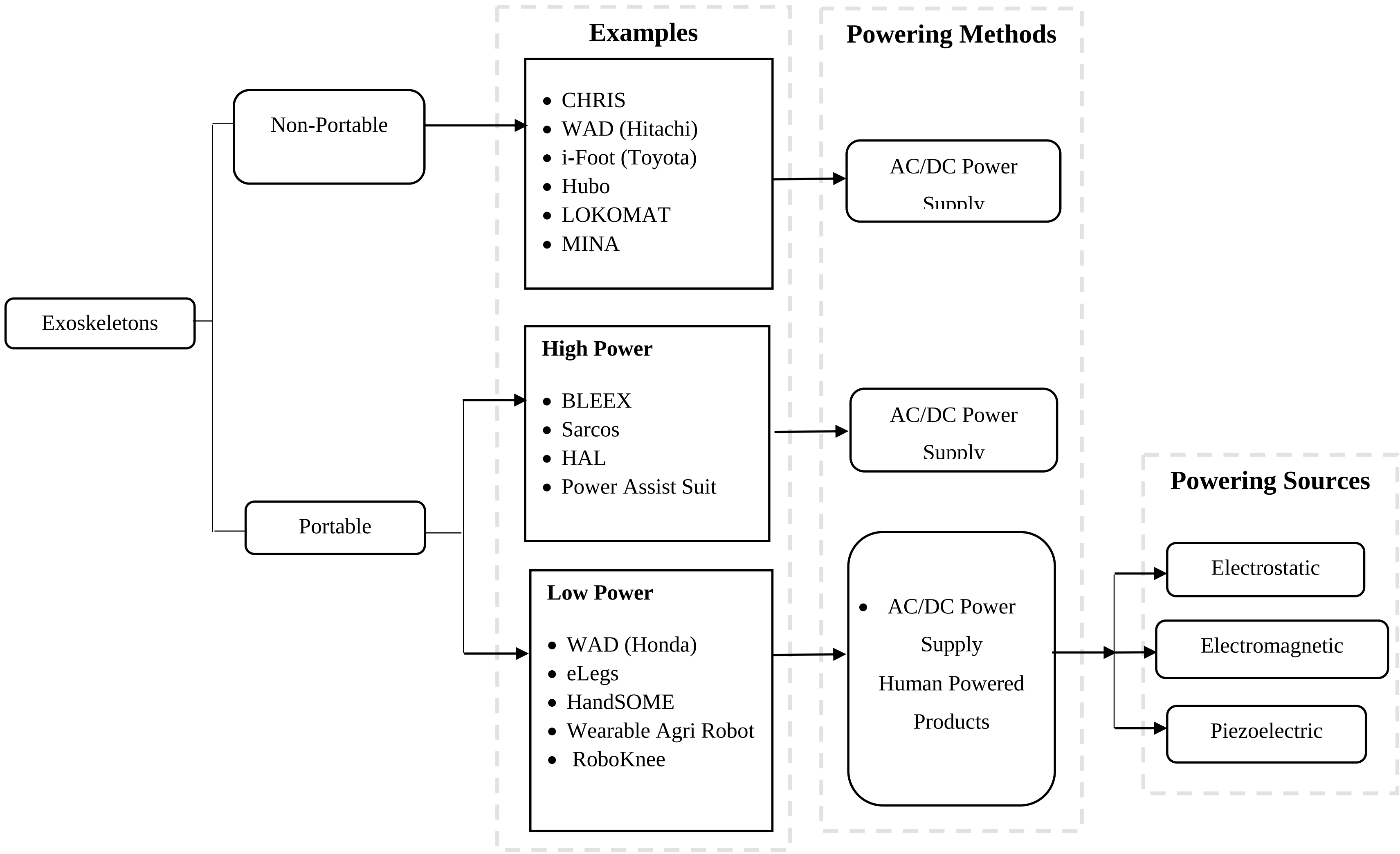


Fig. 2.3: Classification of exoskeletons on the basis of mobility

Tokyo University of Agriculture and Technology has developed an exoskeleton [13]. It has got ten DC motors installed at its ten different joints and various sensors like angle sensor, gyro sensor, pressure sensor, hall sensor etc. The low version of this robot weighs *23 kg*.

Table 2.2: Powering source and methods of various exoskeletons [14]

Exoskeleton Model	**Developer**	**Power Source**	**Method of Powering**
BLEEX	DARPA	Rechargeable Li-ion battery	AC power supply
Power Effector	MMSE Project Team	Direct Power Supply	AC Power Supply
Hybrid Assistive Limb	University of Tsukuba, Japan	AC100V Charged battery	100 V AC Power Supply
Power Assist Suit for nursing care	Kanagawa Institute of Technology	Ni-MH batteries	AC Power Supply
HRP-2 Promet	Kawada Industries	NiMH Battery DC 48 V, 18 Ah	48 V 20 A AC Power Supply
HRP-1S	Honda	Ni-Zn Battery	AC Power Supply

2.2.2 Non-Portable Exoskeletons

a) **Cybernetic Human-Robot Interface System (CHRIS)**: CHRIS has been developed by Hiroshima University, Japan. The probabilistic neural network (PNN) in it detects the human’s intentions and generates the control commands [8]. A *24 V* battery has been employed in it to drive two *150 W* permanent magnet, gear motors. It weighs more than *70 kg* and requires high amount of electric energy to operate.

b) **Walking Assist Device (WAD, Hitachi)**: It is an electrically operated walking assisted device using force sensors [15]. Force sensors have been placed in a U-shaped arm, which detects forward and backward force and adjust them accordingly. This exoskeleton is used for indoor applications like straight walking, for bathroom activities etc.

c) **i-Foot (Toyota)**: i-Foot has been developed by Toyota. It is a two-legged, mountable robot, which provide three dimensional mobility at a speed of *1.35 km/h*. It has a weight capacity of *60 kg* with own weight of *200 kg* [16]. i-Foot provides 12 DOFs and has joystick navigation.

From the above reported exoskeletons, it is clear that most of non-portable exoskeletons are either directly connected to electric source through wires or are operated with the help of large batteries. This limits their mobility within confined space. Similar trend can be observed in some of portable exoskeletons that require large amount of current to charge their batteries. Even though portable, recharging these devices is a concern, which can be addressed by ensuring the availability of a power source. In case of portable exoskeletons, which require low power to operate, user can carry an alternate source of electric power so that in case of emergency, batteries can be recharged. Therefore for low-power portable exoskeletons the use of alternate source of power, that is human power, is presented in this thesis.

2.3 Battery/Storage Medium

Many storage mediums are available for storing this generated electricity depending upon amount and voltage of electric current produced [17, 18, 19, 20]. Each source, be it Li-ion batteries, Ni-MH batteries, mechanical flywheel or Supercapacitor, can be used in any application subject to purpose and performance of storing. Characteristics of different batteries are discussed in Table 2.3. In order to achieve maximum storage capacity and low emission/loses, various multi-objective optimization techniques have been formulated by many researchers [21, 22, 23].

The demand of primary and secondary batteries will rise in the following years due to the generation of energy-hungry portable devices like digital cameras, camera phones. If we focus on powering portable devices, lithium-ion are now the secondary batteries leader of the market and will be in future.

Table 2.3: Characteristics of batteries and supercapacitors [24]

	Battery		**Supercapacitor**
	Li-ion	**Thin-Film**	
Operating voltage (*V*)	3–3.70	3.70	1.25
Energy density (*Wh/l*)	435	<50	6
Specific energy (*Wh/kg*)	211	<1	1.5
Self-discharge rate (% per month) at 20 °C	0.1–1	0.1–1	100
Cycle life (cycles)	2000	>1000	>10,000
Temperature range (°*C*)	-20/50	-20/+70	-40/+65

The Ni-batteries market is shrinking and is being replacing by NiMH for environmental reasons. Alternative rechargeable batteries will make up less than *7%* of all secondary batteries. Fuel cells are not going to play a significant role in secondary batteries market. Cost, size and performance are their main disadvantages. Li-P have a gravimetric energy density greater than oldest rechargeable batteries like Ni-Cd. In addition, the improvement rate is also greater for newest secondary batteries.

2.4 Alternative Energy Methods

There has been a continuous demand of small, environmental friendly, electricity generating renewable energy sources. These sources are not dependent on conventional fossil fuels to produce electric current, but on wind energy, photovoltaic energy, micro hydro-power, tidal energy, human power etc. A lot of research has been conducted in field of mathematical modeling, computer modeling, feasibility study and implementation of alternate energy sources [25, 26, 27, 28, 29, 30]. Solar cells have dominated the commercial markets as an alternate source of energy [31, 32], however their operation is susceptible to the weather conditions, questioning their reliability. The power output from all these sources is either very high (kW in case of wind energy) or very low (mW in case of piezoelectric). Moreover, there are various loses associated with storage of this generated electric current. Therefore, a versatile and readily available source of energy is the need of the hour, which can be exploited in case of an emergency like situation. The focus of this work is to enhance the mobility of an exoskeleton-wearer in remote areas, which are deprived of ample electricity. For this purpose, the use of human power as an alternate source of energy is proposed in this work. The human power can be exploited using various human powered products like cranking, rocking on a chair, walking, pedaling etc. The details of scavenging power from human efforts will be discussed later in upcoming chapter. Moreover, various existing human power products will also be discussed later.

2.5 Human-Powered Products

With human powered-products, a wide range of energy output can be obtained, which is not of prime importance. The most important criterion is the suitability of the HPPs to the application under consideration. Human-powered products employ use of human work for energy generation to power an electronic device. Products that uses human Power, such as upper body motion, motion of lower limbs etc. to produce electricity are called Human Powered Products (HPP). Interactive human-powered products (HPPs) such as hand crank radios compare favorably in energy generation terms to solar and natural energy generators due to factors such as cost, manufacturing methods, materials, complexity, and limited interactivity.

Using human kinetic energy and human-powered product design development can raise the awareness of energy use in everyday life. The other benefit of the human-powered products is the interactivity in use. It is a way of communicating to user for an environmental benefit of using your own energy as alternative power source which is a clean energy. The interactivity of power generation in HPPs is interpreted as educational intervention, communicating with people to appreciate what our body can do. It is also important to make people conscious about the energy generation during use phase otherwise they will lose the purpose of its influential learning process.

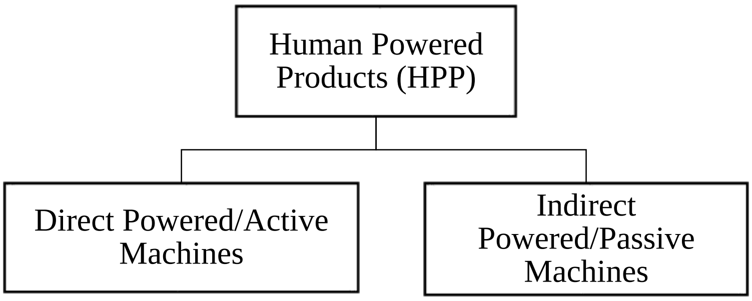


Fig. 2.5: Classification of HPPs

This shows the opportunity for designers to facilitate the learning process through (re)design of products and through designing its interactivity in use. Human Powered Products are of two types as shown in the Fig. 2.5. In the literature, HPPs are defined as active human powered and passive human-powered. Products are said to be actively-powered, when the sole intention of the person is to generate the electricity, for example hand cranking [33, 34, 35], pedaling [36] etc. Whereas, in case of passively-powered products, electric energy output is obtained as a by-product, when the person is executing some daily activity like, walking [37, 38], rocking on a chair [39].

2.5.1 Working Principle

Most of the HPPs are based on three major principles, which are discussed below:

a) **Electrostatic**: In electrostatic generators, the relative movement between electrically-isolated, charged capacitor plates is utilized to generate electric energy. The energy can be harvested by doing some work against the electrostatic forces between the plates. The variation in plate distance limits the voltage produced by these sources [40] in certain range. A lot of work has been done to optimize the power output from electrostatic sources. Roundy [41] proposed two optimized models for electrostatic generators— in-plane gap closing and out-of-plane gap closing for maximum power output. Another concept proposed by Sterken [42, 24], is based on three conditions, namely: (a) maximizing the change in capacitance, (b) changing damping ratio, (c) maximization of polarizing voltage, for maximum power output. The only problem with electrostatic generators is the initial charging of the capacitor. Moreover the power output is low.

b) **Electromagnetic**: These types of generators uses the concept of electromagnetic induction, arising due to relative motion of a conductor in changing magnetic flux. Most of the high power output alternators are based on electromagnetic source of powering. These generators are of two types— axial flux flow type and radial flux flow type. Axial flux permanent magnetic machines (AFPM) have higher power density as compared to the radial flux permanent magnetic machines [43, 44]. A number of hand-crank generators are reported in the literature having power range of *50-70 W*.

c) **Piezoelectric**: These generators are based on piezoelectric effect, means generation of electric current by mechanically stressing the active materials. In [45, 46, 47], Snyder used this concept in a car wheel to power a tire pressure sensor. In his work, wheel vibrations while driving are used to power the generator and abnormal tire pressure is sensed using a suitable pressure sensor. A detailed mathematical model of piezoelectric generator is presented by Roundy and Wright in their work [48], they have derived a relationship between input acceleration and the tip displacement of the cantilever beam. Further, the stress has been calculated, that generates the electric field in layers of a piezoelectric material. As the torque requirements at hip and knee joints of lower-limb exoskeletons are significant, and torque is directly proportional to power, high-powered motors are required. Out of the above discussed three methods, this paper is focused on electromagnetism only the other two methods results in low electric power (in *microwatts*) [49, 50, 51]. HPPs are based on electromagnetic source and are able to generate sufficient power required for lower-limb exoskeletons.

2.5.2 Commercially Available HPPs

Use of Human Powered devices in not a new topic. There has already been many researches in this field. Different methods have been used for electric power generation using Human power. Out of the above three methods, electromagnetism is the methods that can be employed in HPP for energy harvesting. Because the other two methods that is i.e. electrostatic and piezoelectric are used for production of microwatts. Since in our case that is in case of Exoskeletons the torque requirements at hip and knee joints are very high, so a high torque motor is needed at the joints. As we know, torque is directly proportional to power therefore a more power is required for motors. Hence literature is mostly related to using Electromagnetism. Most of the Exoskeletons these days uses external power sources to charge the battery. That puts certain constraints on the application and design of exoskeletons. Various Human Powered devices are reviewed in the literature. Some of which are given below:

Project X^2

Research Department at Nottingham Trent University in *2008* presented two human powered devices to produce electricity named ‘+’ and ‘X^2’. The project ‘+’, meaning that it requires direct human kinetic energy interaction, suggested a lighting system with human-powered generator embedded. From the data given it is concluded that design performs to light *5* super bright LEDs for *5* minutes from *3* pulls of cord connected to the generator. Second project named ‘X^2’ as shown in Fig. 2.6, expresses the meaning of one energy effecting into two functions. It is a design solution that manipulates indirect human kinetic energy into functional power, suggesting concept product that utilizes the human walking energy into chargeable electricity for mobile electronics. Both projects have emphasized the need of further research towards the field of interaction design in relation with free energy generation.

