UTILIZATION OF SMALL CONDUIT HYDROPOWER GENERATION FOR DOMESTIC LOADS

By

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DECLARATION

I, LEONARD NKOSINATHI MBELE, Student Number , do hereby declare that this research project, which has been submitted to the Central University of Technology Free State, for the degree: Master of Engineering in Electrical Engineering, is my independent work and complies with the Code of Academic Integrity, as well as other relevant policies, procedures, rules and regulations of the Central University of Technology, Free State. This project has not previously been submitted by any person in fulfilment (or partial fulfilment) of the requirements for the attainment of any qualification.

L.N. Mbele Date: 1st February **2019**

DEDICATION

To my Lord, my Saviour Jesus Christ; for the many blessings bestowed upon me.

ACKNOWLEDGMENTS

The realization of this work was possible due to the following people, to whom I wish to express my utter gratitude.

To my supervisor, Professor Kanzumba Kusakana, for the trust in my work and the motivation demonstrated during this challenging course. Your support was without a doubt crucial to my dedication for this research.

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I would like to thank my family for always believing that I was capable of achieving my dreams and goals.

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ABSTRACT

The growth in the world's population has led to an increased energy demand. Today and in the near future, renewable energy should be widely implemented, to meet the growing demand for energy. In all various renewable energy technologies, hydropower generation is the most established. A portion of small hydropower generation can be obtained by recovering the energy within water supply systems.

Investing in water energy recovery is of utmost importance, considering the unsustainable use of water on the world level. Therefore, the process of energy recovery should be part of the water cycle. Many countries have begun with the development of this technology, although not much is exploited. The exploitation may contribute to the cost reduction of water supply systems, increasing feasibility.

The current study focused on developing a simulation tool that may be used for conduit hydropower generation. This will assist the conduit hydropower developers to quantify the available energy and evaluate the viability of the conduit hydropower projects. The main findings revealed that the developed model responded effectively under variable pressure. The system was solely active when excess pressure was available. This was due to the pressure difference between PRV pre-set pressure and the system pressure. When the inlet pressure was greater than that of the pressure setting at PRV, the energy recovery turbine utilized the pressure drop to drive the

PMSG. Various output voltages and currents were obtained; the generator did not generate when the pressure drop was zero.

Further research is required to address the factors not covered by this work. This include: evaluation of various turbine and generator technology to validate the model as a universal conduit hydropower model, application of various configurations of the pipeline system and incorporating it to the simulation model and a thorough analysis of the physical losses in the pipeline, in order to accurately match the measured and simulated outputs.

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NOMENCLATURE

\$/kw	United States Dollar per Kilowatt
$\sum K_L$	Secondary Loss Coefficient
B_m	Damping Coefficient (N.m/s)
i_d , i_q	d, q Axis Reference Frame Stator Currents (A)
J_{eq}	Equivalent Rotational Inertia (kg.m^2)
J_g	Rotational Inertia of the Generator (kg.m^2)
J_{wt}	Rotational Inertia of a Water Turbine (kg.m^2)
L_d , L_q	d, q Axis Reference Frame Inductances (H)
R_S	Stator Resistance (Ω)
v_d , v_q	d,q Axis Stator Terminal Voltages (V)
$\frac{fl}{2r_t}$	Main Loss of Coefficient Caused by Friction
€/Kw	Euro per Kilowatt
cm	Centimetre
CO_2	Carbon Dioxide
CO_2-e/kWh	Carbon Dioxide Emission per Kilowatt Hour
GW	Gigawatt
Hz	Hertz

I	Current
km^3/year	Cubic Kilometres per Year
kPa	Kilopascal
Kw	Kilowatt
kWh	Kilowatt Hour
kWh/m^3	Kilowatt Hour per Cubic Meters
l/s	Litre per Second
m	Meter
m^3/s	Cubic Meter per Second
mm	Millimetre
MW	Megawatt
N.m	Newton Meter
N.m/s	Newton Meter per Second
N/m^2	Newton per Square Meter
Pa	Pascal
psi	Per Square Inch
rpm	Revolution per Minute
Te	Electromagnetic Torque of a Generator (N.m)
Tm	Mechanical Torque of a Turbine Rotor Shaft (N.m)
W	Watt

C	Constant Ranging from 0.6 to 0.65
f	Friction Factor
l	Length of the Bypass Pipe
m	Mass of Water
r	Radius of the Main Pipe
r_t	Radius of the Bypass Pipe
rv	Radius of the PRV
v_t	Water Velocity Through the Bypass Pipe
ρ	Water Density

LIST OF ABBREVIATIONS

AC	Alternating Current
BPMDCG	Brushless Permanent Magnet Direct Current Generator
DC	Direct Current
HDPE	High-Density Polyethylene
MDPE	Medium-Density Polyethylene
P	Power
PAT	Pump as Turbine
PMSG	Permanent Magnet Synchronous Generator
PRV	Pressure Reducing Valve
PVC	Polyvinyl Chloride
RSA	Republic of South Africa
US	United States
V	Volts

CHAPTER I: INTRODUCTION

1.1 BACKGROUND

Water supply systems' designs should sufficiently satisfy the water demand requirements for domestic, commercial, industrial and firefighting [1]. In these systems, water is usually transported through pressurized pipes, which may be placed underground or aboveground [2-4]. The movement of water in these conduits depends on the input driving force, which may be either pressure or gravity. The preferred input driving force in water conduit is gravity. However, where gravity is inadequate, pumping systems push water through a conduit.

Water conduits often have excess energy such as high pressure/ static head and high velocity flow rate, which may result to damage of the water supply system [5]. This has negative effects such as ensuing surges, leading to failure of the conduit system and furthering fatigue failure of the pipeline, supports, instrumentation equipment and components. This has led to arrangements being made; the integration of pressure reducing valves (PRVs) into the system to dissipate excess energy and protect the system from damage [5]. Nevertheless, PRVs do not optimize the energy available in the conduit; instead, the energy is wasted in the form of heat.

The optimum use of energy is a key component in any conversion system, particularly in the research field for electricity generation [6,7]. Therefore, a parallel harvesting system may be used to convey excess water energy instead of allowing the dissipation through the valves. This is possible through the use of a specific type of turbine and generator system, to generate electricity, by recovering the pressure head flow. This class of technology is known as "Conduit Hydropower" and is dissimilar from the other classes of hydropower generation [8,9]. The excess energy available in pressurized water conduits is converted into clean and renewable energy. The conduit hydropower requires the least civil work, since it utilizes the existing water infrastructure without environmental impacts [10].

1.2 PROBLEM STATEMENT

The kinetic energy of water may from time to time lead to unfavourable conditions, due to the increasing pressure within the water supply system. An increasing water flow pressure may cause damage to the water supply system. In order to manage excess energy, pressure control valves are often utilized to dissipate excess pressure from the water supply system. Therefore, the available potential energy of water is wasted.

Additionally, none of the studies so far have focused on developing a simulation tool that may be used to analyse the performance of a conduit hydropower system, at any given site, before the pilot stage. The tool should be able to indicate the generated outputs power parameters (dynamic of the system under varying site and operational conditions). This may help the designers to make informed decisions before the piloting stage.

1.3 OBJECTIVES

A sustainable method is needed in order to minimise the inefficient use of energy within water supply systems. Energy recovery is therefore encouraged as a sustainable way of harvesting excess pressure. The water flow inside the pipeline has potential kinetic energy, that may allow small turbines to rotate, as a means of generating electricity. This research is conducted to present how the potential energy from domestic water supply systems may be used as an alternative renewable energy source.

The objective of the study is as follows:

- To review literatures related to conduit hydropower technology, as used for energy recovery process.
- To develop mathematical model for a conduit hydropower system.

- To simulate the proposed conduit hydropower system, in order to analyse its performance as submitted to variable operational conditions, within the domestic water supply system.
- To perform experimental tests on a small conduit hydropower prototype, in order to measure the electrical parameters.

1.4 EXPECTED OUTCOMES OF THE STUDY

- Scientific outcomes:
  - Development of a simulation tool for a conduit hydropower generation system.
  - Experimental testing of a small conduit hydropower as an alternative renewable energy source.
- Social impact:
  - Increase an awareness towards energy recovery in water supply system.
  - Encourage the application of a sustainable, environmentally friendly and clean energy generation technology.

1.5 RESEARCH METHODOLOGY

To achieve the objectives of the study, the methodology is as follows:

- Literature Review: A thorough survey of literatures related to conduit hydropower technology was reviewed. The literature covered all key aspects, such as introduction to energy recovery in water supply systems, key components, configurations and planning of the conduit hydropower system. A broad review on conduit hydropower was essential in determining which data is required during analysis and how it is obtainable.
- Data collection: The required data was used during simulation, data was collected from the typical conduit water supply system and from the turbines and generators manufacturers, respectively. The data from the supply system included water flow (pressure), used as an input parameter, to the pipeline model. The data from the manufactures included the parameters of the selected turbine and generator, used as inputs to the turbine and generator models, respectively.
- System model and Simulation: A mathematical model was developed, to describe the performance of the proposed conduit hydropower system. MATLAB/Simulink software was used to apply the developed model and simulate the behaviour of the proposed system under varying water pressure.

- Prototype: A prototype has been developed to test and evaluate the performance of the small conduit hydropower system.

1.6 HYPOTHESIS

- Domestic water supply systems have enough energy for the development of small conduit hydropower generation system.
- A simulation tool for small conduit hydropower generation system, developed through MATLAB/Simulink, may be used to study the system's dynamic behaviour.
- A prototype properly designed can effectively recover excess energy and correlate the simulation results.

1.7 DELIMITATIONS

The study was conducted with the following limitations:

- The study focuses solely on a domestic water supply system.
- A Pico-scale conduit hydropower system was considered during simulations and testing.

- The modelling of power electronic and mechanical circuits is beyond the scope of this study.
- The design of new turbine, or generator technology was not considered, due to the availability of various technologies in the market.

1.8 PUBLICATIONS DURING THE STUDY

Conference papers:

- L. Mbele, K. Kusakana, “Model-based Design of a Conduit Pico Hydropower System”. 2018 IEEE PES/IAS Power Africa Conference, Cape Town, South Africa, 26-29 June 2018.
- L. Mbele, K. Kusakana, “Overview of Conduit Hydropower in South Africa: Status and Applications”. 2017 IEEE PES-IAS Power Africa Conference, Accra, Ghana, 27-30 June 2017.
- L.N. Mbele, K. Kusakana, S.P. Koko, “Experimental analysis of small conduit pressure hydropower systems”. 2019 International Conference on Domestic Use of Energy (DUE 2019), Cape Town, South Africa, 25-27 March 2019.

Journal papers:

- L. Mbele, K. Kusakana, “Modelling Water Energy Recovery System Using MATLAB/Simulink Software”. Advanced science letters, Vol. 24, No. 11, pp. 8209-8214, 2018.
- L.N. Mbele, K. Kusakana, S.P. Koko, “Simulations and experimental validation of small conduit pressure hydropower systems”. Submitted.

1.9 DISSERTATION LAYOUT

This dissertation is divided into five chapters, structured as follows:

CHAPTER I offers an introduction to the dissertation, which presents the background of the work, problem statement, objectives of the study, methodology, hypothesis, delimitation of the study, as well as the research outputs.

CHAPTER II reports a thorough survey, based on water energy recovery technologies used in water supply systems. These include the recommended technologies to be used in domestic water supply systems, as well as previous energy recovery studies. Additionally, it outlines the sustainability, efficiency and cost effectiveness of the various methods in recovering energy within water supply systems.

CHAPTER III describes the development of the mathematical model for the proposed conduit hydropower system. Therefore, the key components (pressure, flow rate, pipeline, turbine and generator) of the proposed system, are modelled using

MATLAB/Simulink. Additionally, the simulation results of the developed model are further presented and discussed in this chapter.

CHAPTER IV presents and discusses the simulation results, as compared to the laboratory prototype results.

CHAPTER V concludes the work of this dissertation and further suggests future studies to be carried out.

CHAPTER II: REVIEW OF ENERGY RECOVERY IN WATER SUPPLY SYSTEMS

2.1 INTRODUCTION

This chapter provides an overview of previous research on energy recovery in water supply systems. It introduces the framework for small conduit hydropower generation, that comprises of the main focus of the research, described in this dissertation.

The main purpose of the literature review is to survey previous studies on energy recovery for small conduit hydropower generation. The aim is to scope out the key data collection requirements, in order to carry out the new research.

A synthesis of the earlier work provides room for a new research topic, based on the gap. Additionally, review leads to the development of a systemic analysis of the key elements, such as energy recovery, energy efficiency and sustainability, main designs, main sectors, components, planning and an overview of conduit hydropower generation technology, will be discussed in Sections 2.2–2.9. The conclusion, based on the review findings, will be discussed in Section 2.10.

2.2 ENERGY RECOVERY IN WATER SUPPLY SYSTEMS

Currently, energy recovery in pressurized water supply systems (both urban or irrigation water supply), has a great significance. Relative to urban supply systems, the energy consumption in water supply networks represents 7% of the world's consumption of energy [11]. Water supply involves an energy footprint between 0.18 and 0.32 kWh/m^3, according to the California Energy Commission [12]. In addition to energy consumption, energy analysis of these networks has concluded that an increase of pressure is correlated with increased leakage [13].

This problem justifies the installation of PRVs in many water supply systems. These valves reduce pressure and, therefore, the leakage volume. This proportional correlation between leakage and pressure, ensued the pioneering study of alternatives, to recover the dissipated energy by PRV's in water supply systems [14]. An unconventional solution was considered: replacing PRV's by a pump as turbines(PATs) [14,15].

Ferracota et al. [16] published a study on leakage reduction. They presented and integrated a new technical solution, with economic and system flexibility benefits, replacing pressure reduction valves by PAT's. The optimal operating point of the PAT's was selected, by using a variable operating strategy.

Carraveta et al. [17] established a PAT operating scheme, with a PRV in parallel. This operating scheme and the variability of flows over time in network pipelines, due to user demand, have fostered leading studies to develop variable operating strategies in these machines. These strategies allow the variation of the rotational speed of the hydraulic machine [18,19].

Ferracota et al. [20] have begun studies to improve the efficiency prediction in the machine, through experimental tests in semi-axial machines, as the rotational speed varies. Preliminary studies in drinking water systems, have been developed through computational simulations [15,16,21].

Further studies have considered average flows or hourly uniform patterns in all consumption joints, for the development of simulations of water supply systems [21,22]. These energy recovery studies have promoted the use of water supply systems, to generate clean energy, using the dissipated energy in PRV's [22]. These studies have resulted in some pilot installations, emerging for evaluation (e.g., Murcia (Spain) [23], Portland (Oregon) [24], Hong Kong [22], South Africa [25] and Kildare (Ireland) [26].

For developing countries, such as South Africa, the application of this technology is fairly new. Thus, four pilot plants were constructed and the research project indicated economically feasible and technically possible to generate energy from water supply systems, as discussed in the technical paper [3,7]. Table II:1 below, illustrates the developments that took place at the foremost municipalities and water supply utilities, utilizing excess pressure for conduit hydropower.