Fig. 2.6: Project X^2 [52]

Sony ODO

There has also been research carried out in the field between interactivity and human-powered product conducted by global company such as Sony. They have been continuously investing the concept design practices for sustainability. It has been the biggest challenge to persuade users to apply certain kinetic energy when interacting with human-powered products. Sony is seeking ways to generate energy as user play with the devices, adding aspects of fun, playfulness, motivation from curiosity, ambiguity and unusual practices in use. They believe that by using such devices, they will enhance the life value more by having a sense of social consciousness and ecological values. One of Sony's products include the Spin N' Snap, as shown in Fig. 2.7, digital camera that is charged up by placing two fingers in two separate holes and spinning it around a few times to allow a charge.

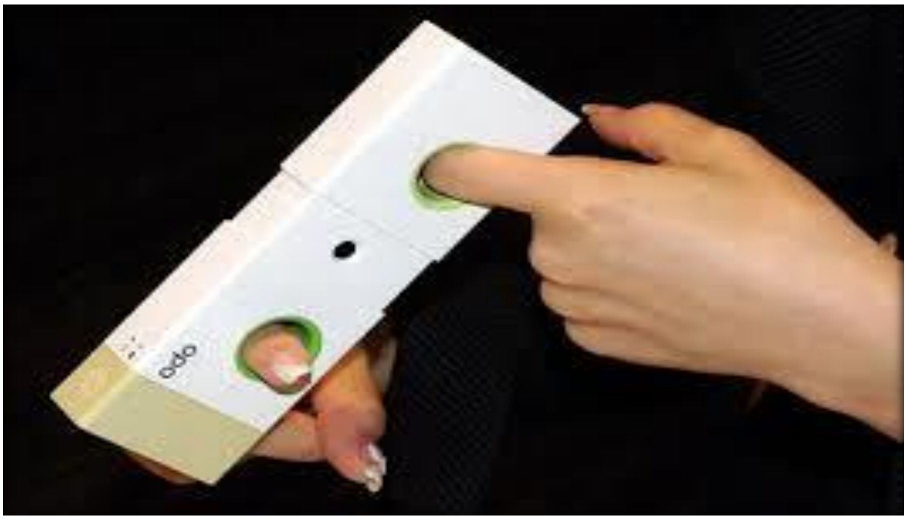


Fig. 2.7: Sony Spin N' Snap [53]

Energy Generating Floors

Vibration-based devices compare well to other potential energy-scavenging sources, including batteries, fuel cells, and solar, temperature, and pressure devices. Energy generating floors was the concept first time implemented at high level by East Japan Railway Company, when they proposed to generate the electric energy using human power. Electro-active polymers based in β-PVDF have been used in order to fabricate an energy harvesting system fully integrated into the sole of a shoe [54]. They made the floors from some kind of piezoelectric material as shown in Fig. 2.8.

Fig. 2.8: Energy-generating floors [55]

When the crowd moves over these kind of floors electricity produces due to the strain in piezoelectric materials. This produced electric energy has been used for gate actuators and to run the computers at ticket counters.

PlayPump

The one challenge for interactive human-powered products will be how to reduce the power generating labor avoiding it from being fatigue. PlayPump, Fig. 2.9, is an interesting design example, although this design is not powered by electricity, consisting two functionalities from one physical kinetic energy. The purpose of this design is to give clean drinking water facility for those who didn’t have the access. When children have fun spinning on the PlayPump merry-go-round, clean water is being pumped from underground into a *2,500-liter* tank, standing seven meters above the ground. The ‘fun’ feature is encouraging user to create the kinetic energy from its physical interaction. The labor of energy generation in this device is compensated by an increase in other forms of quality.

Radio Specks

For several years research groups at Cornell University and the University of Wisconsin–Madison have been working on a way around this power-source roadblock: harvesting the incredible amount of energy released naturally by tiny bits of radioactive material.

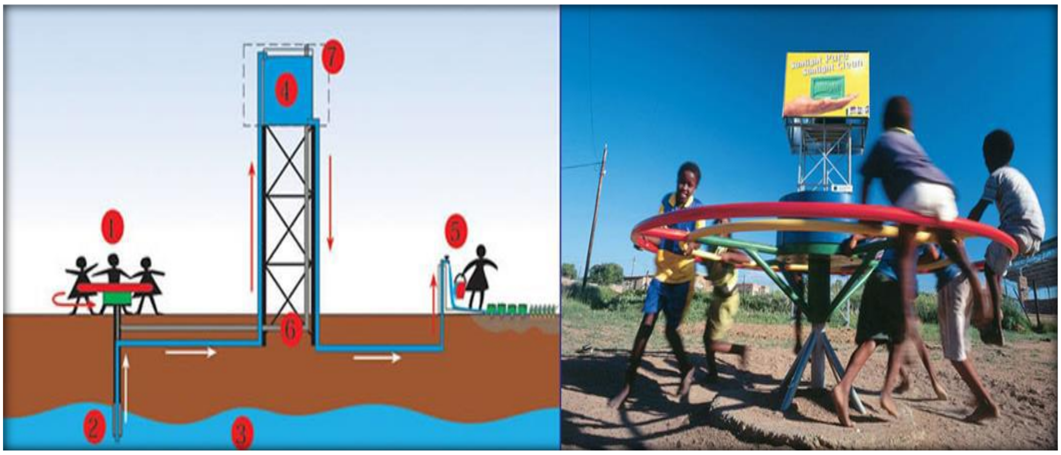
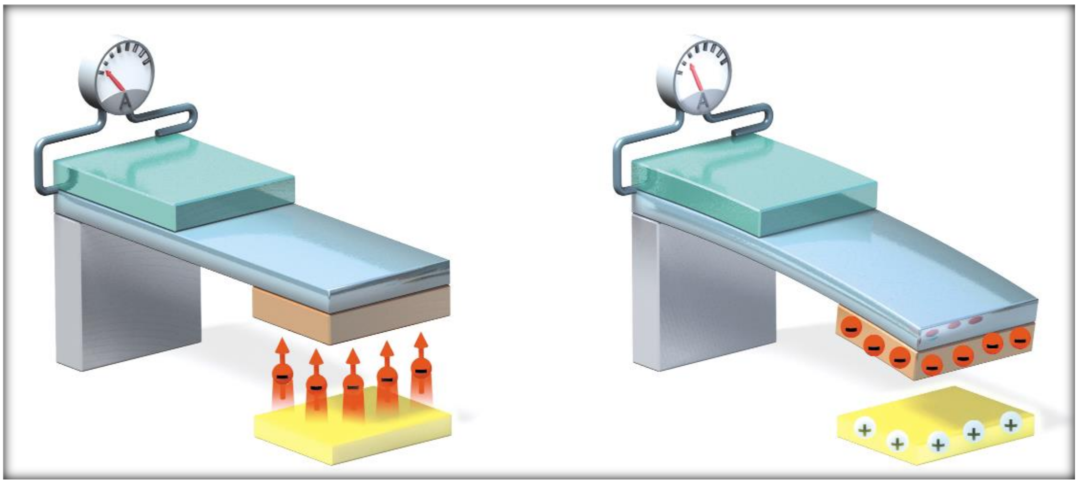


Fig. 2.9: PlayPump [56]

The micro-scale generators they are developing are not nuclear reactors in miniature, and they don’t involve fission or fusion reactions [57] as shown in Fig. 2.10. All energy comes from high-energy particles spontaneously emitted by radioactive elements. These devices, which they call nuclear micro-batteries, use thin radioactive films that pack in energy at densities thousands of times greater than those of lithium-ion batteries. They are using nickel-63 or tritium, as they are less dangerous to human life. They penetrate no more than *25 micrometers* in most solids or liquids, so in a battery they could safely be contained by a simple plastic package. Nuclear batteries can pack in energy at densities thousands of times greater than those of lithium-ion batteries.



(a) (b)

Fig. 2.10: Nuclear Batteries (a) Electron motion from Beta particle to cantilever; (b) Electrostatic attraction [57]

2.5.3 Classification of HPPs Based on Requirement

From all the data collected it has been observed that the average exoskeletons' battery requirement is around *35-60 W*. Moreover, the portability is the main concern. Therefore an effort has been made to classify the HCGs with power output range of the order of *35-60 W* and even more watts. Human powered products are classified into three categories on the basis of requirements—*pedal-powered generators*, *hand-crank generators* and *merry-go-round generators* as shown in Fig. 2.15. Details of these generators is given below:

a) **Pedal-Powered Generators**: The idea behind these generators is to use the pedal work for production of electric energy using appropriate alternator. With the help of pedaling, the mechanical energy is converted to rotational energy and stored in a flywheel. Further this flywheel is connected to the alternator shaft, with belts, gears or chains to produce electricity. Pedal-powered generators are further classified into cycling, foot-powered and feet-powered generators. The average power output from these kinds of generators is approximately *120 W*. A commercial available indoor bike, developed by NEERG trading limited as shown in Fig. 2.11, gives output in the range of *150-200 W*, *14.5 V* DC. This output energy is stored in a *12 V/26 Ah* battery placed in a portable power box provided with the generator.

Fig. 2.11: NEERG Indoor bike [viii]

The weight of the whole unit is around *40 kg*. Tiwari et al. [58]demonstrated in their work, while using a bicycle ergometer as shown in Fig. 2.13, which with optimum pedaling rate of *50 rpm*, *60 W* of power output can be generated. Another human powered bicycle concept, for powering appliances at a fitness club, is proposed by Strzelecki et al. [59]. The output power from this generator is capable of powering various appliances like lighting system, T.V., radio etc. Therefore the wasted human power in any gym can be utilized in a constructive way.

b) **Hand-Crank Generators:** Working principle of hand-crank generators is same as that of pedal-powered generators i.e. to convert the mechanical energy into electrical energy. The only difference is in mechanical energy input method. In case of pedal-powered generators, input method is pedaling whereas in case of hand-crank generators it is hand-cranking as shown in Fig. 2.12.

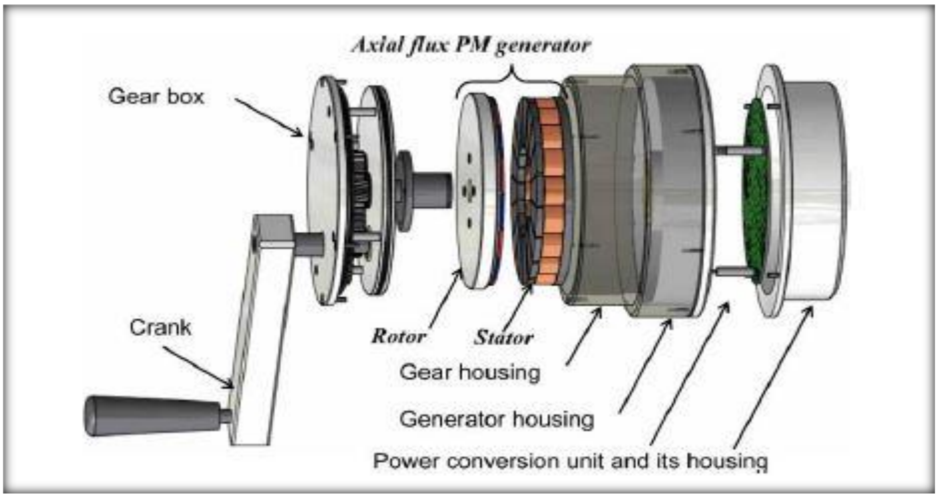


Fig. 2.12: Exploded view of hand-crank generators [34]

Depending on the usage of single or both hands, hand-crank generators are classified into two categories namely―one hand-crank and two hand-crank. A lot of concepts about hand-crank generators using shaking [60], gearless system using pulling [61, 62], and some other methods [63, 64, 65, 66] are developed. Use of portable charkha [67] is one of the examples of hand-crank generators, which can be used in the rural areas as an alternate energy option.

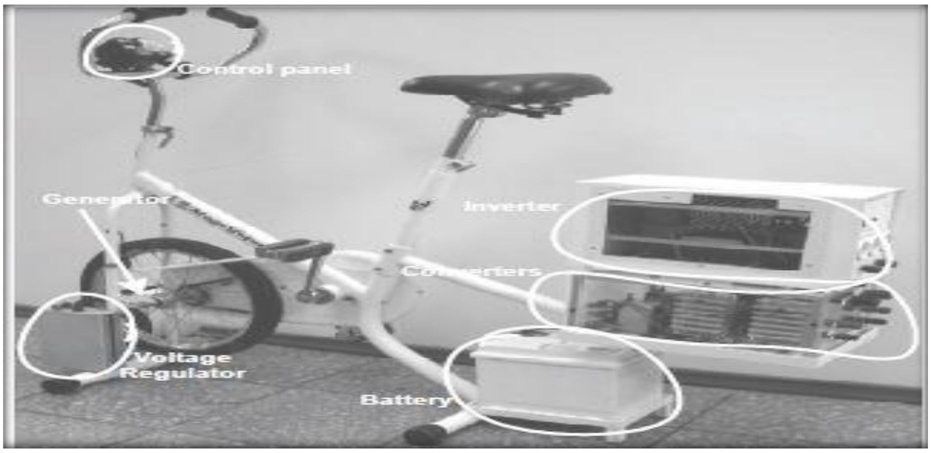


Fig. 2.13: Cycling generator [58]

This spinning wheel like generator can produce voltage in the range *5-9 V* depending upon the input rpm. Hand-crank generators can be used as mobile phone chargers. There are some manual mobile phone chargers [68], which are used to charge phone while travelling and when there is power outage. Using a voltage regulator and microcontroller desired output can be obtained. According to a claim by Windstream Power [69], their commercially available hand-crank generator produces an average continuous power of *50 W*. Comfortable hand cranking speed [70] is around *50-60 rpm*, therefore belts/gears can be used to step-up input rpm [35]. Most of the HCGs use AFPM machines [71, 34, 23], based on electromagnetic source, to convert input cranking to electrical energy. HCGs plays an important role to provide electric power for military operations in remote areas [72]. One such model, named as G-67B/B, is an example of military hand crank generator.

c) **Merry-Go-Round (MGRs) Generators:** As described in Table 2.4, MGRs can produce power in the range of *100-600 W* depending upon the size of alternator and generator unit. The principle behind MGRs consists of harnessing the human power of children playing on merry-go-rounds in school or playground as shown in Fig. 2.14. Therefore, energy conversion process is very much playful. With the help of cylinder containing compressed air, significant power output can be obtained using MGRs and see-saw [73]. In these types of generators, the power is developed by doing some work against the compressed air. The only limitation of compressed air powered generators is their low efficiency. MGRs can also be used for pumping water from the surface of ground [74].