Table II:1- Water supply systems and potential sites for conduit hydropower development [3,7]

WATER SUPPLY SYSTEM	CONSIDERED HYDROPOWER DEVELOPMENT	IDENTIFIED SITES WITH HYDROPOWER POTENTIAL
Bloemfontein Water (regional water utility)	Mini hydropower installations on the pressure Caledon Bloemfontein pipeline	Uitkijk and Brankop reservoirs, totalling approximately to 1 MW (further options are investigated)
eThekwini Water and Sanitation Department	The installation of six mini hydro sets, considered at various reservoirs	Sea Cow Lake, KwaMashu 2, Aloes, Phoenix 1 and 2, Umhlanga 2 totalling to approximately 750 kW
Tshwane Water Supply Area	A pilot plant of 15 kW has been installed at Pierre van Ryneveld Reservoir. Several other sites are available.	Estimated capacity of 8 MW is envisaged among 10 suitable city's reservoirs

Rand Water (foremost water utility)	Conduit hydropower has been identified and evaluated at a 13 MW of hydropower capacity. Another 40 to 50 MW capacity is envisaged to develop	Brakfontein Reservoir (1.8 MW), Hartebeesthoek Reservoir (2.2 MW), Klipfontein Reservoir (3.4 MW), Zoekfontein Reservoir (5.6 MW).

In addition to water supply systems, water irrigation networks are significant for the improvement of energy efficiency in the water cycle. Worldwide, water consumption is 3925 km^3/year [27], which is distributed, so that 69.53% of water is used for irrigation, 18.70% is used for industry, and 11.77% is used for drinking water systems.

Hence, as the volume of water consumed for irrigation is higher than that of urban systems, the modernization of irrigation should not only be associated with high technology and automation, but further with water management, that accounts for the sustainability of this infrastructure.

The study of the installation of Micro and Pico hydropower is because of necessity, as the irrigated surface area is particularly large (approximately 324 million hectares in the world are provided with irrigation installations, of which 86% are gravity irrigation, 11% sprinkler irrigation and 3% drip irrigation) [28].

Table II:2 presents literature relating to energy recovery within the water supply systems, a broad literature analysis concerning the methodologies that additional researchers have undertaken, the focus area in which their studies were based on, as well as the technologies and findings of their research.

Table II:3 summarises the assessment of findings, derived from the literature, relating to the amount of energy recoverable at PRV's within the water supply systems and highlights the number of sites implemented by the country.

Table II:2- Literature survey for energy recovery

TECHNOLOGY	FOCUS AREA	KEY INFORMATION
PAT	Analysis [29], Design and analysis [30], Modelling, analysis and evaluation [31], [32], Analysis and Evaluation [33], [34], modelling, dynamic analysis and Application [35], Application [36], Design, application, analysis and	In recent years, PAT's have become popular for energy recovery, particularly in areas where the availability of turbines is limited, or within water infrastructure, fed through pumps. The major benefit of PATs is that they are more cost-effective than turbines. Application of PAT's may be

	evaluation [37], Design and implementation [38], Economic Feasibility analyses [39-40], Analysis and application [41].	uncomplicated, but determining the performance could be challenging, as compared to turbines. This technology is limited to flow variability.
PELTON	Design and Implementation [42-43], [44], [38], Review, design and simulation [45], Optimization and Application [46].	Applying this technology, where water pressure is not necessary to maintain at the outlet, shows lower initial costs, a turbine system may pay independently, significantly earlier than an all-new hydropower project. It is suitable for application in variable flow and has acceptable efficiency.
FRANCIS	Design and Implementation [42], [38], Design, application, analysis and evaluation	Francis is acceptable for energy recovery, due to its high efficiency. They simplify pressurized operation, but unique

	[47], Optimization and Application [46].	provisions are necessary in accommodating continuous flow, albeit when the turbine trips offline. Lower installation cost is priced for this technology.
TURGO	Design and application [43], [40].	The simplicity of this technology results in it being popular for the application in energy recovery in water supply systems. The application may result in economically profitable installation. Power generated by smaller types are comparable to that of water wheels. Turgo may be suitable for application with variable flow.
KAPLAN	Optimization and Application [46], Analysis and Evaluation [34]	Due to its adjustable runner blades, this turbine is most adaptable to site conditions. Kaplan turbines have the

		efficiency of approximately 87 % and low initial cost.
CROSSFLOW	Design, application, analysis and evaluation [37], Optimization and Application [46].	This technology may attain acceptable efficiencies, over varying flows and is simple in construction.

Table II:3- Sites assessed and potential energy recoverable [3,7]

NUMBER OF SITES	COUNTRY	OTHER INFORMATION
6	US	The average potential energy recoverable is 83 kW
23	Brazil	The average potential energy recoverable is 10 kW, with the 2.6-40 kW range.
1	Italy	The average potential energy recoverable is 9.5 kW
30	Ireland	The average energy recoverable is 8.5 kW, with the range of 0.1-4.7 kW
10	RSA (Tshwane)	The calculated annual potential power generation in Tshwane is +/- 10 000 000 kWh

2.2.1 Economic view

From the economic point of view, the benefits of selling energy and generating income may be quite significant in some cases (although this generation is irregular over time because it depends on the flow, varying in function of consumption in water supply systems). Some particular analyses of these systems (and, more specifically, of PAT's), present payback periods less than five years, with an installed capacity between 5 and 500 kW [8].

However, the importance of these solutions consists of the energy generation for self-consumption by the local communities, i.e. extracting water from personal water wells, electric supply in irrigation communities or individual use at the irrigation points and avoiding investment in the electric grid. Studies by several authors have led to a broader understanding of the economic view point of this technology.

Regarding economic aspects, Kosnik [48] developed an economic analysis based on several small plants, finding a non-linear relationship between the cost of application and installed power (small, micro or pico).

Ogayar and Vidal [49] further analysed the distribution of costs for small hydropower, which is spread among civil work (40%), turbine (30%), electro-mechanical and regulation equipment (22%), and construction management (8%). This type of renewable energy project is feasible, as the required investment is below 2000

$/kW [50], however, particular attention should be given to the environmental and social benefits, provided by these installations.

At the European level, according to the General Direction for Environment, the average cost of investment for plants with an installed capacity below 10 MW is between 2941 and 4072 €/kW, depending on the characteristics of the system (e.g. flow, head, orography) [51]. Mishra et al. [52] proposed formulas that use the turbine, installed power capacity and net head, to estimate the required investment. These expressions may be used to determine the associated costs.

2.2.2 Environmental view

From an environmental point of view, the use of these renewable energy sources reduces the emission of greenhouse gases, when compared with non-renewable energy (e.g., fuel, usually used in electric generators installed in irrigation communities or irrigation points).

Therefore, these recovery systems may supply the users' demand for low energy consumption in their facilities. An annual reduction of 29 × 106 tonnes of CO_2 estimated, as a result of the 13 GW installed capacity in Europe [53].

Amponsah et al. analysed various values of the carbon footprint of small hydropower and established a range between 2 and 74.9g CO_2-e/kWh, based on the installation and the type of power plant. In the particular case of micro-hydropower, Gallagher et al.

[54] analysed the carbon footprint of three plants, with installed capacities of 15, 90 and 140 kW. The results of this analysis were 2.14, 4.39 and 2.78g CO_2-e/kWh, respectively. These values emphasize the positive environmental impact of hydropower solutions.

2.3 ENERGY EFFICIENCY AND SUSTAINABILITY IN WATER SUPPLY SYSTEMS

Water and energy are the two most significant resources linked with the sustainability of cities. Hydropower generation is a relevant measure for energy efficiency, applied in water supply systems that may produce social, economic and environmental benefits [55].

Sustainability should be obtained by utilizing strategies that reduce the carbon footprint in consideration, to all levels of production scales [56]. The focus should be on the new strategies that are aimed in recovering excess pressure energy within water supply systems. Therefore, it is important to have a deep knowledge of the water-energy nexus, for quantifying the potential for energy recovery in pressurized water supply systems [57].

2.3.1 Gravity systems

In gravity systems, it is principal to study the flow distribution over time. The knowledge of the flow distribution should help increase energy efficiency and sustainability of the water supply system, by incorporating energy recovery systems. Therefore, analysing the water supply system should help identify the crucial aspects of the energy recovery system, such as the form of turbine, the operating conditions and best efficiency point [58].

A few studies [59] obtained initial value of energy recoverable, using the mean circulating flows and observing the daily patterns of the flow within water supply systems. Sanchez et al. [60] developed a new approach, to analyse the timely flow variations within the irrigation systems. However, this method may be adapted for use in water supply systems, solely whether demand patterns are known [56]. These patterns allow the water supply system to be simulated to calculate energy balance, by determining the percentage of the dissipated energy due to friction losses, the theoretically available energy and the non-recoverable energy [56]. The results by [60] indicated 2.85 kWh/m^3, which is close to 4.1% of the input energy and 68.7% of the recoverable energy within the network.

An analysis of the water supply system is required, in order to maximize energy recovery [56]. This is due the fact that feasibility of the energy recovery project is not guaranteed by installation of a higher number of turbines into the water supply system.

Samora et al. [61], through simulated annealing, developed a methodology that maximizes the energy recovered within the water supply system [56], [62]. This methodology considers the energy recovered and feasibility of the facilities, based on economic measure [56].

This measure was proposed by Castro [63], to determine the payback period through the investment cost, incomes and maintenance costs of the project, which is dependent of the maximum power installed.

In recent development of the projects, other complex measures have been used, which consider the annual inflation and the interest rates [64, 65]. A study by [60], indicated a 5.28 payback period from the recovery that represents 9.55% of the energy provided in the water supply system.

2.3.2 Pumped systems

Pumped water systems have been analysed by various authors [66, 67] and their main objective has been to minimize the energy costs.

Rodriguez-Diaz et al. [66], proposed a new methodology with energy savings between 10% and 30% in real case studies, considering the most critical consumption points, which depend on needs and location.

Moreno et al. [68], developed a methodology in which characteristic and efficiency curves are optimized, depending on the recorded flows, obtaining a 32.33% average reduction of installed power in the studied networks.

In further research, energy reduction has been carried out using strategies to minimize energy consumption, through optimal operating schedules, in turn reducing energy footprints by 36.4% [69, 70].

Costa et al. [67] presented a general optimization routine, integrated with EPANET [104]. This routine allows the determination of strategic optimal rules of operation for any form of water supply system.

Cabrera et al. [71], developed a methodology to carry out an energy audit, which detects weaknesses in pressurized water supply systems. This methodology is applied in a real case, obtaining energy savings above 40%.

Within all of the cited cases, energy savings correspond to an economic reduction between 35% and 50% of the energy costs.

Ferracota et al. [16] integrated a new technical solution with economic and system flexibility benefits, replacing pressure reduction valves with pumps as turbines. In the majority of methods, when energy optimization is carried out in pumped water systems, the objective is easily defined as minimizing the energy consumption, with the solution being the establishment of optimized irrigation schedules according to the minimum necessary pressure and irrigation needs at each consumption point.

2.4 MAIN DESIGNS FOR CONDUIT HYDROPOWER GENERATION SYSTEMS

Currently, two main designs for energy recovery systems, namely internal system and external system, may be applied in conduit hydropower generation systems [72]. These designs are explained in the subsections 2.4.1 and 2.4.2 below:

2.4.1 Internal systems

In the internal system design, whereby the turbine runner is completely inside the conduit/pipe section and solely the generator extends beyond from the conduit as indicated in Figure II:1. The advantage being the more compact size, makes it appropriate for water energy recovery but not limited, to smaller applications alone. The power output ranges from 5-10 W, sufficient enough in supplying self-powered water metering or monitoring systems, to 100 kW, for more demanding applications [73]. The internal system is based on traditional in-line impellers and tubular turbines, all with horizontal axis parallel to the water flow.

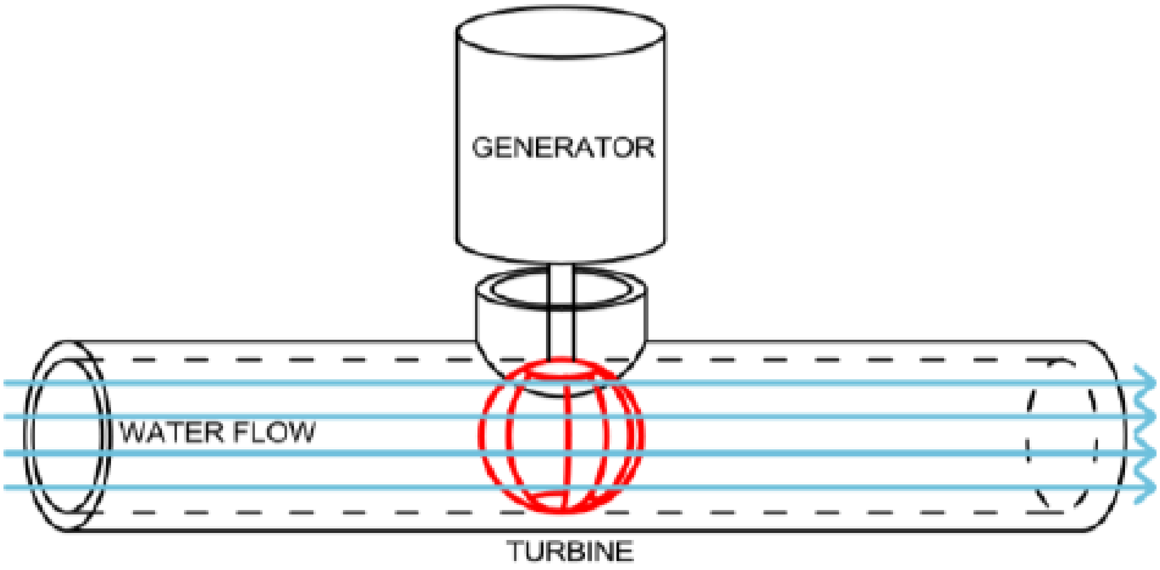

Figure II:1- Internal design of water energy recovery system [73]

2.4.2 External systems

The external systems design is whereby the runner is contained in a secondary conduit, that bypasses the main conduit, as indicated in Figure II:2. External systems do not depend strictly on the conduit size, as the runner is contained in a dedicated conduit, and allowing for more flexibility. However, there is a drawback to this design, as it requires large vaults to house the turbine and generator assembly, making them less suitable for retrofit intervention on an existing water infrastructure [74]. These systems are usually customized in meeting the existing conduit size; the turbine and generator are chosen, based on the available water energy.