Fig. 2.14: Children playing on merry-go-round [75]

However, the overall system is bulky as compared to pedal-powered and hand-crank generators. Comparison of these human powered generators is discussed in Table 2.4, where power output range and unitary capital cost is provided for each of the three cases discussed above.

Table 2.4: Comparison of different human powered generators [76]

Device	**Power range (*W*)**	**Total capital cost (*US $*)**	**Unitary capital cost (*$/W*)**
Bicycle	100–150	75–500	0.25–2.00
Hand-crank	50–100	50–500	1.00–3.00
MGRs	100–600	500–2400	2.00–4.00

As the scope of this thesis is limited to lower-limb exoskeletons, therefore, from the above discussion on all three classifications of human powered products, it has been observed that hand crank generators are suitable as a portable energy source option.

Pedaling involves rotation of the crank using feet or legs motion, which is not possible in case of lower body immobility or partial mobility.

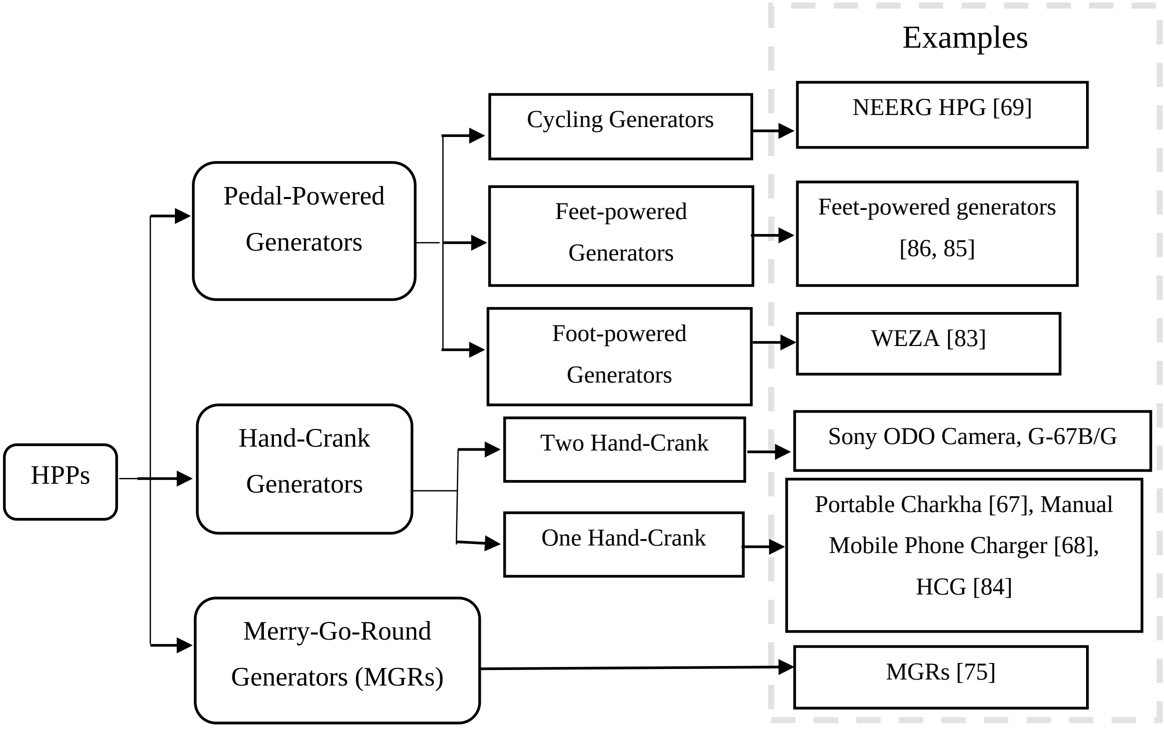


Fig. 2.15: Classification of HPPs based on requirement

Therefore, despite having greater power output than hand-crank generators, pedal powered generators cannot be a candidate for an alternate source of charging an exoskeleton’s battery. Similarly the third case, that is merry-go-round generators, is also out of the scope of this paper. Merry-Go-Round generators can easily produce *100-300 W* power, but these units are bulky and are not portable. Therefore these generators cannot be used for mobile applications of exoskeletons.

A similar work [67], as shown in Fig. 2.16, has been done before using hand cranking for power generation purpose. In this work, the use of manual charkha (a hand-cranked wheel) is proposed as an emergency portable device to power villages. This system is specifically designed for some critical areas in India, where there is no access to electricity. This apparatus works as a simple charkha (spinning wheel) do. A detailed geometry of the proposed equipment is also presented in this research work.

Calculations have been performed to have a rough estimations about the size of various parts (mostly wheels) of this portable generator.

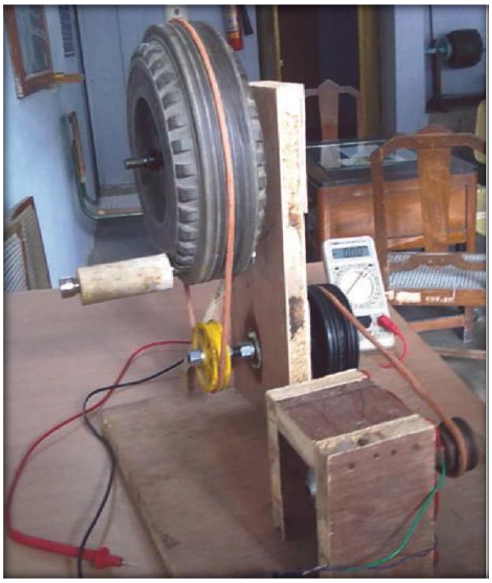


Fig. 2.16: Portable charkha for manual power generation [67]

2.6 Summary

In this chapter, literature review related to each aspect of the power generation and deployment process has been discussed. The literature review started with the exoskeletons and their types, and then followed by various storage mediums, alternate energy methods and in the end proposed method of powering. More emphasis is given on reviewing existing human-powered devices and various principles on which these devices work. In the end of this chapter, a conclusion has been drawn from the above discussion that the hand-crank generators suits the situation very well. Moreover their power output matches with the requirement of exoskeletons. An existing working model of a portable hand-crank charkha has also been presented in last few pages of this chapter. In next chapter, the proposed method i.e. hand-cranking to generate electricity, is discussed in detail. A mathematical model of power generation process is also presented with certain suitable assumptions.

Chapter 3

Mathematical Modeling of HCG

3.1 Introduction

From the discussion in the previous chapter, it is concluded that upper body motion can be used to charge lower-limb exoskeleton. For this purpose, usage of Hand-Crank Generators (HCG) is proposed, which can generate power with human cranking as the input. In this chapter, the every aspect related to HCG is discussed with reference to use it as a portable charger. An attempt to develop mathematical model for powering process is made later in this chapter. Along with this, the block diagram of the overall process is also presented.

An experiment, performed by Peter Slob et al [70], discusses the comfort of humans with the help of Critical Power (CP) Test. The CP-test has been used on cranking with three trained paraplegic subjects (mean ± SD = *36 ± 9 years*). In this test, the shoulder was in line with the axis of the ergometer and the wheelchair was placed so the subject's arm was fully extended when the crank handle was at its greatest distance. It looked like it was one-hand cranking, although this is not clear from the literature. The power outputs used were *25, 37.5* and *50 W*. The test ended immediately, when the subject was unable to maintain a cranking rate of *50 rpm*. Rest periods between each period of exercise continued until the heart rate returned to a range within *10 BPM* of the subject's resting heart rate. Each test was repeated three times in different sessions. Linear regression was expressed by the following equation;

$$W_{lim} = AWC + CP.t_{lim}$$

Symbol	Quantity	Unit
W_{lim}	Work value	*J*
AWC	Anaerobic work capacity	*J*
t_{lim}	Time to exhaustion	*Sec*
CP	Critical Power	*W*

Subject 1 has a Critical Power of *22 W*, subject 2 of *24 W* and subject 3 of *21 W* [70]. The setup used to get results is shown in the Fig. 3.1. The results of the study consists of P_{max}, P_{max} at re-test, W_{lim} and the comfort test. Many types of topologies of magnets have been developed for hand-crank generator. Among all these topologies, Axial Flux Permanent Magnet (AFPM) is widely used technique now a days. All these topologies are discussed below in details.

Fig. 3.1: Setup used to calculate comfort [70]

3.2 Working Principle of HCG

Axial Flux Permanent Magnet (AFPM) topology has distinct advantages of a large power density and compact construction over traditional radial-flux permanent magnet (RFPM) machines due to better flux utilization and improved cooling. Based on these, an attempt has been made to design a portable hand cranked generating system using AFPM generator with a suitable gear to give an output of *60 W* at *3000 rpm*.

AFPM is basically of following three types:

- Single-sided PM machine with distributed windings in slots,
- Single-sided PM machine with concentrated winding around the teeth (in slots),
- TORUS (double-sided) machine with air-gap winding without slots.

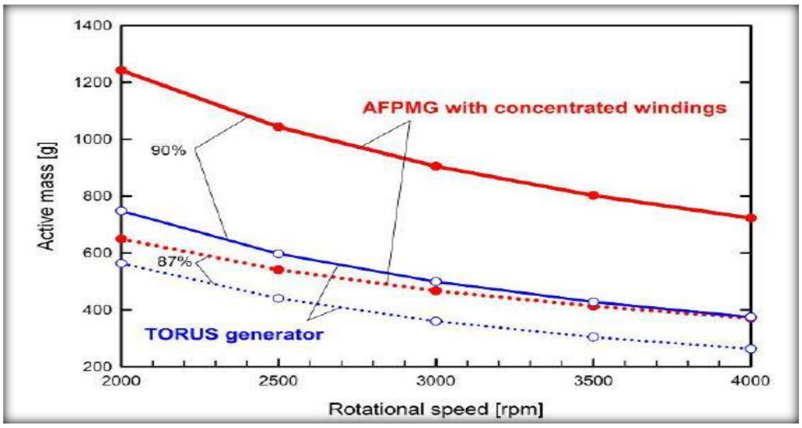
The machine with distributed windings has a major disadvantage of having relatively long end windings which leads to rather high copper losses. On the other hand, compared with a machine with distributed winding having one slot per pole per phase, the machine with concentrated winding has a low fundamental winding factor. They also generate both odd and even harmonics, and some, also produce subharmonics in the MMF which results in high eddy current losses in the rotor back iron and in the permanent magnets. The machine with concentrated winding has a relatively simple winding around teeth and shorter end windings, which results in a significant reduction of the copper losses. The strengths of the TORUS machine is that the stator iron can be eliminated which leads to low iron losses (high efficiency) and potentially low mass. However, winding this machine is probably not so easy because the windings have to be wound around the stator core.

Based on the result of the above research paper one of the research work as shown in [33] describes the possibility to charge a *50 Wh* battery within the speed boundary which is assumed in the design specifications. The weight of the fabricated generating system is *1.68 kg*, and the design object, below *3 kg*, is quite excessively achieved. The study in this thesis deals in design of an axial flux permanent magnet (AFPM) generator which is a key element of a compact size portable and manual generator system composed of a gear system, a generator, a rectifier, and a battery charger. The design objects of the AFPM generator are its compact size, light weight, and high efficiency, and the three design objects are the main criteria to select the value of design variables. A soft magnetic composite core is used instead of a silicon steel core in the AFPM generator to achieve a compact size. In this paper, the overall design process to meet the design goals and the design results are presented with experiment results.

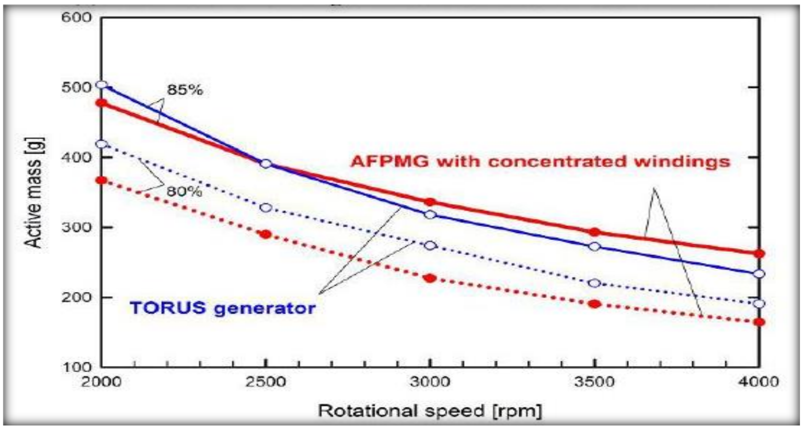
It is assumed that a typical male can comfortably generate over *100 W* using cranking motions with two feet. Using a portable and manual generator, human cranking motions are converted to three-phase ac electric power, and the electric power is efficiently harvested and stored in a battery pack using a battery charging circuit consists of a three-phase boost rectifier and buck converter. The boost rectifier utilizes a mechanical sensor-less method to estimate the generator’s rotor position to reduce size and increase reliability. The overall development processes that include topology selection, parameter selection criteria, battery charging strategy with controller gain values, and experimental results, are presented. The experimental results demonstrate the battery charging capability over *100 W* using a sensor-less algorithm.

There are a number of criteria that are used for design of electric machines some of which are based efficiency, force density, power/volume, torque/volume, power/mass, torque/mass, power/cost, torque/cost etc. Electric machines are generally designed to maximize the value of one or some of the criteria. A better choice for the machine design generally results from a compromise which increases a value of one parameter without penalizing the other ones. One of the results [71] demonstrates the optimum design in the focuses on minimizing the active mass of the Generators. The results from optimum design at *2000*, *3000*, *4000 rpm* at *80*, *85*, *87*, *90* % efficiencies are given. In the optimization process, the following dimensional parameters are modeled as a variable:

- Magnet length
- Outer radius of the stator iron and the magnets
- Slot height
- Stator yoke height
- Rotor yoke height



(a)



(b)

Fig. 3.2: HCG efficiency comparisons (a) *90* % and *87* % efficiencies; b) *85* % and *80* % efficiencies [71]

Fig. 3.2 depicts the design results of the two AFPM generators as a function of the speed and the efficiency. The results of the analytical design and optimization are summarized as follows:

- The AFPM generators with higher rated speeds are lighter than the generators with lower rated speeds.
- The AFPM generators with higher efficiencies are heavier than the generators with lower efficiencies.
- At *90* % and *87* % efficiencies, the AFPM generators with concentrated windings are heavier than the AFPM generators with air-gap windings (TORUS machine) in all ranges of the rotational speeds
- At *85* % efficiency, the AFPM generators with concentrated windings are heavier than the TORUS machines at the speeds between *2500 rpm* and *4000 rpm*, and are lighter than the TORUS machines at the speeds lower than *2500 rpm*.
- At *80* % efficiency, the AFPM generators with concentrated windings are lighter than the TORUS machines in all ranges of the rotational speeds.