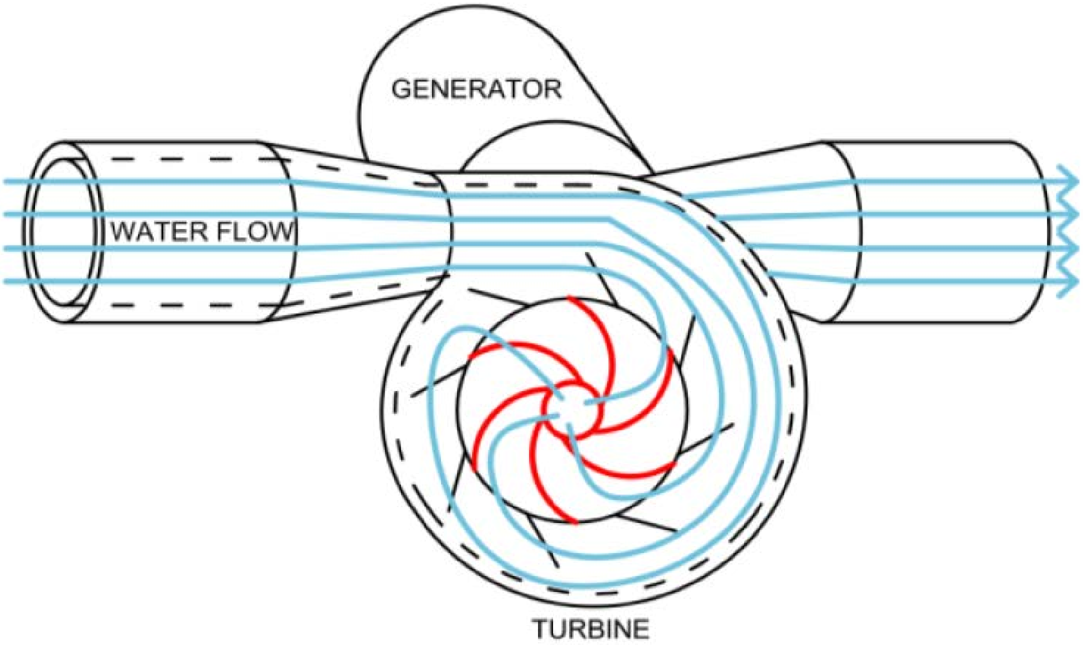

Figure II:2- External design of water energy recovery system [74]

2.5 MAIN SECTORS FOR APPLICATION OF CONDUIT HYDROPOWER GENERATION

The new water infrastructure developments allow all cities to be served by pressurized conduit grids, for the transportation water, where it is required for industrial, commercial or domestic use, while drain and sewerage systems are mostly fed through gravity. Both of these systems provide unused energy, available from an abundant excess of pressure.

Water suppliers install PRV’s to relieve the excess pressure. Theoretically, all systems that employ PRV’s could be replaced, or bypassed, with energy recovery systems, that will harvest the available excess pressure and maintain the pre-set pressure ranges required at the outlets of the water supply systems. Two main sectors of application for conduit hydropower generation systems are explained below:

2.5.1 Urban application

Small turbines may be utilized as a source of power to off-grid water metering and control stations. The application of conduit hydropower includes municipal water supplies and waste water treatment plants. The application provides an opportunity to implement conduit hydropower within these systems, where PRV’s are installed to generate electricity using generators. The system negligible loss of water head and continuously supply power, creating a viable alternative to other renewable energy sources, such as photovoltaic and wind turbines [3].

2.5.2 Building application

Another large potential energy source is available in the conduit systems within residential areas, commercial, shopping malls, tap water supply, drainage, cooling and heating circuits. The excess pressure may be harvested to power building appliances. The application has been extended to air conditioning systems that employ flow and pressure of hot and cold return water, to recover excess pressure and produce electricity [15]. Theoretically, every urban household with an inflow pipe diameter of 20 mm and a flow under at least 10 m head, could generate about 50 W of electricity during each tap opening [75].

2.6 COMPONENTS FOR CONDUIT HYDROPOWER GENERATION SYSTEM

An overview of the main components that are involved in the development of a typical small conduit hydropower system. The focus is mainly on the key components, interconnected in the typical conduit hydropower generation system.

2.6.1 Head and Flow

A small conduit hydropower generation system is based on simple concepts of hydropower. The moving water spins the turbine, which will drive the generator, hence, electricity will be produced. This is the main component in the simple mechanism of hydropower and it is better to start with the basic concept of the water power, head and flow.

Figure II:3 presents two main items involved in small conduit hydropower generation system, as reported by Basar et al. [76]. It should be noted that the water power consists of two important components; namely the head and the flow. Newton's equation states that there will be no electrical power produced by the hydropower generation system if these two components are omitted.

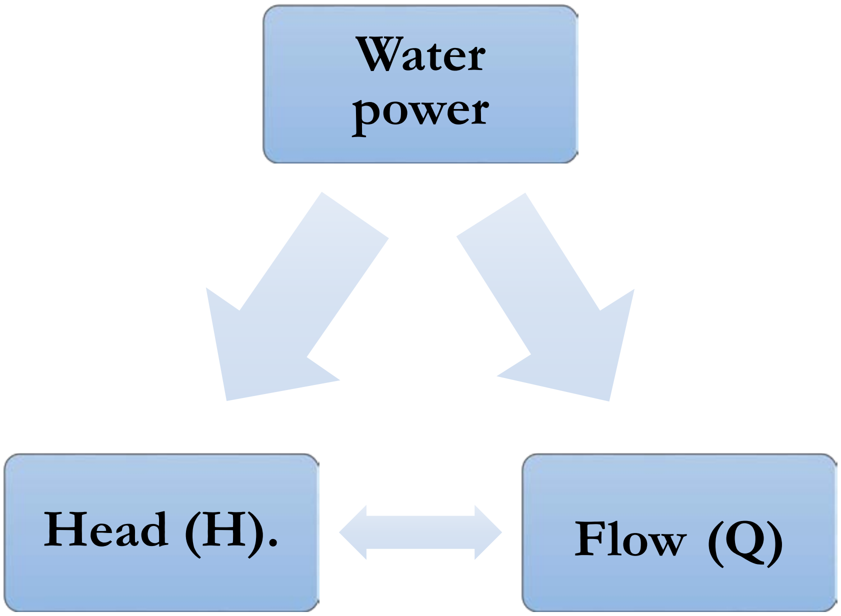

Figure II:3- Head and Flow in water power [76]

Head refers to the water pressure, where it can easily be defined as the vertical fall of water. Head is developed by the elevation difference of the water intake and the turbine.

Head can be expressed as vertical distance (feet, meter) or pressure pound per square inch (psi). On the other hand, pressure (P) may be expressed as a head and it is measured in Newton per square meter (N/m^2) or Pascals (Pa).

In order to produce a given amount of power at a high head scheme plant, it is rule of thumb to use smaller and low cost equipment, as compared to the equipment required at low head sites [76]. Furthermore, a low head site regularly is not cost effective. An argument state exists: in order to have a suitable force for effective power production, it is better to use more head than more flow.

Compared to high head micro hydropower, the low head water wheel requires more water to run. Yet, currently, there is research in finding low flow, that substantiated the system designed capable at producing electricity with high efficiency [77].

Essentially, the gross head is the maximum energy produced by the vertical fall of the water, beginning at the upstream level to the downstream level. The net head, or effective head is the actual head that turbine faces. The net head is slightly less than the gross head, due to losses (i.e. friction, trash rack, entrance losses, pipeline bending), that occurs during the transformation of the water to the system. Meanwhile, static head is the pressure available when the water is turned off. Typically, the net head is less than static head due to the occurrence of the friction losses between water and pipe.

The other component that plays a main role in harnessing the water power is the flow. Flow refers to the water quantity and it is further known as water flow rate. It is the volume of water passing per second and it may be expressed as volume per time, with the unit of cubic per meter second (m^3/s) or litres per second (l/s). Usually, the maximum flow for the hydropower system is designed to be less than maximum stream flow.

2.6.2 Water supply pipeline and Power house

Water supply pipeline is responsible in moving the water to the turbine located inside the powerhouse. The pipeline actually has a significant effect on the head pressure. The more vertical drop, the more water power will focus at the bottom of the pipeline, where the turbine is situated. On the other side, an open stream does not need any penstock, as the energy from the water is obtained as the water flows downhill.

Besides that, the efficiency of the pipeline is highly depending on material, length and diameter of pipe. The larger the pipeline's diameter, the less friction occurs and the more power may be delivered to the turbine, although the cost will be costly. Table II:4 presents the head loss in feet, per 10 feet of pipeline for polyvinyl chloride (PVC) pipe [78]. It may be seen that as the pipe size increases, the head loss tends to decrease.

Instead of piping size, another factor that should be considered is the material of the pipe. The most frequent piping material used in small conduit hydropower generation systems are polyvinyl chloride (PVC), mild steel, high-density polyethylene (HDPE) and medium-density polyethylene (MDPE). Table II:5 illustrates the relative merits for four forms of material, mentioned above that usually used in penstock of small conduit hydropower generation systems [79].

Table II:4- Head loss in PVC pipe [78]

Pipe Size (inches)	**Head loss (Cubic feet per second)**						
1	0.05	0.1	0.2	0.33	0.45	0.66	0.89
2	0.128	0.465	1.680	3.570	6.060	9.920	-
3	0.018	0.065	0.233	0.493	0.836	1.790	3.060
4	0.004	0.016	0.057	0.123	0.202	0.437	0.752
6	-	0.002	0.008	0.017	0.029	0.062	0.103
8	-	-	-	0.004	0.007	0.015	0.025

In small conduit hydropower generation systems, numerous people opt to use a PVC pipe as it is considerably elastic, less friction loss and hard to corrosion. PVC pipes are further easily installed and the cost for the installation is affordable, yet easily transported. Apart from PVC being affordable, PVC pipe has variable sizes ranging from 25mm to 500mm. The user should experience a different pressure rating when varying the wall thickness, although, generally, the outer part remains constant. However, PVC is relatively fragile and its surface cracks easily when continuously exposed to direct sunlight. Thus, the percentage of losses that occur is high, which should further affect the pressure rating of the pipe.

Table II:5- Relative merit for material use in pipeline [79]

	MATERIAL			
	PVC	MILD STEEL	HDPE	MDPE
Friction loss	* * * * *	* * *	* * * * *	* * * * *
Weight	* * * * *	* * *	* * * * *	* * * * *
Corrosion	* * * *	* * *	* * * * *	* * * * *
Cost	* * * *	* * * *	* * *	* * *
Jointing	* * * *	* * * *	* *	* *
Pressure	* * * *	* * * * *	* * * *	* * * * *

*= Poor * * * * *= Excellent

Alternative to PVC piping, are MDPE and HDPE, although both are costly compared to PVC. On the other hand, MDPE and HDPE are uncomplicated to install and recommended to be utilized in a small conduit hydropower generation system. These pipes do not require to be buried, wrapped, painted or covered with foliage, as both do not deteriorate when subjected to sunlight. Having the corresponding criteria as PVC, these pipes have excellent friction loss and corrosion characteristics. The disadvantage is the process of joining the pipes, as the user requires appropriate equipment for heating the ends and fusing the pipes.

An additional form of pipe that is widely used, is the mild steel pipe, due to its robustness in preventing mechanical damage. Yet, it has medium friction loss and is relatively heavy. Generally, it is well protected by surface coating, providing a lengthier life span, up to twenty years.

The powerhouse is a building which protects the main components in small conduit hydropower generation system, consisting of the turbine, generator and system controller. Usually, in a small conduit hydropower generation system, power house may be pictured as a small house, with regards in maintaining the efficiency for the system. If the small house is not accurately designed, for example, the turbine and generator is inaccurately mounted, it could ensue a head loss, friction loss in joining the pipes and power loss at the turbine's moving parts. Thus, it will reduce the efficiency of the small conduit hydropower generation system.

2.6.3 Turbine technology applied in pressurised water supply systems

Turbine is the main part in the small conduit hydropower generation system, where the task is to convert water power to a rotational force in order to drive the generator. It is of importance to select the appropriate turbine, as a majority of the losses are due to this component. Aside from that, the ratio of the generator speed to turbine should not be more than 3:1 [79]. As for example, if the generator used in the system has 3000 rpm, thus the selected turbine must able to spin by at least 1000 rpm. The form of turbines and generators used varies depending on the head, water flow, local condition, financial plan and equipment availability.

In general, a water turbine may be classified by two types; impulse turbine and reaction turbine. Table II:6 below presents various forms of water turbines for small, mini, micro and Pico hydropower generation systems, with reference to the head pressure [80]. Most of the impulse turbines are suitable for high head and medium head with low flow site. In contrast, a reaction turbine is utilized for low head and ultra-low head sites with high flow water, without taking into consideration whether it is horizontal or vertical arrangement.

Table II:6- Turbine technology applied in conduit hydropower generation systems [80]

Turbine Technology	Runner Type	Head pressure
Reaction	Kaplan & Propeller	Extremely low pressures lower than 3 m
Reaction	Kaplan & Propeller	Low pressures above 3 m
Impulse	Cross flow	Low pressures above 3 m

Reaction	Francis, PAT	Moderate pressures above 40 m
Impulse	Turgo, Multi-jet Pelton & Cross flow	Moderate pressures above 40 m
Impulse	Turgo, Multi-jet Pelton & Pelton	High pressures beyond 100 m

2.6.3.1 Impulse Turbine

This turbine has axial flow and it is declared as an impulse turbine because of the occurrence of a direct drive or impulse on the blades created by the water. It operates in an open environment, driven by one or more high-velocity jets of water, which are produced by the nozzle and impinge on the buckets. In the nozzle, pressure head was converted into kinetic energy, where the pressure change occurred. The momentum of water hitting the turbine runners will produce a power of impulse turbine, to drive the generator's shaft. In terms of cost, impulse turbines are more affordable than reaction turbines, as there is a lack of faultless pressure casing and no engineered clearance is needed. Having the same concept as Pelton and Turgo, it operates using the runners, which run without being immersed in water.

In addition, pelton turbine is widely utilized, as it is suitable for a small scale hydropower system and more frequently, in pico-hydropower system [81,82]. A Pelton turbine is the desirable option for places that have a high head and low flow rates of water [83]. It consists of a wheel surrounded with a series of split buckets. The jet water strikes each split bucket (split into two halves), so that each half is turned and deflected back, by approximately 180 degrees. The bucket should propel as the energy of the water moves to the bucket and finally the deflected water runs into a discharge channel.

As mentioned by Alexander and Giddens [84], the pelton and propeller turbine have been applied in ultra-low head pressure and low head pressure (2-40 m) hydropower systems and are able to produce power up to twenty kilowatts. Small conduit hydropower generation, using a Pelton turbine, is shown in Figure II:4 below.