3.3 Mathematical Modeling of HCG

In order to assess the potential of human powering methods for assistive exoskeletons it is important to assess the energy requirements and how suitable amounts of power can be generated. For this, a mathematical model of the cranking process is needed and such a model is developed here starting with the torque generated at the crank and the current output produced to charge a battery. Two different approaches have been discussed to derive the mathematical model of the cranking process. Since the user have to put his mechanical power to shaft of the rotor in the form of cranking, so first approach is based on the mechanical power transferred to the shaft of generator. This mechanical power transferred to shaft is compared with the input power, and hence a condition for maximum power transferred has also been discussed. In the second approach, the relation between torque exerted at crank and direct output in form of current has been discussed. Basic law of physics i.e. Newton’s second law is used to describe the relation.

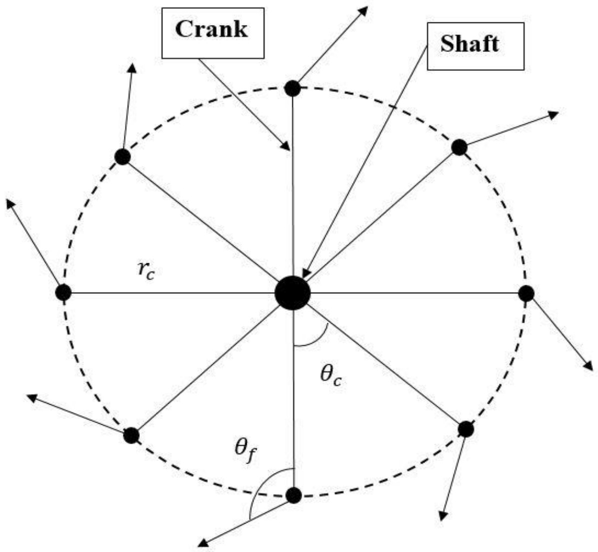


Fig. 3.3: Direction of applied force

3.3.1 Considering Mechanical Power Transfer

Consider F_t is force applied by hand, as shown in Fig. 3.3, at an angle θ_f with the crank. If radius of crank is r_c then the torque transmitted to the shaft of generator (τ_c) is given by:

$$\tau_c = r_c . F_t . \sin\theta_f , \tag{3.1}$$

Total work transferred to the generator shaft for '*N*' rotations of crank can be calculated by integrating τ_c over total angle turned θ. Where $\theta = 2N\pi$

$$W_t = \int_0^{\theta} \tau_c . d\theta_c = \int_0^{\theta} r_c . F_t . \sin\theta_f \, . d\theta_c , \tag{3.2}$$

Now, the total work transferred by the human limbs (W_{t_Human}) in rotating the crank, needs to be calculated. Let dS_c is the small displacement obtained by applying the force F_t and by moving the angle $d\theta_c$ along circumference. For this:

$$W_{t\_Human} = \int_0^{S} F_t . dS_c = \int_0^{S} r_c . F_t \, . d\theta_c , \tag{3.3}$$

Since $0 \leq \sin\theta \leq 1$, closely inspecting the (3.2) and (3.3), following conclusion can be obtained [77]:

$$W_t \leq W_{t\_Human}. \tag{3.4}$$

It is clear that total work done by human limbs can't be fully transferred to the generator/alternator shaft. For maximum efficiency θ_f should be nearly equal or very close to one. Which practically is not possible. Therefore to make θ_f close to one, length of arm should be as large as possible. Far the person from the cranking wheel, more the angle θ_f will be closer to *90°*. So for better utilization of input power into work transfer to shaft, user must crank from as far as possible. This can be achieved by using links.

3.3.2 Considering Torque Exerted

In the second approach the torque (*T*) exerted is considered which is directly related to current (i_q) output as described in (3.5).

$$T = K_T . i_q, \tag{3.5}$$

Here, K_T is generator/alternator coefficient, which depends on:

- Number of stator coils
- Number of magnetic pole pairs at rotor
- Air-gap between stator and rotor
- Type of the core material
- Internal and outer radius of rotor and other generator parameters [78]

According to Newton's second law,

$$J . \ddot{\theta} = \sum T, \tag{3.6}$$

where, J = Polar moment of inertia, $\ddot{\theta}$ = angular acceleration and $\sum T$ = net torque acting on the system. Above equation can be written in the form:

$$J.\frac{d\omega}{dt} = T = K_T.i_{q,} \tag{3.7}$$

Taking Laplace on both sides:

$$s\varpi(s) = \frac{K_T}{J}I_q(s), \tag{3.8}$$

$$\Rightarrow \qquad \varpi(s) = \frac{K_T}{Js}I_q(s), \tag{3.9}$$

The equation (3.9) gives direct relation between input speed of cranking and the corresponding current output, which is known as the transfer function of generator/alternator.

Similarly, the relation between the voltage generated (V_g) and input cranking speed is given by the following relation:

$$V_g = \frac{(P\emptyset NZ)}{60A}. \tag{3.10}$$

where,

P = number of field poles
$\emptyset$ = flux produced per pole in Wb
N = rotational speed of armature (rpm)
Z = total no. of armature conductors
A = Number of parallel paths in armature

It is clear from (3.10) that the output voltage produced is directly proportional to the input cranking speed. More the speed of cranking, more will be the output voltage. All other factors are called generator constants i.e. for a given generator, these parameters have constant values and the working of the generator does not affect their values up to a certain extent.

3.4 Block Diagram of Overall Process

A block diagram representation of the energy generation process is shown in Fig. 3.4. The aim is to charge the battery with an input human effort. The charged battery is then used to supply power to drive the actuator of an assistive exoskeleton. The human effort applied via a hand cranking device so that it feeds the generator (normally an AFPM generator) to provide electrical power as output. In most of the cases, the output from the generator is around *24 V* DC, which can be modified according to the charging requirement of the battery by using a suitable DC-DC step down converter. Finally, the charged battery can be used to power the electrical motors to move the exoskeleton joints. Human power input is given as**:**

$$P_{human} = \tau.\omega = \tau.\frac{2\pi N}{60}, \tag{3.11}$$

Electrical power output from the AFPM generator is calculated as:

$$P_{elec} = V \times I. \tag{3.12}$$

Where,

τ = Input torque
V = Output voltage from generator
I = Output current from generator

Fig. 3.4: Open-loop block diagram of energy generation/supply process

Clearly for a given hand crank generator with efficiency η,

$$P_{elec} = \eta \times P_{human.} \tag{3.13}$$

The number of actuators in exoskeletons depends upon the degrees of freedom of that exoskeletons. Sometimes various mechanisms, e.g. gear-train, belts and ropes, are used to actuate two or more joints using a single actuator. Fig. 3.5(a) shows the Exo-Leg used to help partial disabled person in walking, climbing/descending stairs etc. A commercially available hand-crank generator is shown in Fig. 3.5(b), which can be used to charge a battery of Exo-Leg. The output of these of generators falls in the range of *24-33 V* DC. A constant *12/24 V* DC is required to charge the battery, which can be achieved by using a DC-DC step-down converter, as shown in Fig. 3.5(c).

(a) (b) (c)

Fig. 3.5: (a) Exo-Leg and actuator position [79], (b) HCG [80], (c) DC-DC converter [81]

The human-power input in the form of a mechanical work is defined as the product of torque and angular displacement, and is written as:

$$W = \int_0^{\theta} \tau d\theta = \int_0^{t} \tau \omega dt. \tag{3.14}$$

The above equation states that the work done by human-limbs (arm in this case) to crank the generator for a specified time 't' can be calculated using torque and angular velocity.

3.5 Battery Charging Time Estimation

The torque requirement varies for different joints in lower body to perform one sit-to-stand (STS) posture. These torque requirements are inversely proportional to the STS time. To perform a STS posture with a jerk, high amount of torque is produced at various joints. For different STS times the maximum torque required at the hip, knee and ankle joints are calculated and listed in Table 3.2. Assuming the lower body of person is fully disabled, for a *90 kg* person performing one STS posture in *4 seconds*, *86.4 J* of energy is required for actuation at each joint, as reported in Table 3.1.

For *20* such STS postures the amount of energy required is *1728 J* and the power requirement is around *432 W*. Total power required (assuming losses 100 %) will be double than the actual value i.e. *864 W*. Hence, the amount of power required to perform one STS posture comes out to be around *20 W*. It is clear that the requirement of power to actuate one joint of exoskeletons can be satisfied using HCG having output more than *20 W*. The output voltage of the HCG can be increased or decreased depending upon the voltage rating of the exoskeleton battery using boost or buck converter respectively. Summary of various assumptions and corresponding calculations are as follow:

Table 3.1: Various assumptions and calculations

Parameter	**Units**	**Value**
Weight of the person (Considered)	*Kg*	90
Energy required per STS posture	*J*	86.4
Energy required for 20 STS postures	*J*	86.4×20= 1728
Power required for 20 STS postures (Assume it takes 4 seconds to complete 1 STS)	*W*	432
Total Power Required (Assuming Losses 100 %)	*W*	864
Power required for 1 STS postures	*W*	20 (Approx.)

Table 3.2: Maximum Torque requirements for sit-to-stand (*Nm*)

STS Time (*Sec*)	**Hip**			**Knee**			**Ankle**		
	70 *kg*	80 *kg*	90 *kg*	70 *kg*	80 *kg*	90 *kg*	70 *kg*	80 *kg*	90 *kg*
1	91	104	117	80.3	92	103	56	65.3	72
2	57.3	65.3	73.7	70	80	90	33.3	38.3	43
4	49.7	56.8	63.9	67.2	76.8	86.4	28.7	32.8	36.9
7	45.3	52	58	66.3	76	85	25.6	29.3	33

For estimating the charging time, some rough calculations are done using a *3.7 V 2000 mAH* rechargeable Lithium-ion mobile battery. The maximum amount of energy that can be stored in this battery is *7.4 Wh*.

Assume that this battery is being charged using a *30 W* hand-crank generator. In most of the field tests, the loss factor for hand-crank generators is assumed to be *2.5*.

Therefore, time required to fully charge this battery = $\left(\frac{7.4}{30}\right) \times 2.5$

= *0.6166 hours* or *37 minutes*

This is just a rough estimate of charging time when the battery is charged using the HCG directly. Sometimes the output of HCG does not match with voltage requirement of the battery. To tackle this problem, a DC-DC step-up or step-down converter is used to achieve required charging. In actual practice, some losses are always associated with this converter, which means that the actual charging time will be more than the calculated charging time.

3.6 Summary

Starting with the basics of proposed method of using human power to charge exoskeletons, various types of hand-crank generators has been discussed in this chapter.

An attempt to develop a mathematical model based on two different approaches has also been discussed. In the end of the chapter, a rough estimate of the battery charging time has been calculated. These calculations gives an idea about the charging time using a hand-crank generator. To validate these calculations, an experimental setup is developed, output from which is discussed in next chapter in detail. Various relations obtained in this chapter are used to validate the experimentation results using hand-crank generator set-up in next chapter.

Chapter 4

Development of HCG Test-Rig

4.1 Introduction

In the previous chapter, mathematical modeling part is covered, which is totally theoretical and an approximate value of power requirement to perform one STS is calculated on the basis of torque requirement at one joint (knee) only. In order to check the feasibility of Hand-Crank Generators (HCG) to use as an emergency portable charger, it is mandatory to analyze its output first. For this purpose, series of experiments are performed using hand-crank generator test-rig. This chapter is divided into six main sections including introduction part. In second section, detail of test-rig is given along with its technical specifications. Next, the input torque and power are measured with the help of prepared test rig. Further, the output of the generator is captured by measuring the voltage and current both on-load and off-load. In this way, the efficiency of the generator and various losses involved in conversion from mechanical input to electrical output is calculated. Based on above conclusions, a comment on using human power to charge exoskeletons is given in the end of this chapter.

4.2 Details of HCG Test Rig

As the scope of the thesis is rehabilitation for elderly people, it is not possible to do the experiments iteratively in the realistic scenario, where the human being is supposed to crank, as and when the need arises. A HCG test-rig is built to do experimentations for feasibility investigation of human-powered exoskeletons. In this test-rig various components are used to get required output and some automatic option to crank the generator for the testing phase are given, details of which are given below:

4.2.1 Hand-Crank Generator

Based on application, different types of HCG are available in the market. After exploring several options, two appropriate HCGs were bought by the Swedish group in

University of Gavle, Sweden and sent to Thapar University for further experimentation. First HCG is a military hand-crank generator, as shown in Fig. 4.1 (a), which is an emergency powering device used by military personnel. Head size of the this HCG (with handle) is *205 mm × 180 mm × 120 mm*, with a weight of *6.7 kg*, which creates problem with its portability. Rated output of this HCG is *65 W* with *24 V* output and *1-2.5 A* current range. Torque requirement to crank this generator is high as compared to other HCG with almost similar output characteristics. Second HCG, as shown in Fig. 4.1 (b), is a light weight, easily portable device and smaller in size, which can used in any condition. Dimensions of this HCG are *106 mm × 64 mm × 39 mm*, excluding the handle and it weighs around *480 g*. As far as the output of this HCG is concerned, rated power output of this generator is *30 W* with *1.5-2 A* of rated current at *0-28 V*. Since the output power range of this generator matches with the requirement of exoskeleton, therefore the *30 W* HCG is used for experimentation in this thesis.

(a) (b)

Fig. 4.1: (a) Military two-hand operated HCG; (b) Single-hand operated

A commercially available HCG, as shown in Fig. 4.1 (b), is used for converting human effort into electric power. Specifications of this HCG are described in **Annexure A1**. From the Technical characteristics of the HCG, as given in Table 4.1, it is clear that HCG can generate a power up to *30 W* when cranked at different speeds with rated torque. The generator discussed above is light in weight and easy to operate. There are two wires (Red (+) terminal and Black (-) terminal) coming out of the generator that gives output. There is one strip at the back of the generator, which helps in easy handling.

A crank/handle with adjustable crank length is provided to crank the generator. The length of the handle can be increased or decreased depending upon the torque requirement. The cranking speed of the handle can be as high as *150 rpm* and as low as *10 rpm* depending on whether the generator is on-load or off-load. Cranking speed also varies from person to person, for example, a young man can crank up to *150 rpm*, whereas an old person will be able to crank maximum up to *80 rpm*.