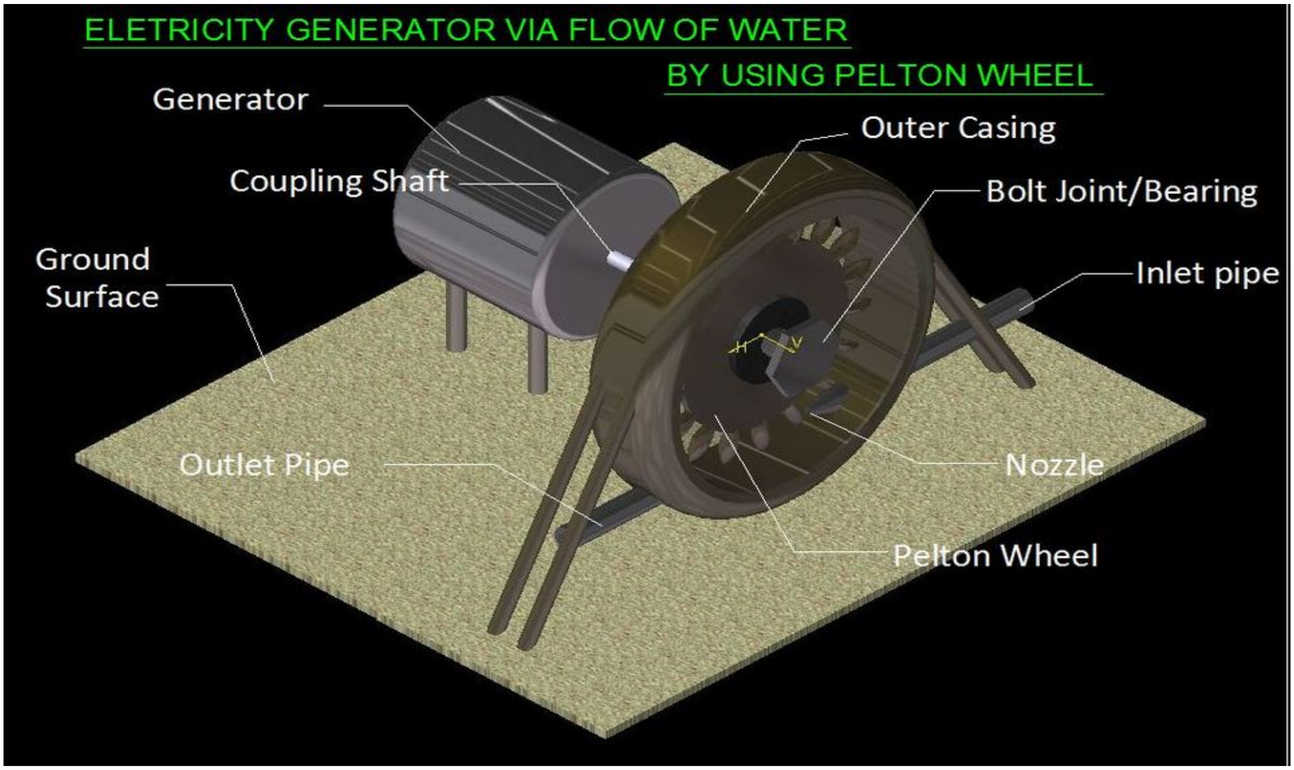

Figure II:4- Pelton turbine for conduit hydropower generation [84]

Turgo turbine is akin to the Pelton turbine, although the jet strikes the plane cup of the runner at a specific direction or angle. The water enters the runner on one side and exits through the other. In a Pelton turbine, it is effective as the jet impinges solely on a single bucket per jet, at any instant, whereas, in a Turgo wheel, the jet impinges on several buckets continuously. In addition, for equivalent power, Turgo turbines commonly have a smaller width runner, in comparison to the Pelton. Figure II:5 below presents a typical Turgo turbine used in conduit hydropower generation.

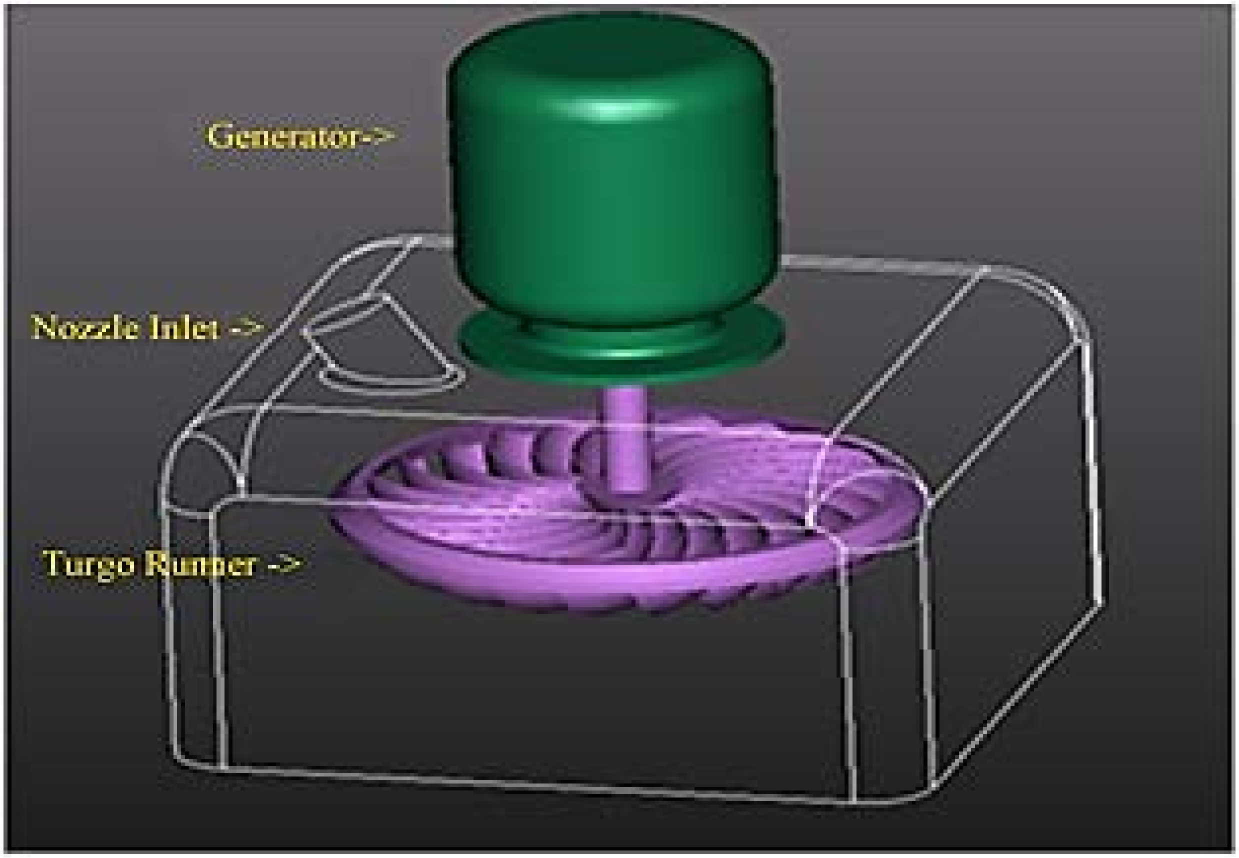

Figure II:5- Turgo turbine for conduit hydropower generation [84]

However, a cross flow turbine further known as a Mitchell-Banki turbine is operated with the partial air admission and the runner partly immersed in water, although it is considered family of the impulse turbine. It operates using the water that passes through a large opening with a rectangular shape, and strikes the runner, named a squirrel cage. Montanari, R. [85] recommended in employing a Mitchell-Banki turbine for small head and modest flow rate with respect to the cost benefit and potential power produced. Therefore, the Francis and Kaplan turbines have high initial cost for the same condition. A crossflow turbine is presented in Figure II:6 below.

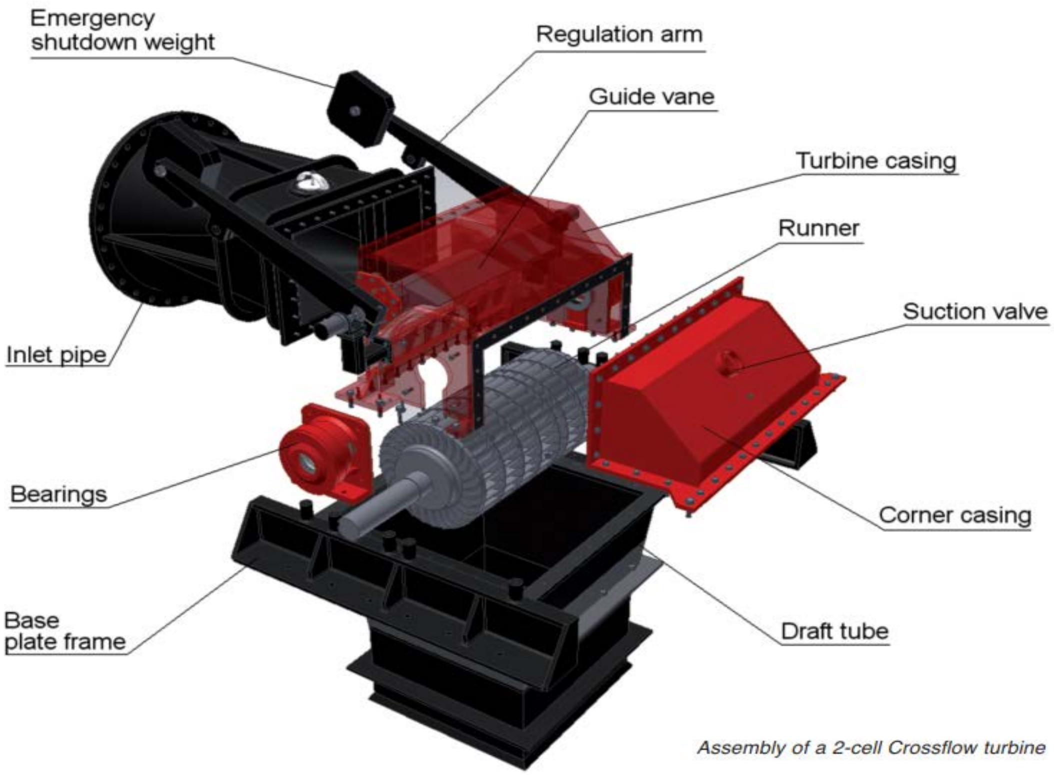

Figure II:6- Crossflow turbine for conduit hydropower generation [85]

2.6.3.2 Reaction turbine

According to Newton's Third Law; for every action, there is an equal and opposite reaction. A reaction turbine is radial flow, using a runner that is fully immersed in water and is enclosed in a pressure casing or volute. This machine is suitable for low head and high flow rate water [79]. The turbine rotates by reactive force, rather than direct push. The turbine blades turn in reaction to the pressure of the water falling on them.

In larger hydropower systems, the most popular turbine is a Francis turbine, although it is a generally more complex and expensive machine. This turbine has an outer ring and inner ring. The outer ring is a stationary guide blade, fixed to the turbine covering. The inner ring has a rotating blade, structuring the runner. The guide blades are in charge of organising water that enters into the turbine in a radial direction and discharged in an axial direction. As the water passes over the rotating blades of the runner, it will cause a reaction force, which drives the turbine. A typical Francis turbine is presented in Figure II:7.

The propeller turbine consists of a propeller and is similar to a ship's propeller. It has three to six blades, however, for a low head, three blades are adequate. The wicket gates or swivelling gates are responsible in regulating water flow. The propeller turbine has a runner with blades, which water passes through in an axial direction, with respect to the shaft. The pitch of the blades may be fixed or moveable.

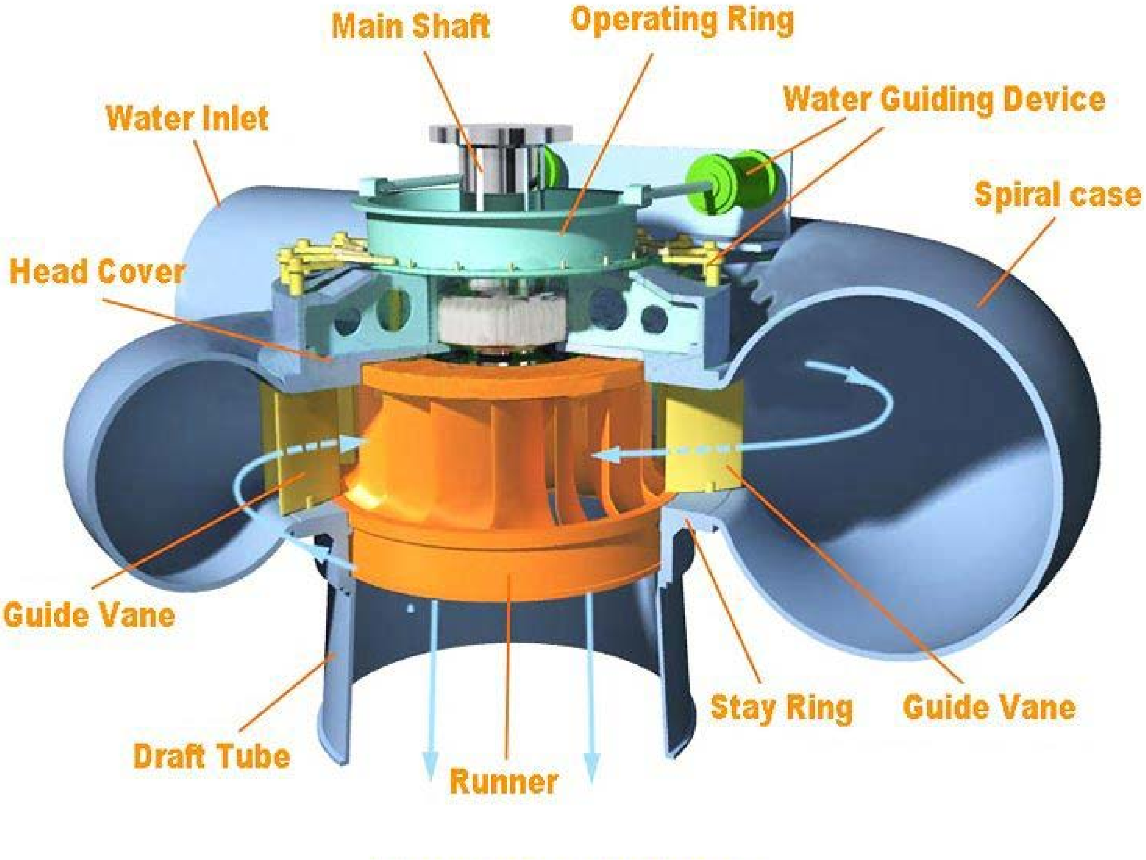

Figure II-7: Francis turbine for conduit hydropower generation [79]

Another form of Propeller turbine is recognized as the Kaplan turbine. A Kaplan turbine is a further sophisticated version of a propeller turbine and is suitable to be used at large scale hydropower sites. The wicket gate may be adjusted to maintain the high efficiency under part flow conditions. In addition, the wicket gate is designed to induce tangential velocity (or whirl) within the water. The dissimilarity of both turbines is that the pitch of the blades may be altered in the Kaplan, in order to obtain desirable results of the power generation process, although this operation is not suitable for the Propeller turbine [79]. A typical Kaplan turbine is presented in Figure II:8 below.