Table 4.1: Technical characteristics of HCG [80]

Parameter	**Units**	**Rating**
Rated power	*W*	0-30
Output voltage	*V*	0-30
Rated current	*A*	1-1.5
Max. current	*A*	0-3
Net weight	*G*	650
Dimensions	*mm* × *mm* × *mm*	106 × 64 × 39

4.2.2 Drilling Machine

Direct calculations of the torque can be done using a digital torque meter, which is costly and not available in the institute for torque measurement. The idea of using a torque meter seems valid when we need to calculate the exact amount of torque applied. In this thesis, the scope is limited to torque estimation only, which is necessary to have some output from the generator. Automatic cranking for torque estimation is achieved by exploring the following options:

a. Manual Cranking

One option for cranking HCG to do experimentation is manual cranking. Manual cranking involves use of human hand/arm motion to crank the generator shaft, as shown in Fig. 4.2. Manual cranking gives best results when HCG is used in actual practice. In case of experimentation, manual cranking produces sub-standard results as compared to other automatic options of cranking. Inability to capture the human effort and torque applied during manual cranking is the main reason behind sub-standard results of manual cranking.

Fig. 4.2: Manual cranking of HCG

Other drawbacks associated with this involve inability of a person to crank continuously and iteratively for a longer period of time. Apart from this, a lot of jerks are associated with manual cranking, which results in output fluctuations. For this purpose, the concept of automatic cranking is preferred.

b. Cranking using Motor-Generator Setup

One option to automate the cranking process is to use motor-generator setup, as shown in Fig. 4.3. A coupling is used to connect the generator shaft to motor shaft. Different rating motors are available for providing sufficient torque to crank the generator. Benefits of using motor-generator setup includes the ease with which cranking speed can be changed. Cranking speed of motor can be changed by changing the value of resistant connected to it. However, many drawbacks are associated with the motor-generator setup like overheating of motor at high loads and improper clamping of motor to the base platform, on which it is mounted.

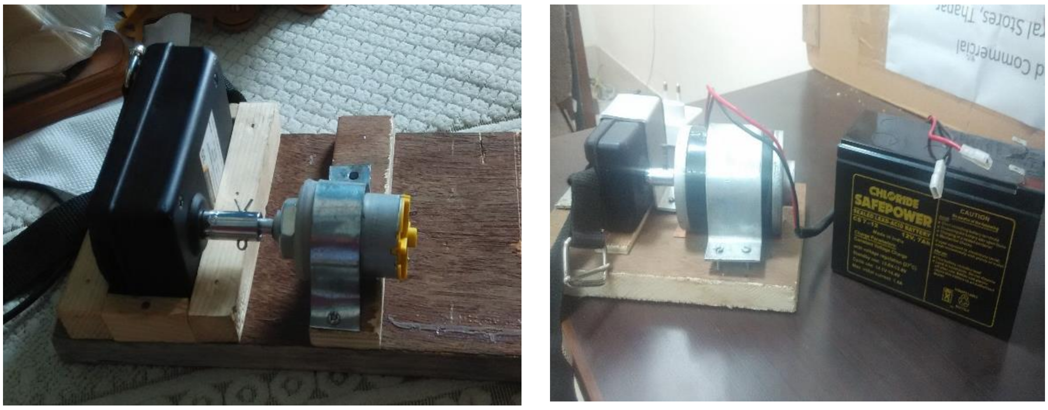


Fig. 4.3: Motor-generator cranking setup

c. Cranking with a Drill Machine

Alternatively cranking can be automated by using a drill machine also. Mechanism using drill machine is somehow similar to the one using motor. Overheating is not a problem in case of drilling machines as these machines are made to work in tough environment. Handling of the drill machine is also easier than clamping of motor. One added advantage of using drill machine is that these machines are very efficient in working, i.e. losses associated with drill machine are less compared to the motors.

From this discussion, it is clear that the use of drilling machine to crank the generator serves multi-fold purposes like:

- Automating the cranking process.
- Estimation of human effort required to crank the generator, which is difficult to calculate otherwise.
- Higher efficiency of the drilling machines (as compared to motors) makes them better candidate to be used in this experiment

Several drill machines are investigated in order to select the right model, which can provide adequate torque for cranking. Finally an appropriate drill machine (**Bosch GSB 501**) is selected to crank the generator, as shown in Fig. 4.4. Technical details of the drill machine are given in **Annexure A2**.

Fig. 4.4: Setup using drill machine for cranking

4.2.3 Battery

A mobile battery, as shown in Fig. 4.5, is used to calculate the effective charging time. Charging capacity of this battery is *2000 mAh* at *3.8V*. Validation of analytical charging time estimation can be done by charging this mobile battery. Charging a mobile battery is preferred over ordinary batteries as simultaneous percentage display on mobile gives the rough idea about the amount of charging time.

Fig. 4.5: Mobile battery used in experimentation

4.3 Calculation of Input Torque and Power

Since the torque provided by the user to crank of HCG is used to generate electric current, it is necessary to calculate the amount of torque required to cause rotation of the crank. Moreover, estimation of the torque input can give power input by human arm on the crank of HCG as these terms are related as:

Power input; $$P_{in} = T \times \omega, \tag{4.1}$$

where,

T = Torque input by human;

ω = angular cranking speed (rad/sec)

Calculation of the term ω is simple, as it can be estimated precisely from the cranking speed (rpm). Whereas the other term T i.e. torque calculation is quite cumbersome. Direct calculations of the torque can be done using a digital torque meter, which is very costly. The idea of using a torque meter seems valid when we need to calculate the exact amount of torque applied. In this thesis, the scope is limited to torque estimation only, which is necessary to have some output from the generator.

To calculate torque, a drilling machine is used to crank the generator, details of which are given in **Annexure A2**. The power output at the jaws of the drilling machine is known priory from the datasheet provided by the manufacturer. By rotating the shaft of the generator with the help of drilling machine, at rpm gives required value of torque. Rewriting (4.1) to get relation for torque:

Torque $$T = \frac{60P_{in}}{2\pi N}, \tag{4.2}$$

where, 'N' is the cranking speed (rpm).

The results from the above explained experimental test-rig are explained below:

Generator output:

Voltage output at *12 Ω* resistant = *11.45 V*

Current output at *12 Ω* resistant = *2.1 A*

Total power output from the generator = ***24.045*** *W*

Input to generator:

Rotating speed of the generator shaft = *180 rpm*

= *18.85 rad/sec*

Power consumed by drill machine = *500 W*

Power available at the jaws (P_{in}) = *250 W*

The torque input to the generator is calculated as:

$$T = \frac{250}{18.85} = 13.26\ Nm$$

Thus the torque required at the generator shaft is approximated from all the calculations listed above. However, this much amount of torque seems large if a human has to apply it with hand. Since this is the rotary torque requirement at the generator shaft, applied force can be minimized by using longer crank lengths. The various combinations of crank lengths and corresponding applied force values are reported in Table 4.2.

Diameter of the shaft = *8 mm*

Effective crank length = $\frac{8}{2} = 4\ mm$

Applied force to achieve = $\frac{13.26}{0.004}$

= *3315 N*

Applying this much force can easily exhaust a person in one or two minutes. In order to reduce input applied force, the length of crank can be increased by keeping the value of torque same. The value of applied force corresponding to crank length is listed in the Table 4.2 and the trend of the line is shown in Fig. 4.7.

Table 4.2: Crank length and applied force combinations for same torque

Crank length (*mm*)	**Applied force (*N*)**
50	265.2
100	132.6
150	88.4
200	66.3
250	55.04

4.4 Measurement of Generator Output

In order to check its performance, the generator is cranked at both on-load and off-load condition. Here off-load means open circuit i.e. generator is not connected to any resistance and on-load means closed circuit i.e. generator is connected to a resistant of pre-known value. Table 4.3 gives the output results of the voltages, current and power in both the cases i.e. off-load and on-load. To provide a pre known value of input rpm to the shaft of the generator, it is connected with a Lathe machine, as shown in Fig. 4.6, which has rated values of rpm.

Fig. 4.6: HCG connected to Lathe machine to measure generator output

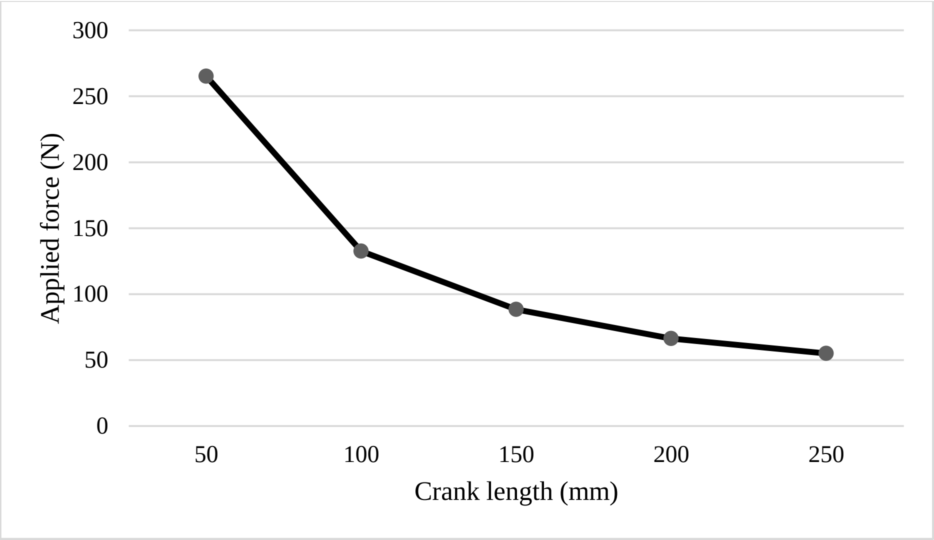


Fig. 4.7: Applied force v/s crank length graph

A multimeter is used to calculate the voltage and current output. The rpm of Lathe machine are also measured using Tachometer. For voltage measurement, multimeter is simply connected parallel to the output of the generator. The value of the voltage output at various speeds is given in the Table 4.3 and Fig. 4.8. To measure the value of the current produced by the generator, it is connected with a load of *12 Ω* (bulb).

Table 4.3: Output from generator (On/No Load) at specified speeds

Speed (RPM)	**Voltage (No Load) (V)**	**Voltage (On 12Ω Load) (V)**	**Current (On 12Ω Load) (A)**	**Power (W)**
32	6	1	0.51	0.51
52	10	2.1	0.9	1.89
88	18	4.5	1.36	6.12
150	30	9.3	2.1	19.53

From the data reported in Fig. 4.8, it is clear that there is a significant drop in the voltage output of the generator, when it is working in on-load condition. This drop is an obvious phenomenon, as the generator has to overcome back e.m.f. on-load first. Moreover, it is demonstrated well in Fig. 4.10 that the increase in voltage is in linear relationship with cranking speed, which has been proved in (3.10) in last chapter, where all other parameters depends on generator configuration.

The maximum output current of the generator is rated as *0-3 A*, which is directly linked to the torque input at the generator shaft and the speed of cranking. During this experimentation process, a maximum of *2.1 A* of current value is obtained as output from generator at *150 rpm*. Clearly, near about *3 A* of current can be generated from the current if cranked at faster speeds. Considering safety precautions and to avoid accident, the maximum speed given as input to generator is restricted to *150 rpm*.

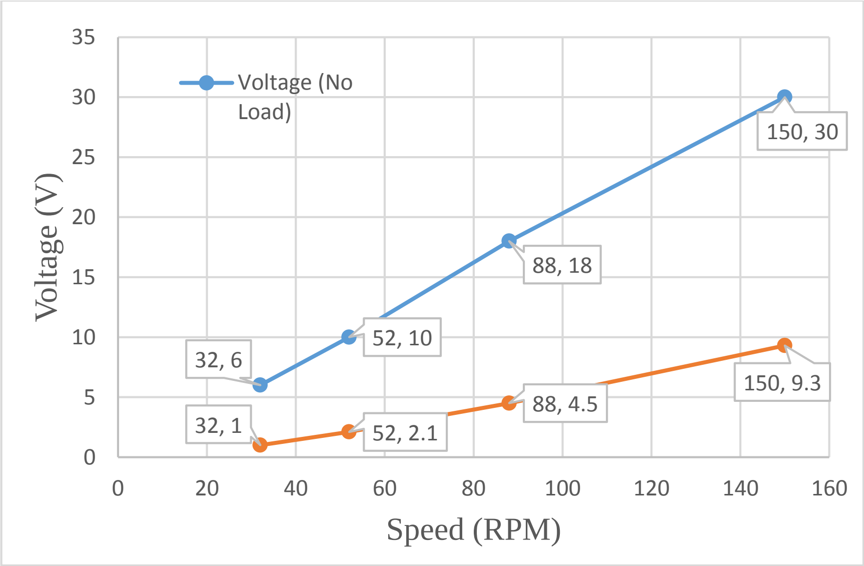


Fig. 4.8: Output voltage v/s speed plot for on/no load

From the results of experiment, reported in Table 4.3, it is clear that the output voltage of ranges between *6 V* to *30 V* when operated in off-load condition and *1 V* to *9.3 V* in on-load condition. Similar voltage range (*1-9 V*) is also found in the literature with experiments on a Charkha generator [67], discussed in Section 2.5 and is given in Table 4.4. The results of our experiment are given in Table 4.3. It is clear from Table 4.3 and Table 4.4 that the output voltage range in both the experiments is almost same. The only difference is the value of generator rpm. In charkha experiment, due to the use of larger diameter spinning wheel, same voltage output may be achieved with more speed (rpm) values.

Table 4.4: Output voltage from charkha experiment

Speed of Generator (rpm)	**Output Voltage (V)**
645	5.00
750	6.28
775	6.50
910	7.50
950	7.85
1030	8.00
1105	8.55
1193	9.00

The plot of current output for different cranking speeds is shown in Fig. 4.9. From the plot shown in Fig. 4.9, it is clear that the relation between current and input speed is almost linear, which satisfies the relation given in (3.7) in previous chapter. Hence the output of the generator varies linearly with the input.