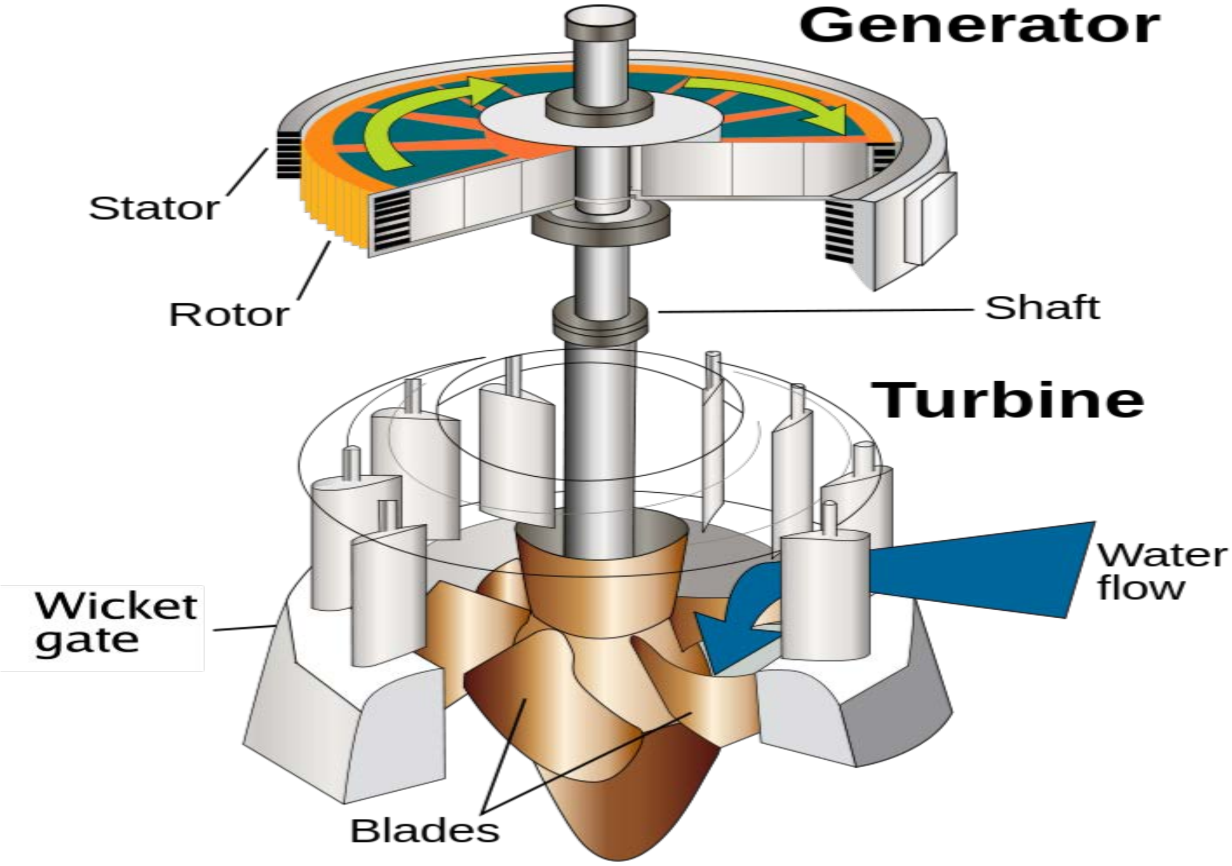

Figure II:8- Kaplan turbine for conduit hydropower generation [79]

Furthermore, there is a project that employed the pump as a turbine (PAT) concept in a small conduit hydropower generation project, in isolated communities. One of the projects is a 2 kW PAT scheme in Lao Peoples Democratic Republic, as reported by

Mariano Arriaga [80]. The PAT concept is suitable to be used at low head and low flow. Generally, the application of PAT in small hydro systems has advantages in terms of cost effectiveness, maintenance and efficiency. The concept is to utilize a standard water pump, reverse engineer the pump curve to run the pump backwards efficiently, and run the penstock into the standard discharge outlet. A typical PAT is presented in Figure II:9 below:

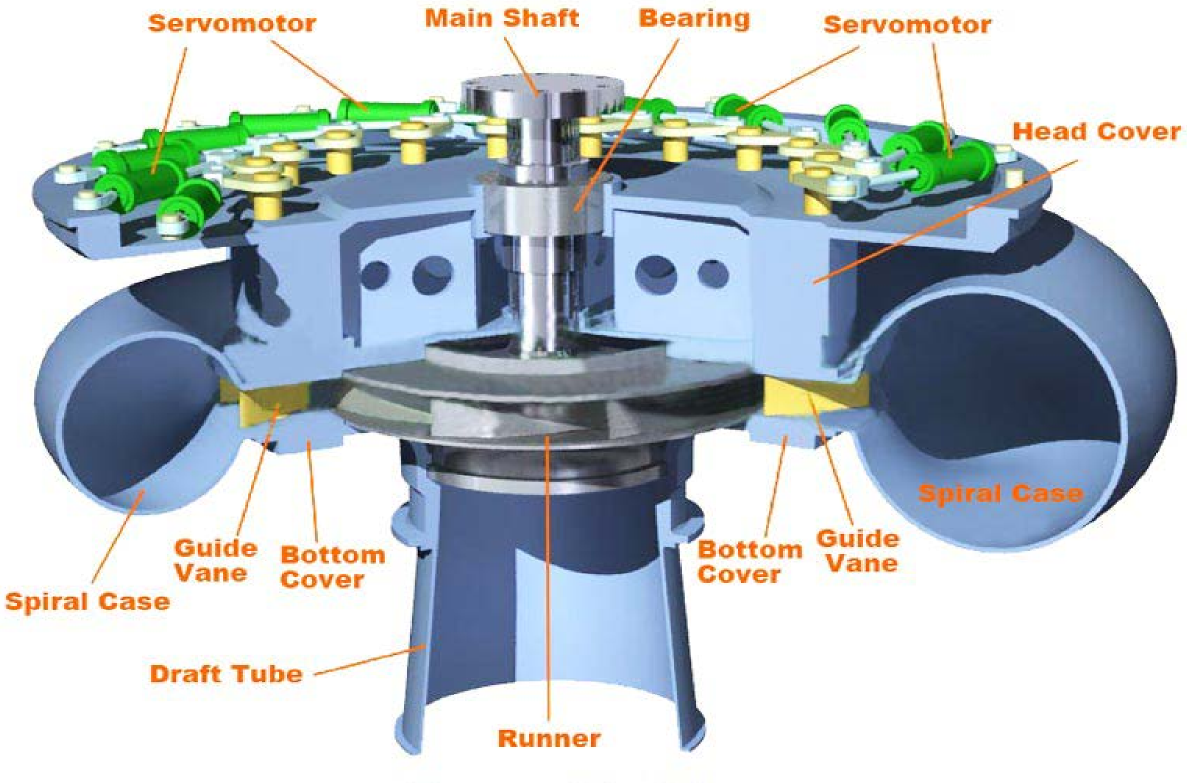

Figure II:9- PAT for conduit hydropower generation [79,80]

2.6.4 Generator technology applied in pressurised water supply systems

Generators are machinery used to convert the rotational energy from water turbine into electricity and at this stage, there should be a reduction in efficiency. However, with facilitating modern technology, well-built generators deliver acceptable efficiency.

Alternators or DC generators, are typically utilized in small household systems. They are usually connected with rectifiers, batteries and inverters. In contrast, AC generators, whether single-phase or three-phase, are typically used with a system producing approximately 3Kw, or more. Generally, this generator is installed with a voltage regulator and transformer, thus able to connect to the transmission lines. An important point to note is that, AC has a frequency which is determined by the rotational speed of a generator shaft. In order to obtain 50 or 60 Hertz frequencies, the turbine controller should be used to regulate the frequency.

Generally, pico-hydro systems use an AC generator, either induction or synchronous machine type, as electrical power produced may be used to supply AC electrical appliances, controlled by a set of modified light dimmers, dummy load circuits [86].

However, a Brush/Brushless Permanent Magnet DC Generator (BPMDCG), is preferred in pico-hydropower system, as proposed by the Zainuddin, H. [87]. This generator has a significant advantage, compared to AC generator, as it is designed to provide high currents, at minimum voltage requirement, to charge the battery and operate direct current loads.

This is related to the load type to be supply. Moreover, a permanent magnet generator is selected, as it is more affordable and has a smaller overall size rather than of wound field. Other than that, this form of generator is more efficient, as no power is wasted in generating the magnetic field [88].

2.7 CONFIGURATIONS FOR CONDUIT HYDROPOWER GENERATION

Installing a turbine directly into the main pipe of the water supply system is not expected. Doing so will disturb the main supply cycles and carries the risk of the device dropping off into the main pipe.

For these reasons, the turbine should be installed into the secondary pipe, for various configurations. There are three possible configurations for implementing small conduit hydropower generation system.

The configurations include: Pressure management, Water discharge and Pressure drop after PRV.

2.7.1 Pressure management configuration

In this configuration, the PRV is replaced with the Pilot tube. The inlet of the Pilot tube is located inside the main pipe of the water supply system, whereas the outlet gives feedback into the main pipe.

The system utilizes the Pilot tube to drive the energy recovery turbine. This form of configuration enables continuous pressure management, utilizing all the excess pressure during low demands in water supply systems. Figure II:10 illustrates the design for this configuration.

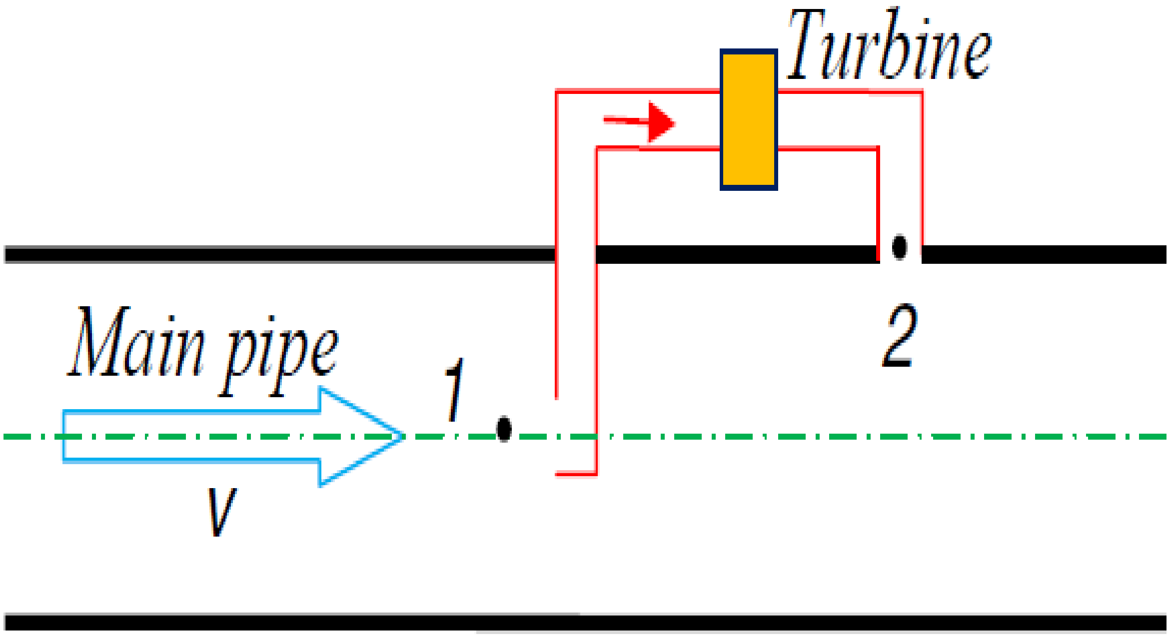

Figure II:10- Pressure management utilizing a Pilot tube [86,88]

2.7.2 Water discharge configuration

In this configuration, water is released from the secondary pipe. Generally, PRV's are omitted from the water supply system. The configuration is designed to maximise energy recovery in water supply systems. Figure II:11 illustrates the design for this configuration.

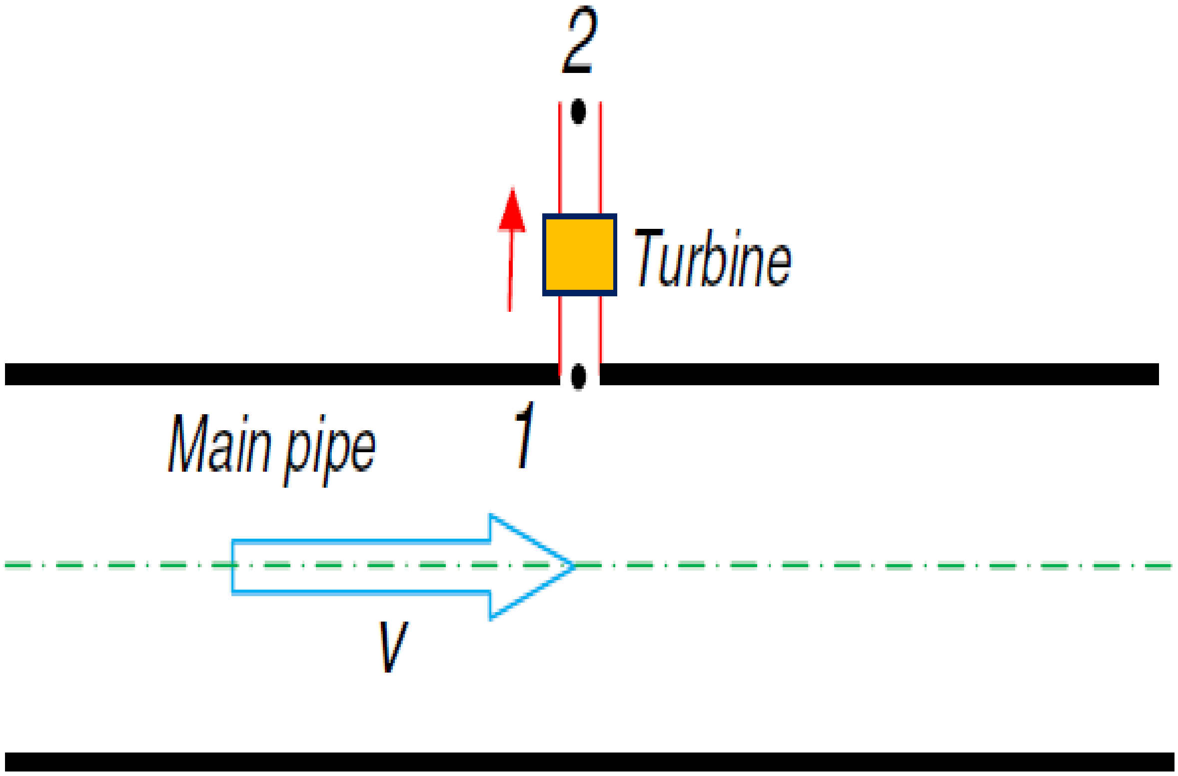

Figure II:11- Water discharge configuration [86,88]

2.7.3 Pressure drop after PRV configuration

In this configuration PRV's are not replaced. Instead, a bypass secondary pipe is installed in parallel with the PRV.