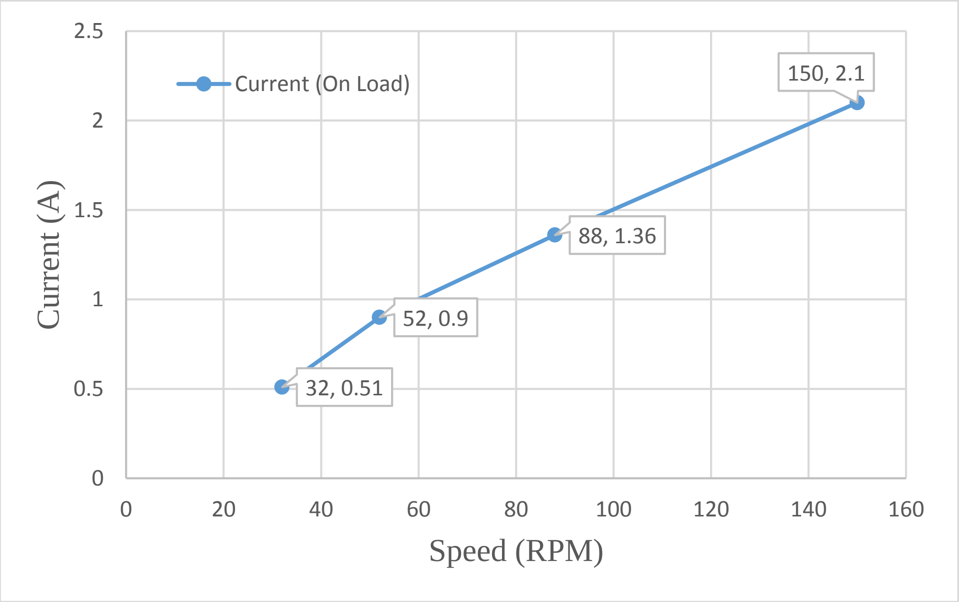


Fig. 4.9: Output current v/s speed plot on 12Ω load

From (3.10), the value of power is calculated as the product of voltage and the current output in on-load condition. i.e.

$$P_{elec} = V \times I$$

where, P_{elec} is the electric power output, corresponding to voltage 'V' and current 'I'. The variation of power output with input cranking speed is shown in Fig. 4.10.

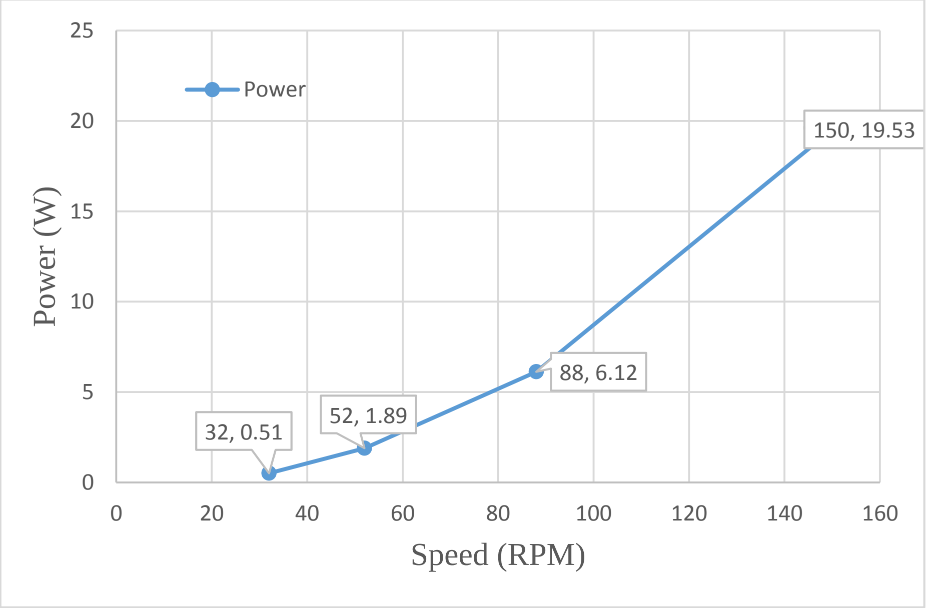


Fig. 4.10: Output power v/s speed plot on *12 Ω* load

As it can be seen from the experimental data, that the output of the generator on *12 Ω* load is *19.53 W* at *150 rpm*, which falls in a close region to power required (*20 W*) to actuate one (knee) joint as discussed in previous chapter. In order to validate the objective of this thesis, mere getting output from the generator is not sufficient. To prove the effectiveness of the generator, a battery is charged with this output of the generator.

A *3.7 V 2000 mAH* mobile battery is charged with HCG for getting the results. Charging voltage required for this battery is *5 V*. Since the output of the generator is around *24 V*, a DC-DC convertor, as shown in Fig. 3.5 (c), is used to drop down the voltage to *5 V*. Charging process is completed in three cycles i.e. charging battery by *1%, 2% and 3%*. Charging time is noted for each cycle and listed in Table 4.5.

Table 4.5: Charging time v/s charging percentage

Charging Percentage		**Charging Time (Sec)**
% Charging	**Effective Charging**	
14-15%	1%	70
14-16%	2%	146
15-18%	3%	205

Fig. 4.11 shows the plot between charging percentage and charging time. It can be seen that the line in the graph is following almost a linear pattern. Considering the charging process to be linear, time to charge the battery to a level of *100%* can be estimated.

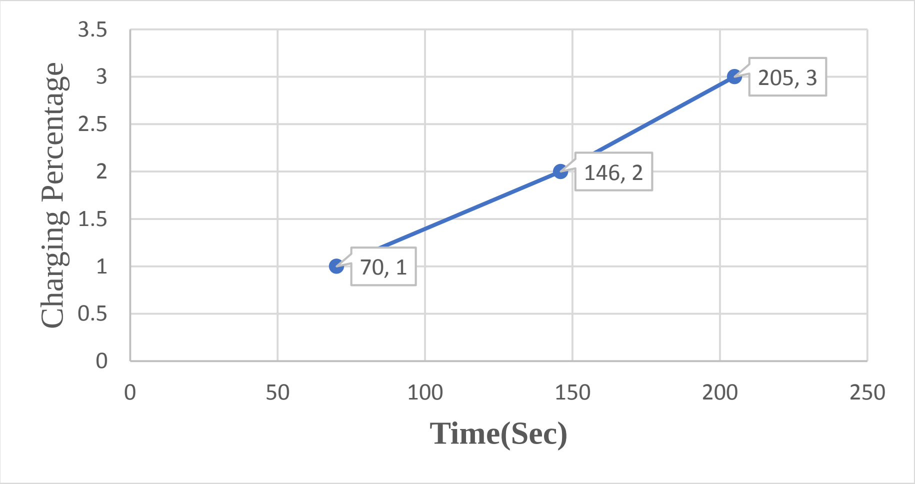


Fig. 4.11: Charging percentage v/s time for 2000mAH mobile battery

Since,

Time to charge *3%* of battery = *205 sec*

Time to charge *1%* of battery = *68 sec*

approximate time to charge *100%* of battery = *6800 sec*

= *113.33 min.*

= *1 hr. 53 min.*

It can be seen that the time to charge *100%* of a battery is *1.88 hours* or *114 minutes* approximately. This means continuous cranking of HCG for *114 minutes* can fully charge a *2000 mAH* or *2 AH* battery.

4.5 Various Losses and Efficiency

In this section, calculation of losses and generator efficiency is calculated. Since the input and output power of generator is already calculated, next step is to calculate the efficiency of HCG. It is a known fact that the efficiency of the generator depends upon the internal configuration of the generator. Therefore, calculation of efficiency and losses can also help in designing a new HCG, and ensures its suitability for a particular application. In Section 4.3, it has been calculated that:

Output from the generator = *24.043 W*

Input to the generator = *250 W*

Losses = *250 – 24.043*

= *225.957 W*

Loss % = $\frac{225.957}{250} \times 100$

= *90.38 %*

Efficiency of the Generator = $\frac{Input}{Output}$

= $\frac{24.043}{250} = 0.0962$

= *9.62 %*

From the above calculations, it is observed that the efficiency of this HCG is around *10%*, which is obviously too less. This less efficiency is, mainly, due to various losses like losses in coils, back e.m.f. etc. Further, all the reported calculations are corresponding to small crank length i.e. mounting the drill machine directly on the generator shaft. These results can be improved by using a longer crank length, such that the required torque will be less than the one used in this calculations.

The estimation of the charging time has been reported in Section 3.5 using certain assumptions, which is around *37 minutes*. However, as mentioned earlier, this estimated time does not consider any losses associated with converter. From the experimental results obtained in Chapter 4, the actual battery charging time is obtained near to *113 minutes*. This much different in expected and actual time for battery charging is due to various losses like:

- Loss due to heating of generator coils
- Power loss to overcome back e.m.f. generated inside the generator
- DC-DC converter losses
- Fluctuations in the output of the generator

$$\begin{aligned}\text{Actual charging time} &= \textit{113 mins}\\ \text{Expected/analytical charging time} &= \textit{37 mins}\\ \text{Loss percentage} &= \frac{113-37}{113}\times 100\\ &= \textit{67.25\%}\end{aligned}$$

4.6 Summary

Experimentation approach to demonstrate the charging process has been discussed in this chapter. A series of experiments have been performed to analyze the input and output of the HCG. Detail of test-rig, used for getting output, has been given along with the output results. To capture human effort, various methods adopted for automatic cranking, including their pros and cons, has also been discussed. First of all, the torque requirement at the shaft of generator is calculated and various changes in its value, upon changing crank length, has been reported. Next, the output of the generator, both in off-load and on-load condition, has been captured by using a load of *12 Ω*. Input and output of the generator aids in calculating overall efficiency and hence various losses associated with the power generating process. Various relationships like output voltage versus speed, output current versus speed and output power versus speed, which were derived in Chapter 3, has also been verified using output of experiments. Actual time required to charge a battery is obtained and compared with the expected charging time that was calculated in previous chapter and losses in charging time are also calculated.

Chapter 5

Matlab/Simulink Based Control of Generator Output

5.1 Introduction

In Chapter 3, mathematical modeling of the hand-crank generators has been discussed in details, whereas in Chapter 4 same has been verified with the help of experimental method. It has been observed during experimentation that there are always some ripples in the rated voltage output of the hand crank generator. These ripples/spikes can harm the battery of exoskeleton. During experimentations, a simple step down DC-DC converter is used to convert rated output voltage of HCG to a required value for mobile/exoskeleton charging. After this step, ripples are still observed in the output of the converter. In order to tackle this problem, a PID controller based solution is proposed in this chapter. Basically, this chapter deals with the Matlab/Simulink simulation of rectified DC as well as AC output of the hand crank generator at a particular speed.

The proposed rectifier is a bridge made up of four thyristors, which is used to convert AC to DC. Rectifier is discussed in detail later in this chapter. A PID controller is employed to damp the fluctuations in the output of the generator. Simulation of the proposed technique is performed in Matlab/Simulink environment. Output results from Simulink are shown sequentially throughout this chapter.

5.2 PID Control

An effort has been made to control spikes/ripples using a PID controller and fully controlled Thyristor Bridge. The input voltage is controlled by changing the firing angle, because it has been observed that this method of controlling the voltage output is quite efficient and easy. Most of industrial controllers these days employ PID controllers as these controllers aid on-site adjustment or parameter tuning. Tuning can be done both manually as well as automatically depending on the requirement of the plant. PID controller can be implemented to a plant even if the mathematical model of that plant is not known. In this type of controller, firing angle is constantly changed, in order to get the voltage output equal to (preferable) or nearly equal to the required preset/reference value of voltage. PID controller consists of three parameters i.e.: Proportional gain (P), Integral gain (I), Derivative gain (D). The transfer function of a PID controller is described as:

$$H(s) = K_P + K_D s + \frac{K_I}{s} \tag{5.1}$$

K_P, K_D and K_I are constants of proportional, differential and integral respectively. These constants can be found out using following two methods:

1. Using Bode plot when the transfer function of the system is known
2. Using experimental techniques when the transfer function is not known

If $Z(s)$ is the output of a controller with input $U(s)$, then:

$$Z(s) = K_P U(s) + K_D s U(s) + \frac{K_I}{s} U(s) \tag{5.2}$$

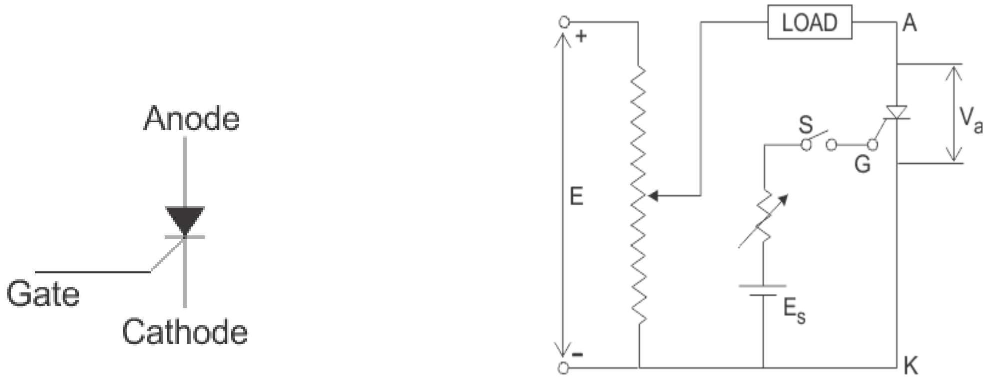
Physical significance of PID controller can be understood from the fact that, integral part, $\left(\frac{K_I}{s}\right)$ has pole at the origin due to which it tries to increase the type of the closed-loop system, hence reducing the steady-state error. Similarly, the derivative part, $K_D s$ and the proportional part, K_P are used to place two zeros of H(s) at appropriate location to change phase characteristics of closed-loop system. The phenomenon of changing the values of K_P, K_D and K_I in order to achieve the desired closed-loop characteristics is known as *Tuning*.

5.3 Rectifier/Thyristor Bridge

A bridge-type circuit made of four thyristors is used as rectifier. The purpose of the Thyristor Bridge is to convert the input AC to DC as output. The invention of thyristors has significantly eased the process of AC to DC conversion. Thyristor is basically a four layer three junction *p-n-p-n* semiconductor device, which may be consisting of at least three *p-n* junctions. The main function of a thyristor is that, it can be used as an electrical switch for high power operations. A thyristor mainly consists of three basic terminals— *anode*, *cathode* and *gate* mounted on the semiconductor layers of the device. The symbolic representation and the fundamental circuit diagram is shown in the Fig. 5.1.

In this chapter, phase controlled AC to DC converters using thyristors are employed for changing constant AC input voltage from AC source to controlled DC output voltage. When the AC voltage supply is passed through the thyristor, which is operated in reverse-biased mode, it automatically turns off provided anode current has fallen to a level below the holding current. This commutation or turning off of a thyristor, with the help of supply voltage, is called as *line commutation*.

The concept of phase control can be adopted by triggering the thyristor at desired firing angle with the help of firing pulse. Measurement of thyristor firing angle is done at the instant it would start conducting if it were replaced by a diode. Firing angle can be defined as the angle measured from the instant silicon control rectifier (SCR) gets forward biased to the instant it is triggered. The variation in firing angle aids as easy and accurate rectified output. This thyristor bridge will act as a rectifier when the firing angle is between *0* to *90°*. When the value exceeds *90°*, the bridge acts as inverter.