The system considers a turbine driven by the pressure drop after PRV. This system is suitable for excess pressure recovery, that is normally dissipated by PRV's. Figure II:12 illustrates the design for this configuration.

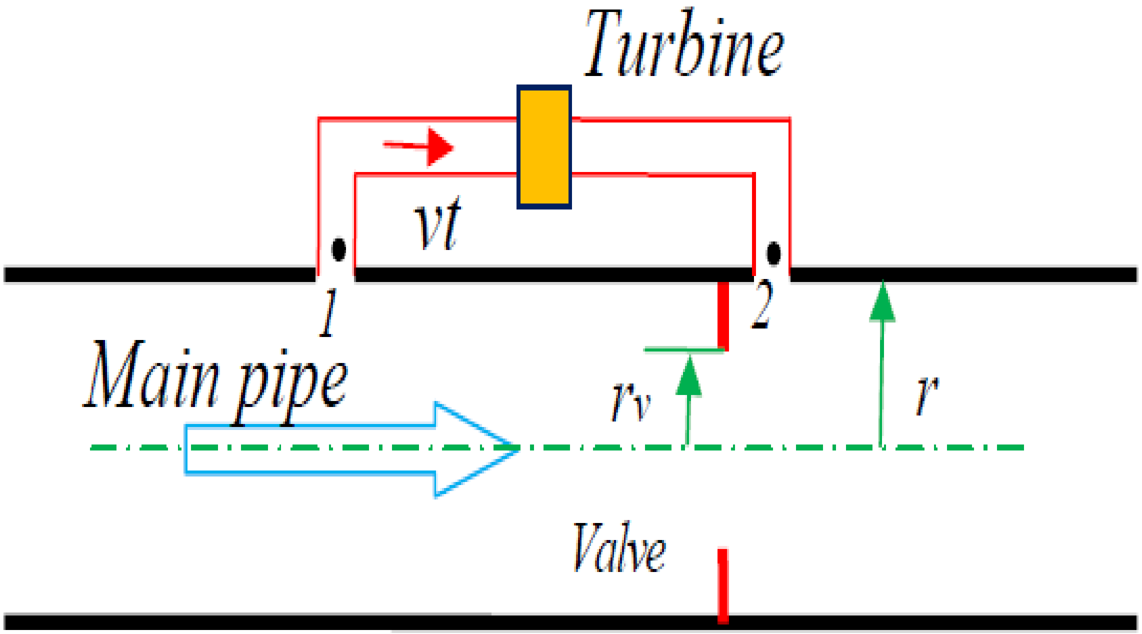

Figure II:12- Pressure drop after PRV configuration [86,88]

2.8 CONDUIT HYDROPOWER PLANNING

The key aspect for conduit hydropower development, is planning. There are several factors that need to be considered before implementation; the suitability of the system is validated by the following factors:

- The amount of power available from water flow in the pipelines. This includes water pressure, volume of water available and friction losses in the pipelines.
- The type of turbine and the available generator type and capacity.
- The type and capacity of loads to be supplied by the conduit hydropower generation system.
- The cost of developing the project and operating the system.

2.8.1 Water flowrate measurement

Flow measurement is the quantification of bulk fluid movement. Flow may be measured in a variety of ways. Positive-displacement flow meters accumulate a fixed volume of fluid and count the number of times the volume is filled to measure flow. Other flow measurement methods rely on forces produced by the flowing stream as it overcomes a known constriction, to indirectly calculate flow. Flow may be measured by measuring the velocity of fluid over a known area. For large flows, tracer methods may be used to deduce the flow rate from the change in concentration of a dye or radioisotope.

2.8.2 Generator selection

Generating system, for a hydro power scheme, is selected based on the estimated power of a hydropower system, type of supply system and electrical load: constant load or variable load, available generating capacity in the market and cost effective generator [88].

Other considerations for selection of generators are: run away speed of turbine, horizontal or vertical construction, isolated or parallel operation, availability of grid supply and, reactive power supply. Selection of the generators, based on size of scheme is presented in Table II:7.

2.8.3 Turbine selection

The selection of turbine is principal in the design and development of a hydropower system. Sharma, R.K and Sharma, T.K [16] explained that there are a few factors that need to be considered in selecting a turbine, which are based on the specific head, maximum head, head variation, load variation, efficiency of turbines for various loads, discharge availability and power house. The chart in Figure II:13 can be used as a guide to select the most suitable turbine, based on the available head pressure.

Table II:7-Selection of generators based on size of scheme [88]

Size of scheme	Up to 5 kW	Up to 10 kW	10 to 25 kW	More than 25 kW
Type of generator and Phase	Brush/Brushless Permanent magnet DC generator	Induction or Synchronous, Single or Three-phase	Induction or Synchronous, Three-phase	Synchronous, Three-phase

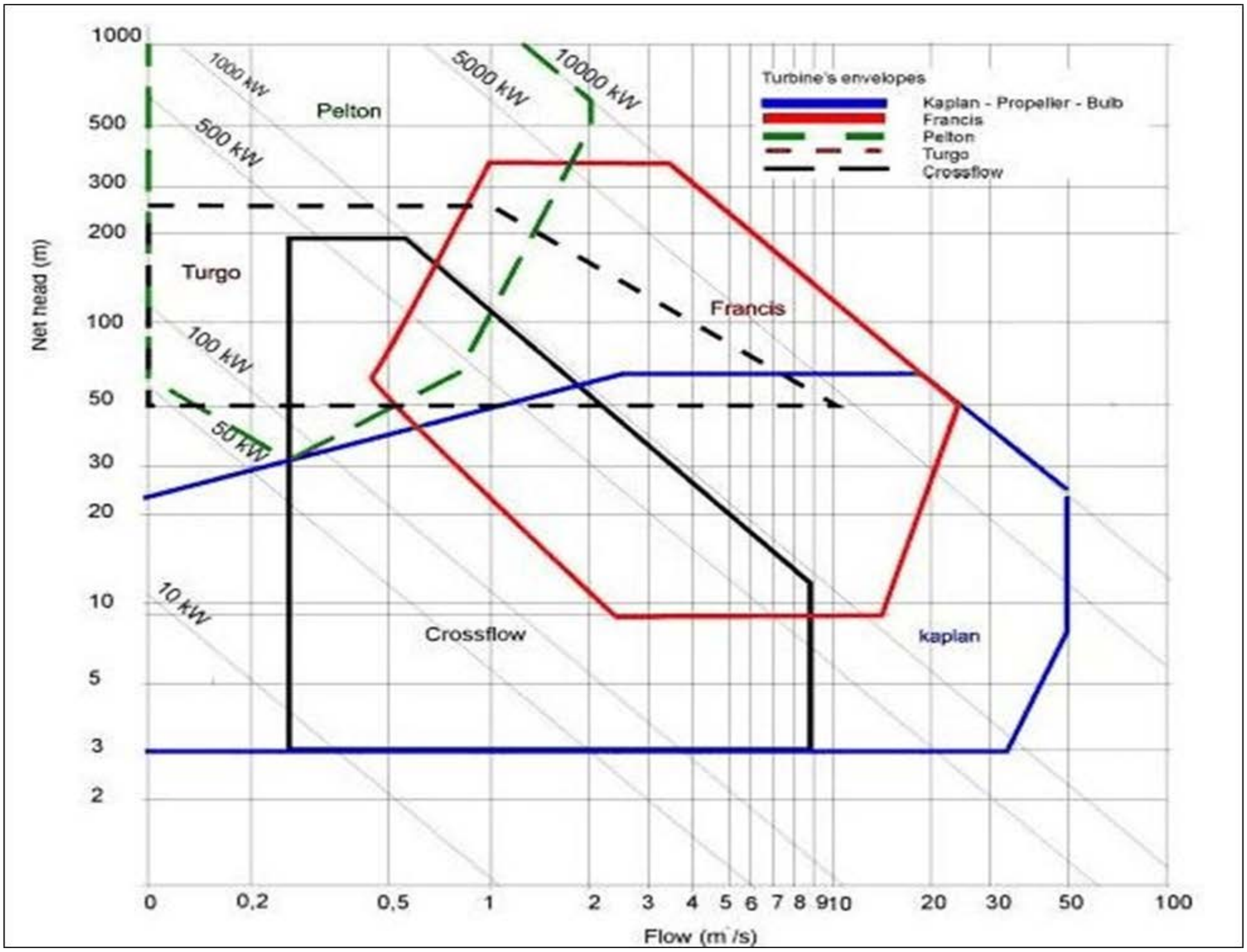

Figure II:13- Turbine selection chart [88]

The selection of turbine may further be done, with reference to the nomogram in Figure II:14. This figure illustrates the various types of turbine, based on flow rate and net head. Furthermore, the turbine is selected, based on the speed range and power capacity of the alternator to be used [88].

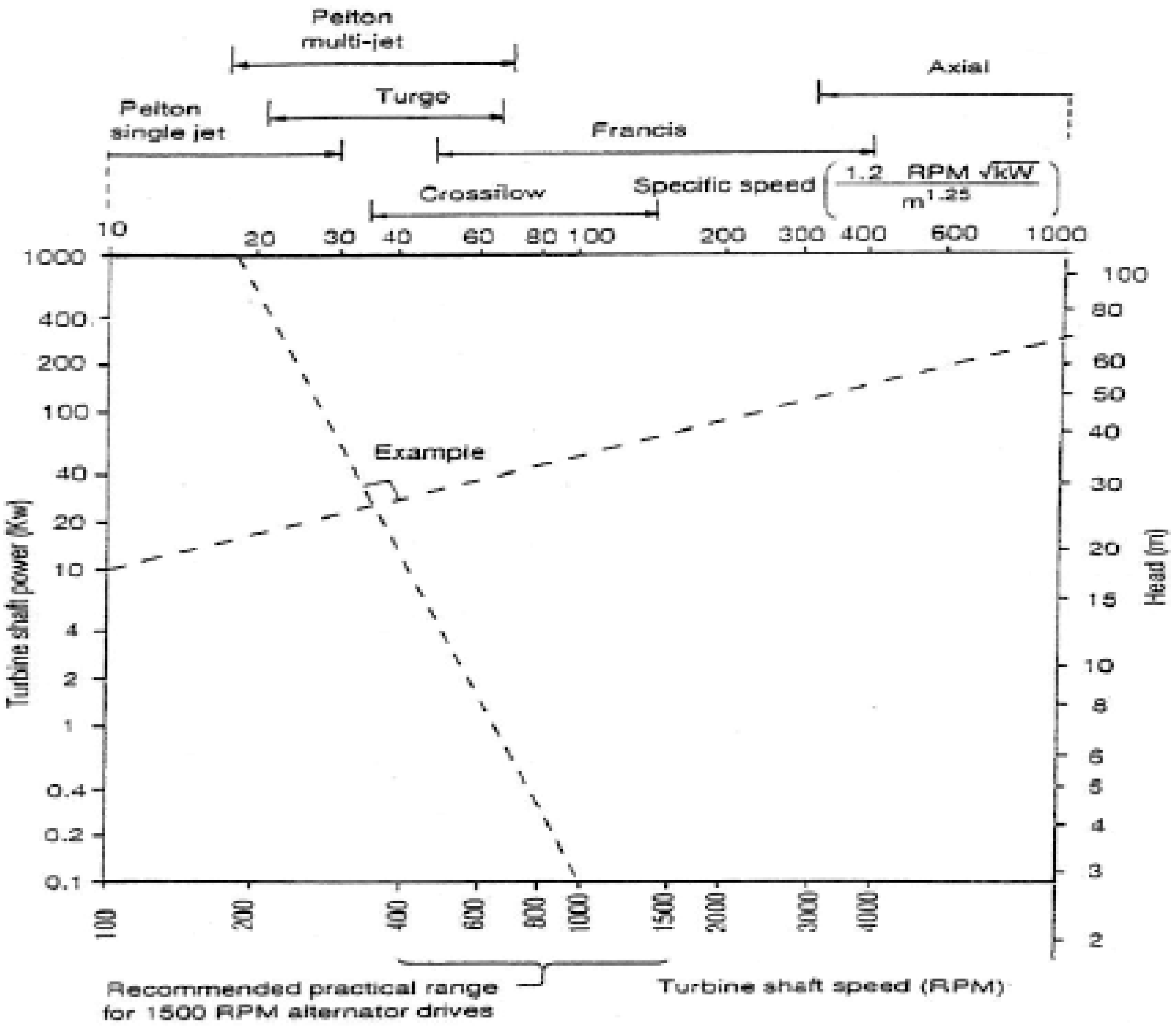

Figure II:14- Nomogram for turbine selection [88]

Besides that, a significant factor in selecting a turbine is the relative efficiencies. Figure II:15 presents the typical efficiency curves, where the efficiency percentage versus turbine flows relative to design flow. Referring to the curves, Pelton and Kaplan turbines hold considerably high efficiencies, however, the efficiency of the Crossflow and Francis turbine falls away drastically when operated below half the regular flow [87,89].