(a) (b)

Fig. 5.1: Thyristor (a) Symbolic representation; (b) Circuit diagram of thyristor

The rectified DC voltage output, shown in Fig. 5.3, from the source of power gives voltage around *24±1 V* after giving initial overshoot. Similarly, from the output waveform graph, as shown in Fig. 5.3, it can be concluded that there are spikes in the voltage output from the generator, which occurs periodically after certain interval of time. Since the reference voltage is *24 V*, which is required to charge the battery of an exoskeleton, these ripples/spikes can cause damage to battery being charged. The use of PID controller and rectifier to get desired output is discussed, in detail, in next section.

5.4 Simulation of Rectified Output of Generator

A source with *32 V* AC supply is used to represent a generator with AC output, which is further rectified using thyristor bridge circuit to convert into DC voltage. The AC output of the generator, without rectifier, is shown in Fig. 5.2.

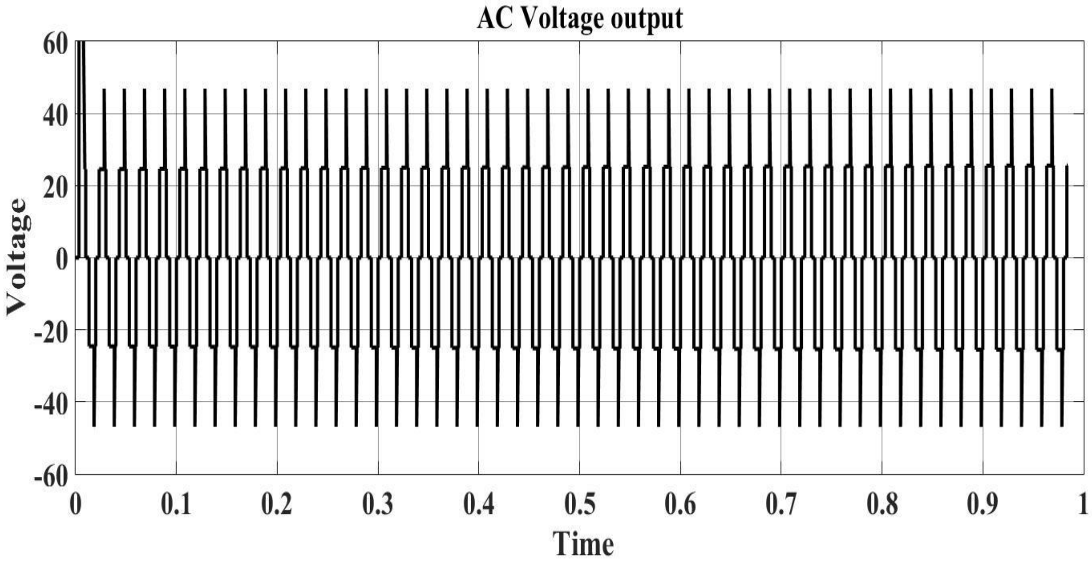


Fig. 5.2: AC output voltage without PID controller

It can be seen from the output that ripples even exist in the AC output. Bridge Rectifiers are the circuits which convert alternating current (AC) into direct current (DC) using the thyristors arranged in the bridge circuit configuration. They usually comprise of four or more number of thyristors, which cause the output generated to be of the same polarity irrespective of the polarity at the input. **Error! Reference source ot found.** shows such a bridge rectifier composed of four thyristors in which the input is supplied across two terminals, while the output from the rectifier is collected at two opposite terminals and is shown Fig. 5.3. The AC output of the generator, as shown in Fig. 5.2, is converted into DC output.

However, the problem still persists as the value of DC output is fluctuating in nature with ±*1 V*. Moreover, the spikes in AC voltage output needs to be damped in order to avoid any damage to the equipment. In order to address this issue, a PID controller is employed in the simulation. The main objective of the PID controller is to avoid the spikes/ripples in the output by comparing it with a reference voltage of *24 V*.

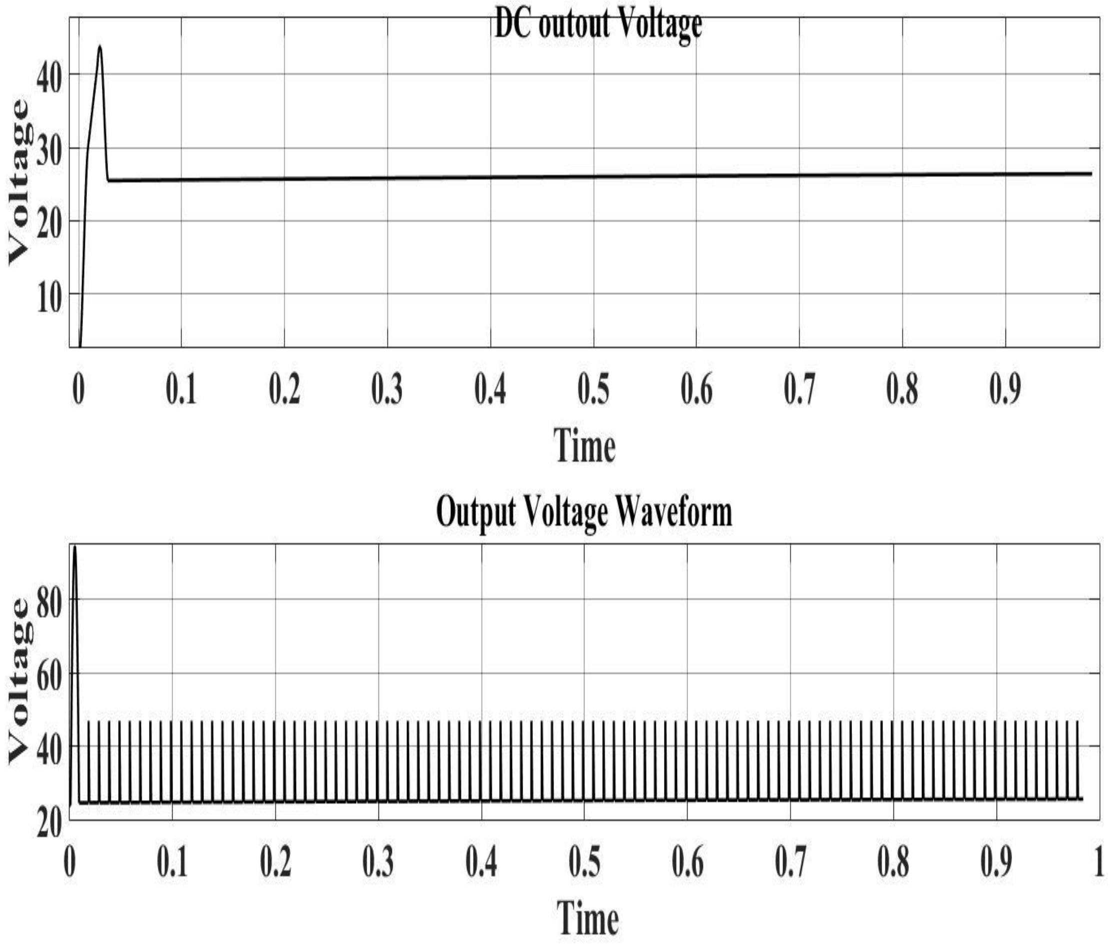


Fig. 5.3: DC output voltage and waveform output without PID controller

The error between actual voltage output and the reference voltage is compensated with the help of this controller. The ripples in AC output, as shown in Fig. 5.2, are damped after using PID controller. The resultant output AC voltage without ripples is shown in Fig. 5.5. PID controller compares the AC output voltage with reference *24 V* voltage periodically and adjust the firing angle accordingly to damp the ripples in the output. Thus, the AC output can be rectified as well as can be made ripple free using this technique.

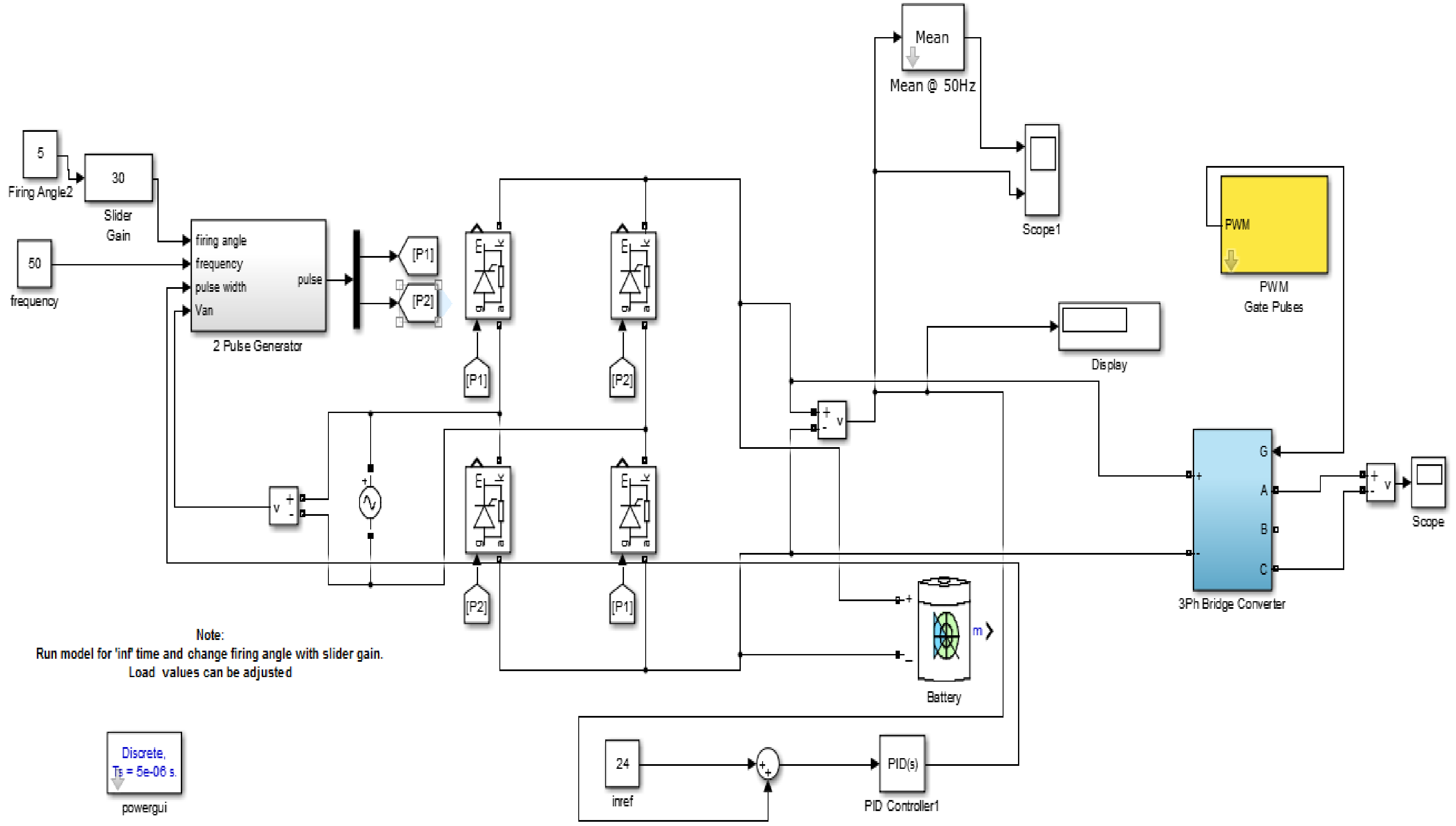


Fig. 5.4: MATLAB/Simulink circuit diagram with PID controller

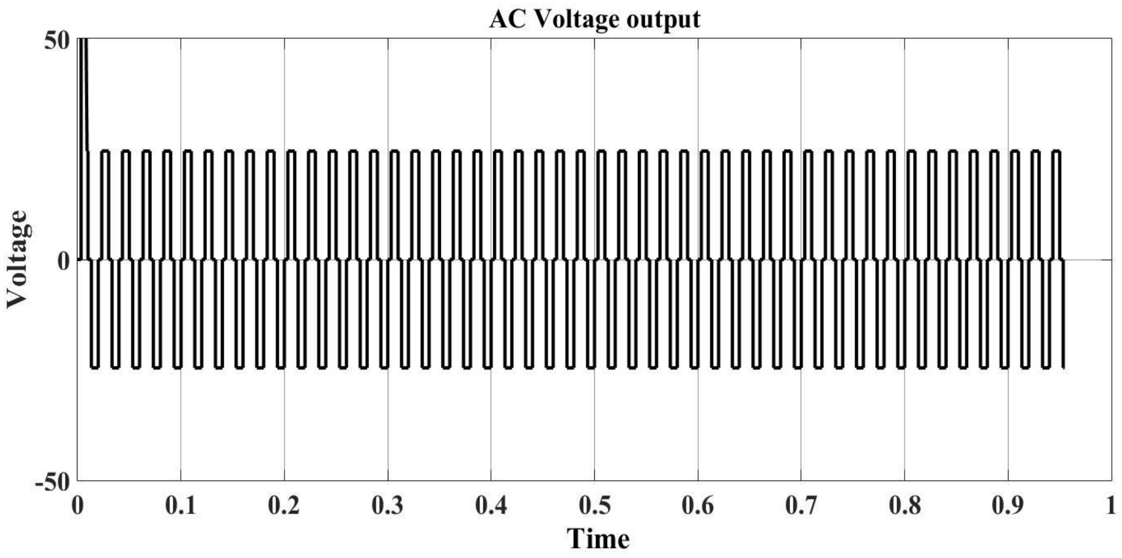


Fig. 5.5: AC output voltage with PID controller

The value of proportional, integral and differential constants are chosen on the basis of hit and trial method, so as to get the output voltage near to *24 V* that too without ripples/spikes. The values of K_p, K_d and K_I are *1, 1, 0* respectively. DC output from the generator, as shown in Fig. 5.3, can also be rectified and made ripple free using PID controller and rectifier bridge in same manner as it is done in case of AC output. The results after using PID controller for DC output voltage as well as output waveform is shown in Fig. 5.6.