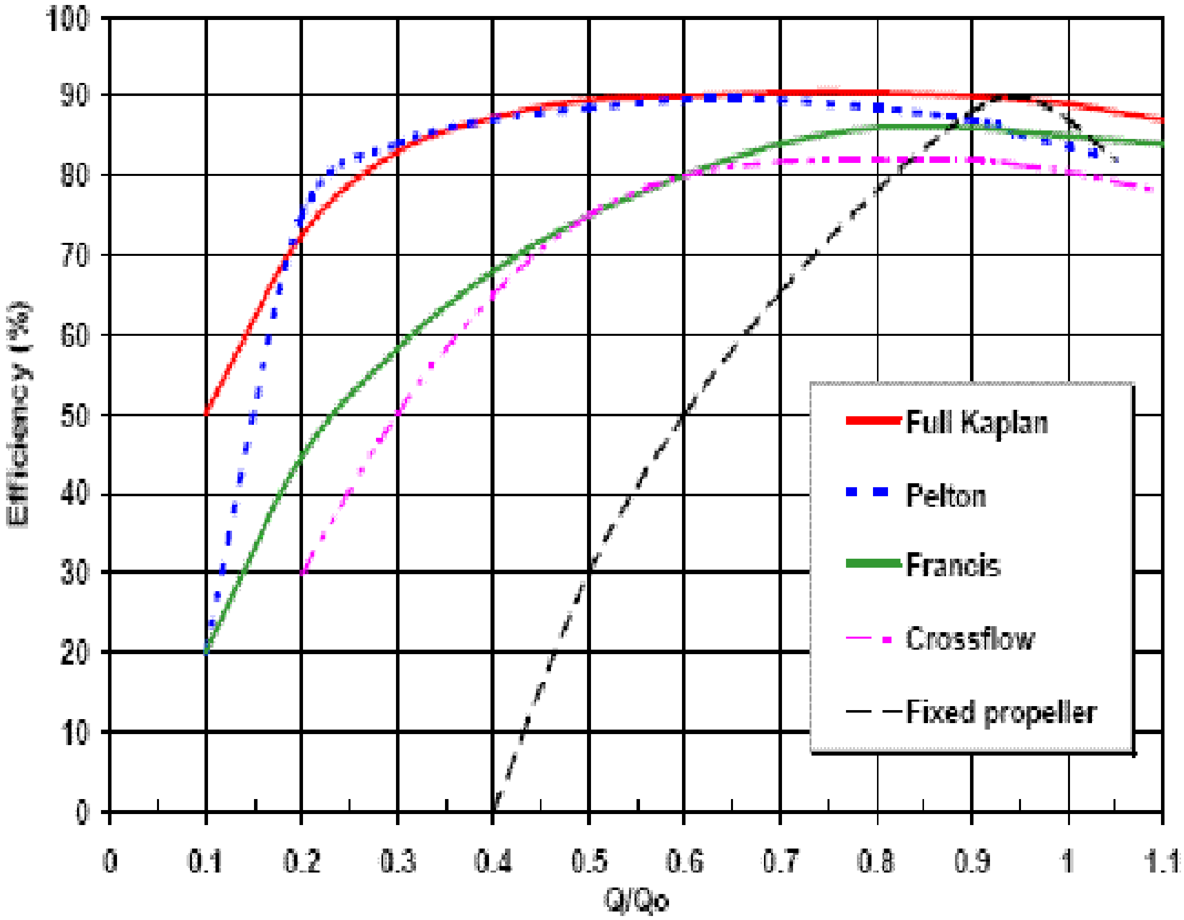

Figure II:15- Typical efficiency curves for turbine selection [89]

2.8.4 Type of loads

Electrical loads are usually connected within houses. This is a general name given to any device that utilizes electricity. The type of loads connected to a small conduit hydropower generation system, depends significantly on the amount of power generated. Utilizing the power wisely may add additional more benefits. At domestic level, particular loads are to be carefully selected, due to the amount of available energy. The type of load may include: LED lighting, smart metering, water usage indicator, rechargeable batteries and gate motors [27].

2.9 SUMMARY

An in-depth review has been presented, analysing the production levels, the economic and the environmental points of view, as well as the description and classification of the hydraulic machines used in pressurised conduits.

It should be noted: there are several components involved in the small conduit hydropower generation system. A DC generator is mostly preferred in facilitating the charging process, although there are also advantages of using the AC generator. Employing inaccurate water turbines, generator, penstock and intake system also affected the efficiency rate of the system and simultaneously wastes the water power available. As a conclusion, the understanding of working mechanisms of the small conduit hydropower generation system is essential for selecting the key component in order to obtain a highly efficient small conduit hydropower generating system.

CHAPTER III: MODEL FOR SMALL CONDUIT HYDROPOWER GENERATION SYSTEM

3.1 INTRODUCTION

This chapter presents a mathematical model for analysing the behaviour of the proposed energy recovery conduit hydropower system. The overview of a conduit hydropower generation system is presented in Section 3.2. The main components of the system to be modelled include the energy recovery turbine, drive train and a permanent magnet synchronous generator (PMSG), to be discussed in Section 3.3 to 3.5. A combined detailed model is presented in Section 3.6. The component size and simulation parameters are presented in Section 3.7, while the model simulation results are presented in Section 3.8. A summary of work presented in this chapter is discussed in Section 3.9.

3.2 OVERVIEW OF A CONDUIT HYDROPOWER GENERATION

In an effort to harness the power from high pressured water that flows through water supply systems every day, more and more countries are exploring the possibility of conduit hydropower technology. Fig. III:1 shows the general layout of the conduit hydropower system. In conduit hydropower generation, small energy recovery turbines or PAT's, are installed in water supply systems where dissipation of pressure is necessary. The pressure is commonly dissipated using pressure reducing valves (PRV's), which dissipate the energy associated with the flow across the pressure differential. The installed turbines or PAT's, aim to recover a portion of the energy and convert it into useable electricity that may be used to supply a few loads [11].

The conduit hydropower system is installed parallel to a new or existing PRV (or V2). This parallel valve becomes the turbine bypass valve. If no excess pressure is available, water will flow normally through the primary conduit via V1, V2 and V3. When excess pressure is available from the high pressure side, excess energy recovery initiates from the bypass/secondary conduit, opening TSV (or V4), to allow flow through a turbine down towards V5 and out to the low pressure side. When the turbine is down for emergency or maintenance, water may continue to be delivered to consumers, without interruption. An automatic, fail-safe valve TSV (or V4), is installed on the high pressure side of the turbine operates, as a turbine shut-off valve. This valve allows the generating equipment to be safely shut down in the event of power outages, or emergency situation. The turbine control system automatically transfers water flow from the turbine to the bypass control valve and back upon start up and shut down.

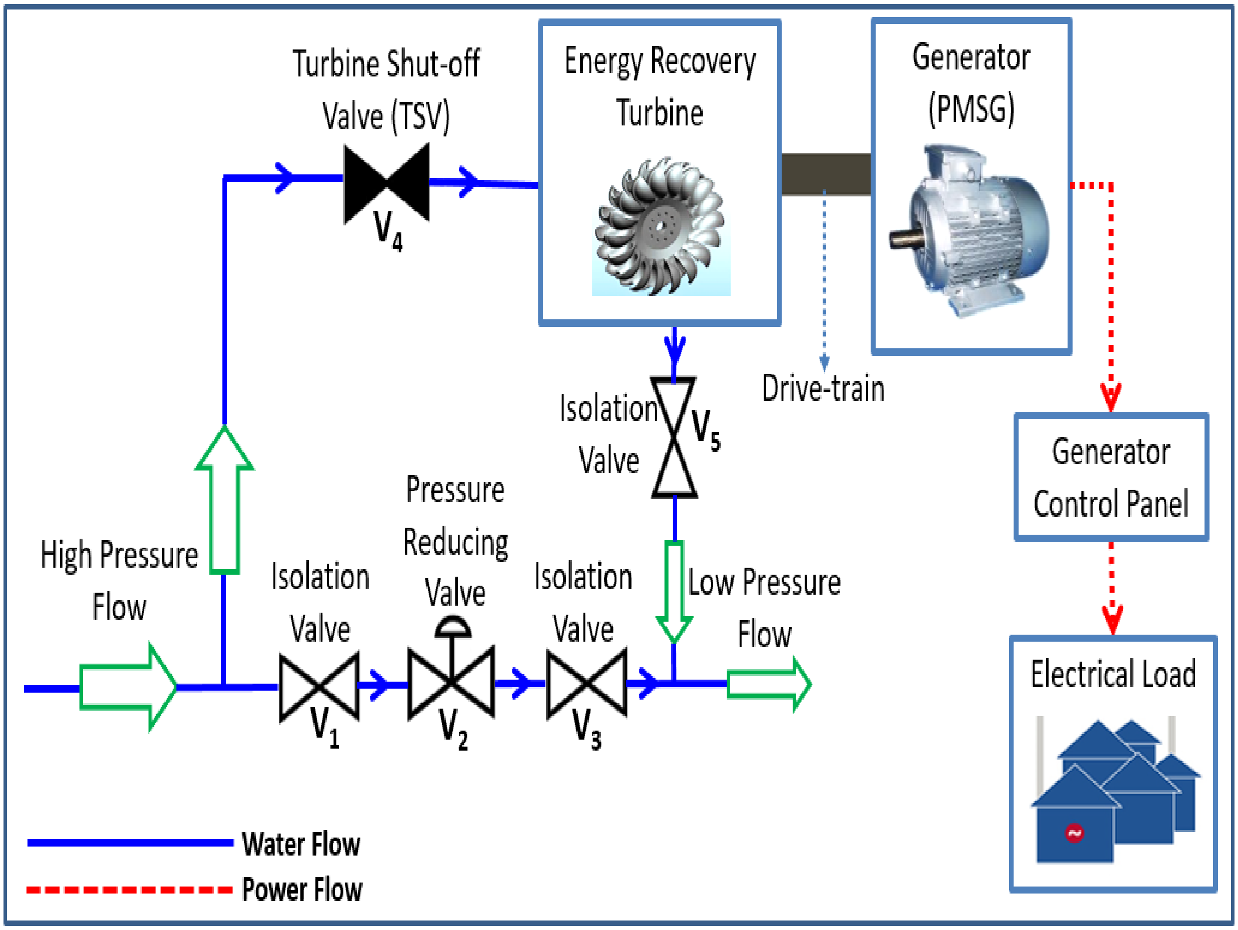

Figure III:16- Layout of a typical conduit hydropower generation system

3.3 TURBINE MODEL

Water energy is particularly direct within water supply systems. The water kinetic energy (E) is extracted, for a certain period/time (t) and using a specific turbine with efficiency η. Therefore, the mechanical power generated by the water turbine may be expressed by [5]:

$$P = \frac{E}{t} \times \eta \tag{3.1}$$

$$E = \frac{1}{2} m v_t^2 , m = \rho \pi r_t^2 t \tag{3.2}$$

Where:

m= the mass of water;

ρ= the water density;

v_t= the water velocity through the bypass pipe;

r_t= the radius of the bypass pipe.

Substituting eq. (3.2) into (3.1), the power generated by the water turbine may be expressed by [5-7]:

$$P = \frac{\rho \pi r_t^2 v_t^3}{2} \times \eta \tag{3.3}$$

The turbine is embedded directly into the bypass pipe, as presented in Figure III:2. The choice of this configuration is motivated by an idea of minimizing the disturbances in the main supply cycles.

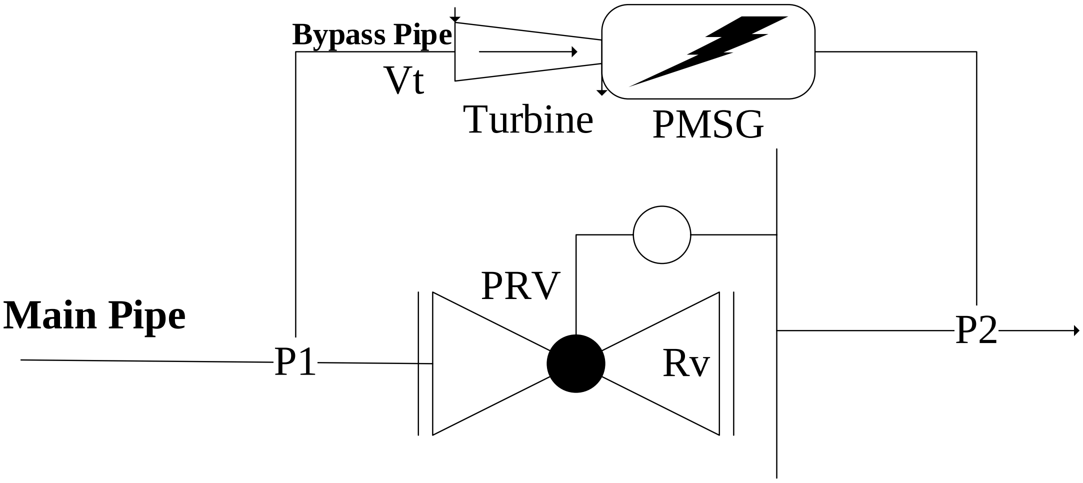

Figure III:2- Energy recovery bypass system at PRV

This system is configured in such a way that the water turbine is driven by the change in water pressure after a PRV. Two points 1 and 2 are located at the bypass inlet and outlet, respectively. The velocity at the inlet (point 1), is equal to the outlet velocity (point 2). The pressure difference is dependent on flowrate (Q) and is given by [5,7]:

$$p_1 - p_2 = \frac{Q^2 \rho}{2\pi^2 r_v^4 c^2}\left[1-\left(\frac{r_v}{r}\right)^4\right] \tag{3.4}$$

Where:

C = the constant ranging from 0.6 to 0.65;

r_v = the radius of the PRV;

r = the radius of the main pipe.

To generate the mechanical energy in eq. (3.3), water velocity should to be definite considering a turbine driven by the pressure drop at PRV. The water velocity in the bypass pipe is given by the equation (3.5) below. Considering all the losses in the bypass pipe, such as the main loss coefficient, that is caused by the friction of the straight section of the bypass pipe and secondary loss coefficient, that is caused by alternative components of the bypass pipe, such as the entrance at the inlet point 1, elbows of the bending sections, and the exit at the outlet point 2.

$$v_t = \sqrt{\frac{2(p_1 - p_2)}{\rho\left(\frac{fl}{2r_t} + \sum K_L\right)}} \tag{3.5}$$

Where:

$\frac{fl}{2r_t}$= main loss of coefficient caused by friction,

f= friction factor,

l= length of the bypass pipe,

$\sum K_L$= secondary loss coefficient of other component in the bypass pipe.

The losses caused by the turbine are neglected in eq. (3.5), as it is already considered in the efficiency of the turbine. The final model for energy recovery turbine is represented by Figure III:3 below:

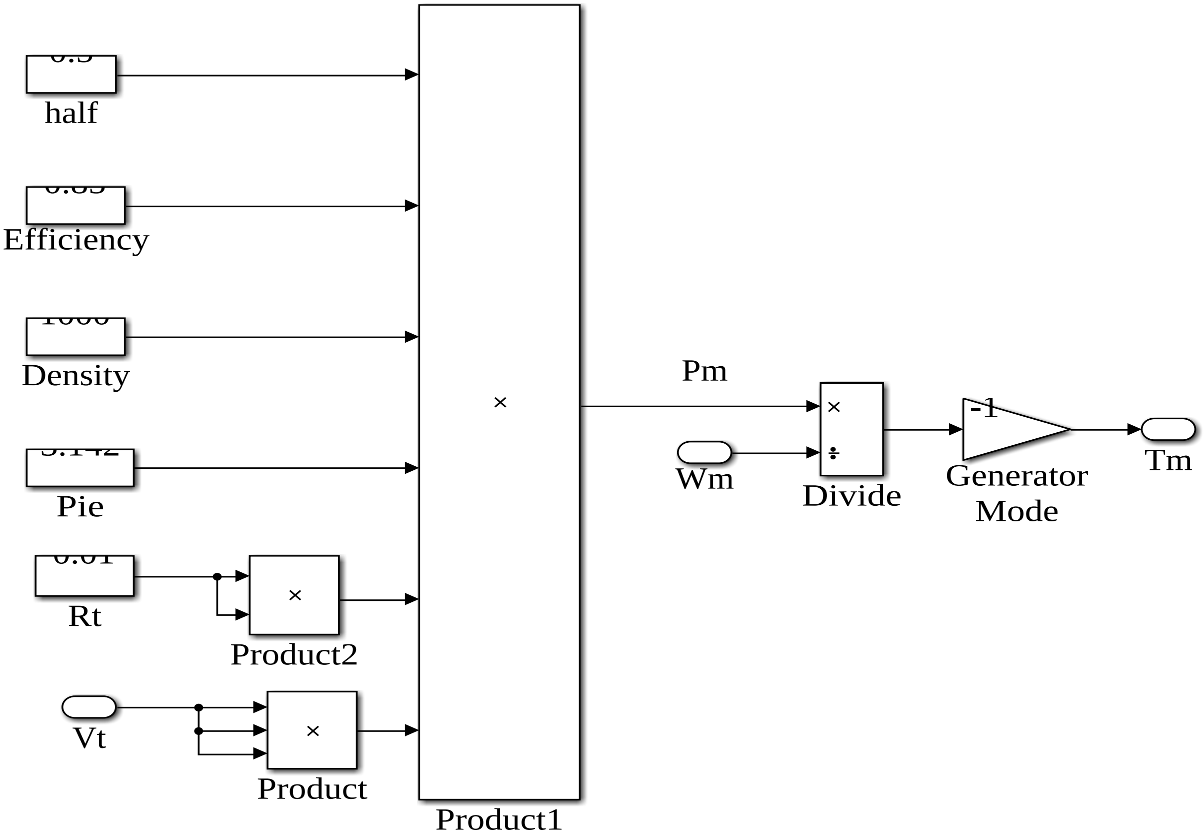

Figure III:3- Model for energy recovery turbine

3.4 DRIVE TRAIN MODEL

Drive train enables the conversion of kinetic energy of water, flowing in the energy recovery system, into useful mechanical energy. The drive train may be in the form of gears or directly driven. If gears are used in the shaft, the gearbox within the drive train connects the low speed shaft (on the water turbine side), with the high speed shaft connected (on the PMSG side). This coupling provide high rotational speed required by a generator, to produce electricity to a specific level.