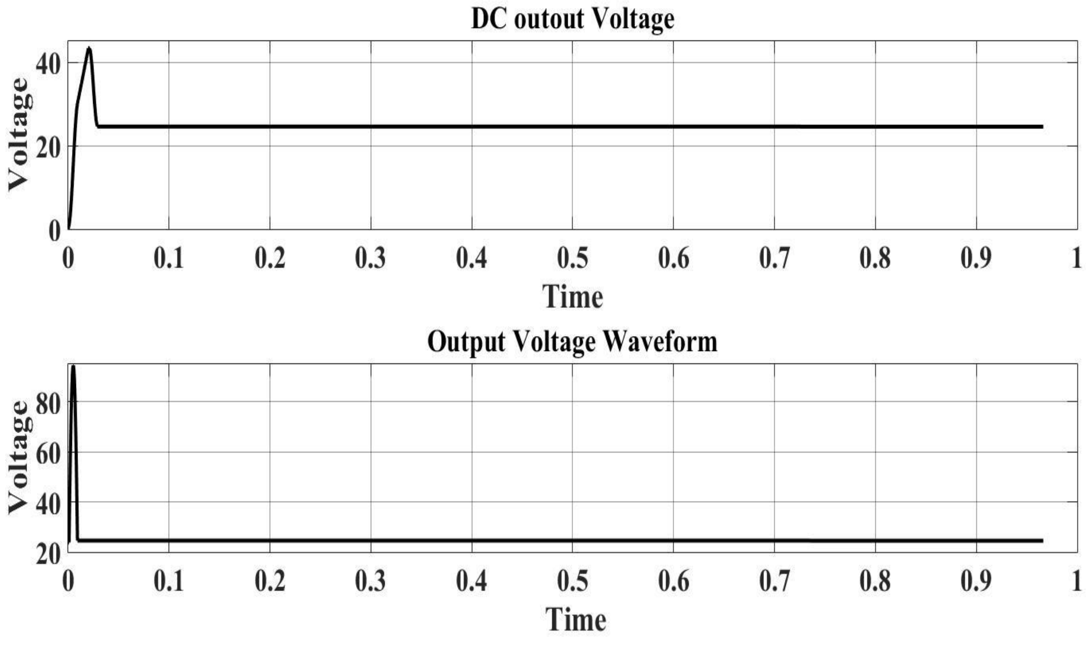


Fig. 5.6: DC output voltage and waveform output with PID controller

5.5 Summary

From the simulation results, it is clear that any fluctuating output from the generator can be rectified and made ripple free by using a rectifier and a controller. The rectifier used in this simulation consists of a bridge that uses thyristors. The use of thyristors, as compare to conventional method of using diodes, makes the process fast and efficient. Moreover, thyristors provide easy latching when used as switching device. In order to damp the ripples, PID controller has been employed. The gains of PID controller are chosen by hit and trial method to achieve the required output. However, an appropriate algorithm can be employed to automatically implement the optimum values of these constants. Simulation results shows the effectiveness of the proposed rectifier as well as the PID controller in controlling the fluctuation of the generator output.

Chapter 6

Closing Remarks

The main objective of this thesis is to investigate the feasibility of using human-power to charge lower-limb exoskeletons in case of emergency. Various discussions on the output range of the HCG and its feasibility to power lower-limb exoskeletons are discussed in this chapter. The output of the generator is closely observed and some conclusions are drawn from this information. Possible future work to optimize the charging process and other factors are also discussed at the end of this chapter.

6.1 Conclusions

Based on the modeling of energy generation and deployment process, experimentation using HCG and Matlab/Simulink based simulation, following observations are made:

- From the torque data for sit-to-stand posture provided by the Swedish group and experimentation results, it has been reported that the output range of hand-crank generators is close to the requirement range of a low-power lower-limb exoskeletons.

- A complete mathematical model has been developed in this thesis for energy generation and deployment. From the modeling part covered in Chapter 3, it is clear that the relation between output voltage and input cranking speed is linear in nature. Similar linear trend is obtained from the results experimentation done in Chapter 4.

- To validate the mathematical model, an experimentation test-rig has been developed. It has been demonstrated well that the relation between current and speed is linear and analytical results are found in close agreement with the experimentation results. The relation between output power and input cranking speed are also reported to be linear during experimentation, which satisfies the relation developed mathematically in Chapter 3.

- There are some losses associated with each step included in energy harvesting and deployment process, due to which discrepancy is observed in actual charging time and estimated charging time.

- Reported efficiency of a hand-crank generator during experimentation is low, yet the use of HCG can be recommended in some difficult conditions where other portable charging techniques are not applicable, and the main supply problem exists in remote areas.

- It has been observed that there is no such direct method or equipment available to capture the human effort during cranking. However, some secondary methods has been tried used to calculate the same by adopting automatic cranking.

- The torque requirement to crank the generator is high, that restricts the generator shaft to crank at high speed. To tackle this problem, use of gear mechanism, belt drives and some other means are proposed.

- A lot of fluctuations are observed in the output of the generator during experimentation. To suppress these fluctuations, a Matlab/Simulink based PID controller has been proposed in this work. Results from the Simulations are encouraging as the fluctuations can be damped after adopting suitable PID gains.

6.2 Future Work

It has been observed that some more research can be done on this topic in order to make it simple in working and enhance the performance of overall system. Some directions, which can be explored in future are discussed below:

- Some losses are observed in the power generation and deployment process, which can be explored, in detail, for each step. After exploring various losses, some suitable optimization technique can be implemented with an objective to minimize these losses.

- A problem to capture human power is observed in this work, for which use of torque sensors is recommended. The problem with torque sensors is their high cost. Therefore, some other means to capture human effort can be explored.

- A full-scale experimentation test-rig can be developed to boost the generator output and monitor the energy generation process. A prototype of a low power lower-limb exoskeleton can also be developed in order to perform the charging process.

- More advanced HCGs are available in market, output power of which is more than the conventional HCGs. Some more added advantages associated with these HCGs are their light weight and easy portability, thus making process of charging easy and less tiring.

- According to requirement of the exoskeleton battery an AFPM based hand-crank generator can also be designed from the scratch.

- Alternate charging options, using human power with less input effort, can also be explored. These options include the use on rocking chair, pull-cord generators, shaking generators etc. Depending on the requirement of the exoskeleton battery, any suitable method can be employed.

ANNEXURE

Annexure A1

Specifications of HCG [79]

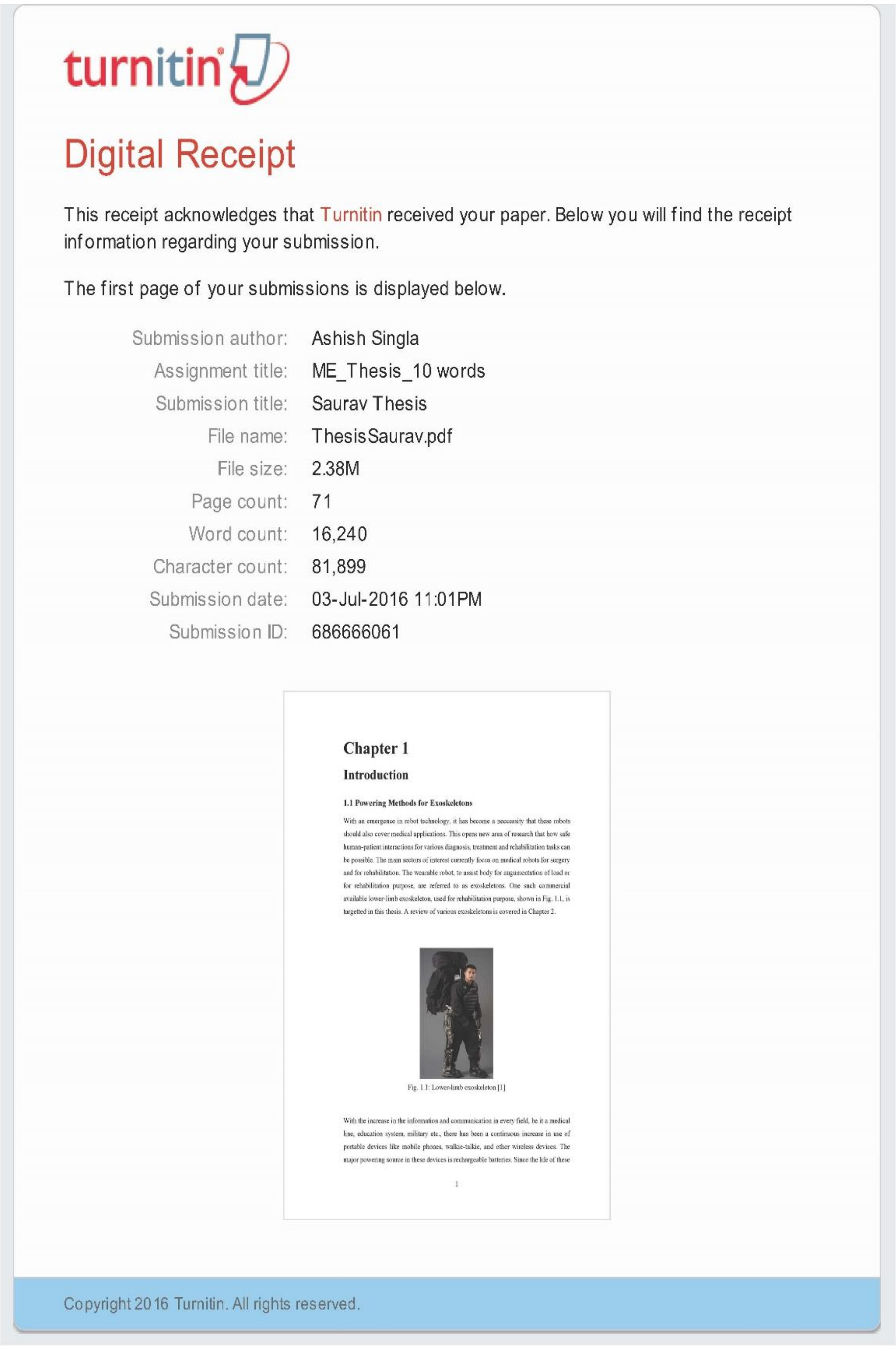
Material	High strength aluminum composite alloy
Principle	High-tech magnetic conversion technology
Temperature range	*-40℃* to *60℃*
Relative humidity	*80%* to *90%*
Altitude	≤ *5000 m*
Other specifications	Water resistant, Shock resistant, Current overload and overheat protection

Annexure A2

Specifications overview of the Drill machine [81]		
Parameter	**Value**	**Units**
Rated power input	500	*W*
No-load speed	0 - 2600	*rpm*
Power output	250	*W*
Weight without cable	1.5	*kg*
Drill spindle connecting thread	3/8"-24	-
Chuck capacity	1 – 10	*mm*
Impact rate at no-load speed	0 - 41600	*bpm*

Drilling range [81]		
Parameter	**Value**	**Units**
Drilling diameter in concrete	10	*mm*
Drilling diameter in wood	20	*mm*
Drilling diameter in steel	8	*mm*

Annexure A3



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Chapter 1

Introduction

1.1 Powering Methods for Exoskeletons

With an emergence in robot technology, it has become a necessity that these robots should also cover medical applications. This opens new area of research that how safe human-patient interactions for various diagnosis, treatment and rehabilitation tasks can be possible. The main sectors of interest currently focus on medical robots for surgery and for rehabilitation. The wearable robot, to assist body for augumentation of load or for rehabilitation purpose, are referred to as exoskeletons. One such commercial available lower-limb exoskeleton, used for rehabilitation purpose, shown in Fig. 1.1, is targetted in this thesis. A review of various exoskeletons is covered in Chapter 2.

Fig. 1.1: Lower-limb exoskeleton [1]

With the increase in the information and communication in every field, be it a medical line, education system, military etc., there has been a continuous increase in use of portable devices like mobile phones, walkie-talkie, and other wireless devices. The major powering source in these devices is rechargeable batteries. Since the life of these

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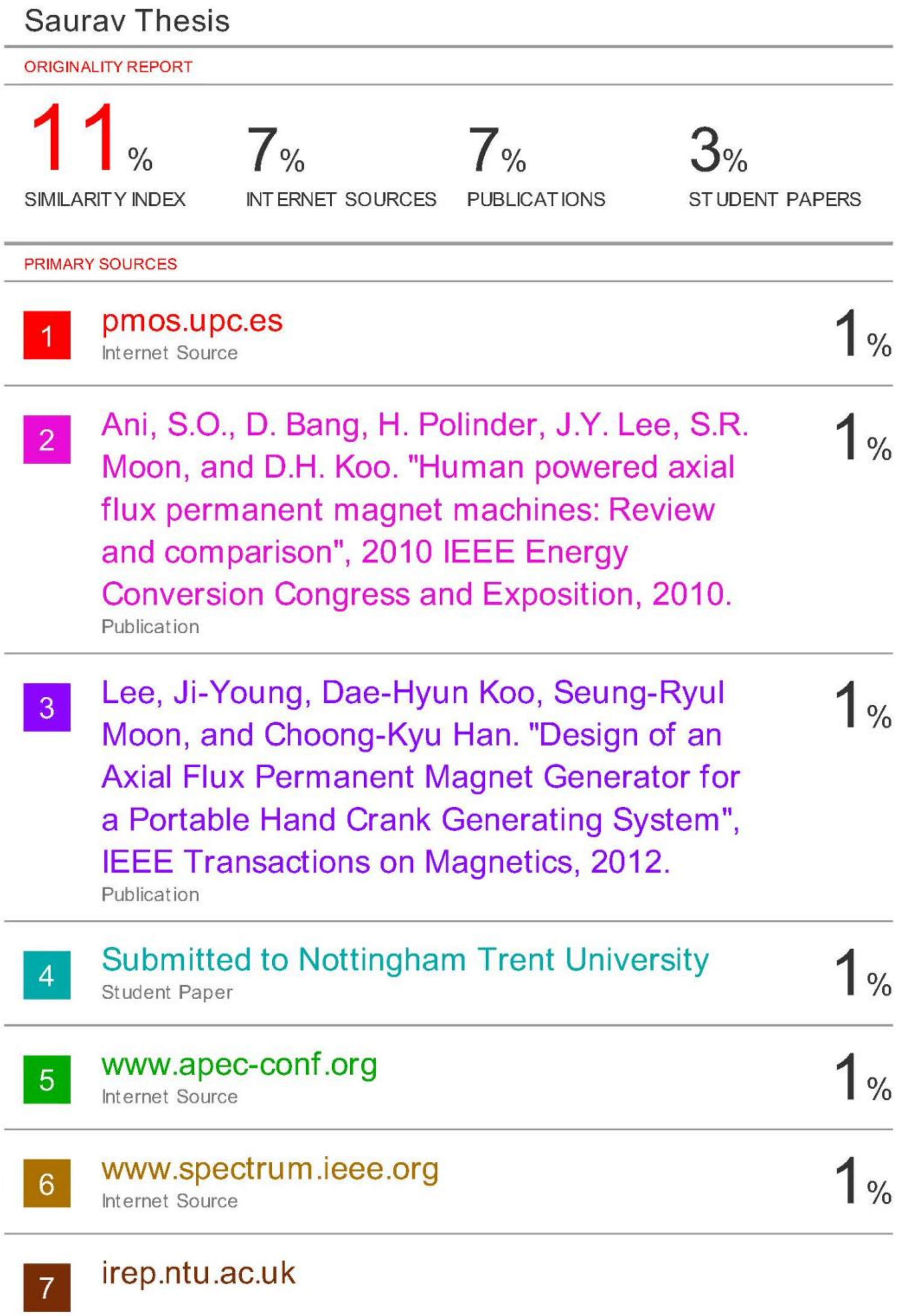

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