Nonetheless, the use of this coupling may increase project costs, reduce the reliability and efficiency of the system, due to energy losses and regular maintenance required to maintain the system [8-9]. Hence, a direct coupling is the preferably efficient method.

The drive train may be modelled using various methods, such as one-mass, two-mass or three-mass [9]. Since the aim of this study is to recover energy from excess pressure and generate electrical output energy, the drive train was treated as one-mass.

This means that all inertia components are modelled as one rotating mass, or direct coupling. This coupling allows for mechanical torque from the water turbine $\mathrm{T}_{\mathrm{w:g}}$ to be equivalent mechanical torque of the generator T_{m}, the rotor angular speed of the turbine ω_{g}, to be equivalent to the rotor angular speed of the generator ω_{m}. The relationship is then given by the following equations respectively [9].

$$\boldsymbol{T}_{w:g} = \boldsymbol{T}_{m} \tag{3.6}$$

$$\omega_g = \omega_m \tag{3.7}$$

The mechanical torque from the turbine to the generator, may allow the generator to produce electromagnetic torque T_e. This relationship is given by [9]:

$$T_e = J_{eq} \times \frac{d\omega_g}{dt} + B_m \times \omega_g + T_{W:g} \tag{3.8}$$

Where:

B_m = damping coefficient (N.m/s);

J_{eq} = equivalent rotational inertia of a generator and turbine (kg.m^2), which is determined by eq. (3.9) below:

$$J_{eq} = J_g + J_{wt} \tag{3.9}$$

Where:

J_g = rotational inertia of the generator (kg.m^2);

J_{wt} = rotational inertia of a water turbine (kg.m^2).

The advantage of using PMSG, is that they are low inertia machines. Since J_g is negligibly small, making J_{eq} almost equivalent to J_{wt} [9]. Figure III:4 below, presents a MATLAB/Simulink block diagram, for a one-mass drive train, or a direct drive coupling, assuming the following:

The turbine inertia (5 kg.m^2) was used as J_{eq}.

Rotational damping coefficient was assumed to be equal to zero.

From eq. (3.8), the angular speed of the generator shaft ($\frac{d\omega g}{dt}$) may be expressed as indicated by eq. (3.10) below:

$$\frac{d\omega_g}{dt} = \frac{T_e - T_{w:g}}{J_{eq}} - \frac{B_m}{J_{eq}} \times \omega_g \tag{3.10}$$

Integrating both sides, the output angular acceleration of the generator may be obtained. The angular acceleration ω_g, becomes an input energy to the PMSG. This energy is converted to electrical angular speed ω_e of the generator. The relationship between the two is dependent on the number of pole pairs (p) in the PMSG.

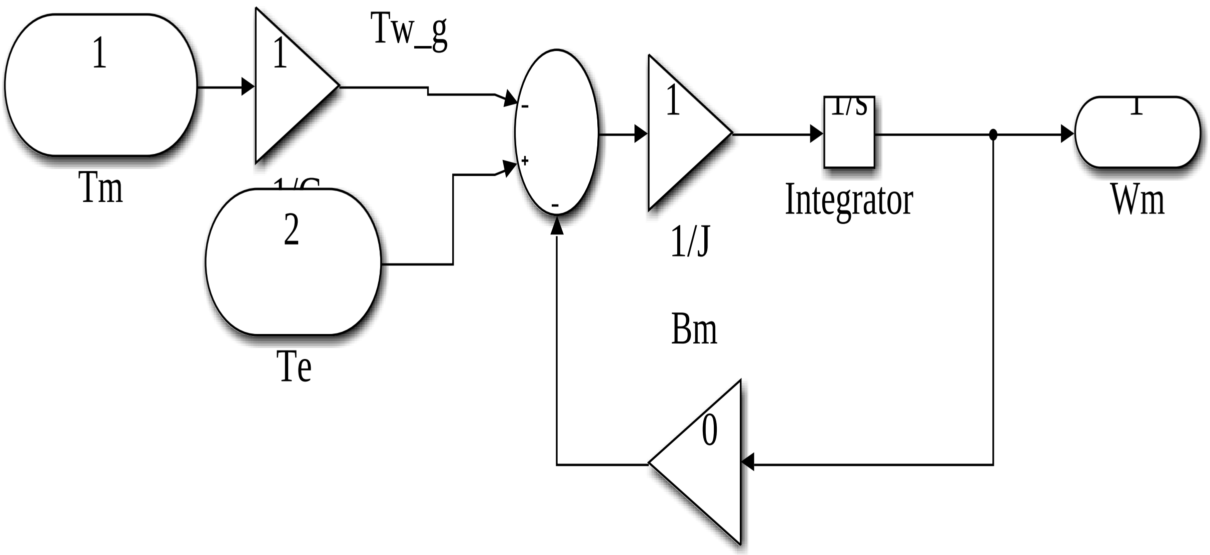

Figure III:4- Drive train

3.5 GENERATOR MODEL

The PMSG model may be developed initially, assuming a commonly accepted picture, that the rotor may be fairly represented by three windings: one being the field and the other two being the d- and q- axis "damper" windings, representing the effects of the rotor body and other current carrying paths. The damping effect is assumed to be negligible (of both the rotor and magnets), the flux distribution in the rotor is sinusoidal, unsaturated magnetic circuit, negligible iron losses and the absence of field current dynamics [9].

An appropriate transformation may be applied to the stator variable, in order to study the response of PMSG. To begin, assume that the PMSG can be appropriately represented by five equivalent windings. Three of these windings, the armature phase windings and the other two, representing the effects of distributed currents on the rotor, further known as the "damper" windings. Park Transformation is mostly used for modeling three phase machines. It transforms the parameters and equation from the stationary form, into direct-quadrature (d-q) axis [9]. It converts three-phase quantities to direct current quantities, ABC to d-q transformation. The dynamic model of PMSG is derived from a two-phase reference frame, in which the q-axis is 90° ahead of the d-axis, with respect to the direction of rotation. The relationship between the electrical angular speed and rotor angular speed of the PMSG, is represented by eq. (3.11), considering the electrical angle (θ_e) between the stator phase A axis and the d-axis [9].

$$\frac{d\theta_e}{dt} = p \times \omega_g = \omega_e \tag{3.11}$$

When the rotor position is concluded, Park's transformation may be applied to compute the direct-axis, quadrature-axis and zero sequence values, in a two rotating reference frame, for a three-phase sinewave signal. These components can be controlled, to influence the active and reactive power, respectively.

Assuming that the flow direction of the negative stator current is out of the generator positive polarity terminals, the d-q reference stator voltages can be represented by eq. (3.12 and 3.13), respectively [9]:

$$v_d = R_s i_d + L_d \frac{di_d}{dt} - \omega_e L_q i_q \tag{3.12}$$

$$v_q = R_s i_q + L_q \frac{di_q}{dt} - \omega_e \psi_{pm} + \omega_e L_d i_d \tag{3.13}$$

Where:

v_d and v_q = the stator terminal voltages in the d-q axis reference frame (V);

R_S = the stator resistance (Ω);

L_d and L_q = the d, q axis reference frame inductances (H);

i_d and i_q = the d, q axis reference frame stator currents (A).

Equations (3.12) and (3.13) can be simplified, to obtain the output d and q currents of the generator, as represented below by eq. (3.14) and (3.15):

$$i_d = \int \left(\frac{v_d}{L_d} - \frac{R_s}{L_d} i_d + \frac{L_q}{L_d} \omega_e i_q \right) dt \tag{3.14}$$

$$i_q = \int \left(\frac{v_q}{L_q} - \frac{R_s}{L_q} i_q + \frac{L_d}{L_q} \omega_e i_d - \frac{\psi_{pm}}{L_q} \omega_e \right) dt \tag{3.15}$$

In the rotor frame, the developed electromagnetic torque is dependent on the cross-product of stator flux and stator current. The expression is given by eq. (3.16) below:

$$T_e = \frac{3}{2} \left(\psi_{pm} i_q + \left(L_d - L_q \right) i_d i_q \right) \tag{3.16}$$

The conversion for three-phase voltage variables (Vabc) into DC voltage variables (Vd-q), is represented by eq. (3.17), ignoring the zero phase sequence, in order to simplify the transformation [9-11]:

$$\begin{pmatrix} v_d \\ v_q \end{pmatrix} = \frac{2}{3} \begin{pmatrix} \cos\theta_e & \cos\left(\theta_e - \frac{2\pi}{3}\right) & \cos\left(\theta_e + \frac{2\pi}{3}\right) \\ \sin\theta_e & \sin\left(\theta_e - \frac{2\pi}{3}\right) & \sin\left(\theta_e + \frac{2\pi}{3}\right) \end{pmatrix} \begin{pmatrix} V_a \\ V_b \\ V_c \end{pmatrix} \tag{3.17}$$

The transformation for the corresponding Three-phase currents is obtained through reverse transformation of the DC currents ($I_{d\text{-}q}$), ignoring the zero phase sequence current (I_0). The three-phase currents are represented by eq. (3.8) below:

$$\begin{pmatrix} i_a \\ i_b \\ i_c \end{pmatrix} = \frac{2}{3} \begin{pmatrix} \cos\theta_e \sin\theta_e \\ \cos\left(\theta_e - \frac{2\pi}{3}\right) \sin\left(\theta_e - \frac{2\pi}{3}\right) \\ \cos\left(\theta_e + \frac{2\pi}{3}\right) \sin\left(\theta_e + \frac{2\pi}{3}\right) \end{pmatrix} \begin{pmatrix} i_d \\ i_q \end{pmatrix} \tag{3.18}$$

The final model of a PMSG is represented by Figure III:5 below:

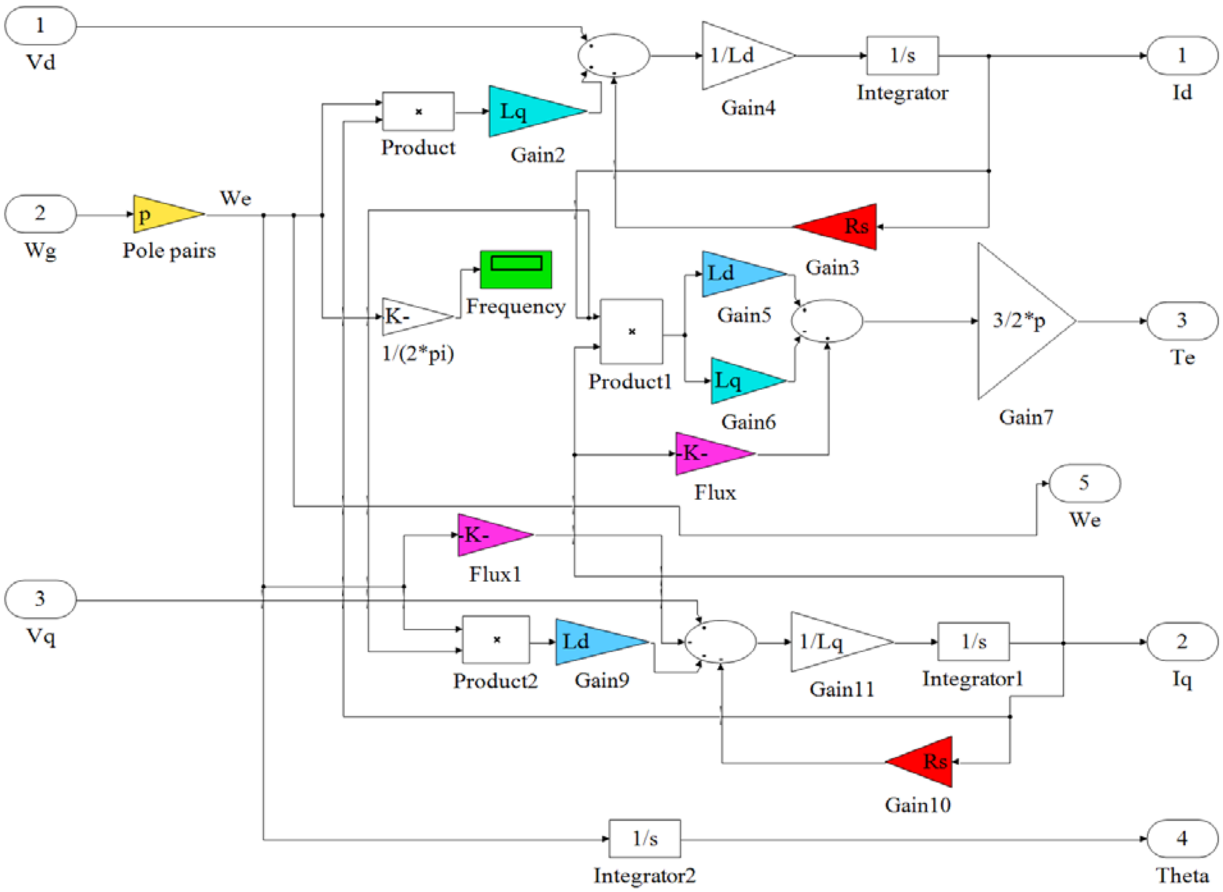

Figure III:5- Final PMSG model

3.6 COMPLETE CONDUIT HYDROPOWER GENERATION SYSTEM

The final energy recovery system is represented by Figure III-6 below. This block consists of various components of the system, connected together.

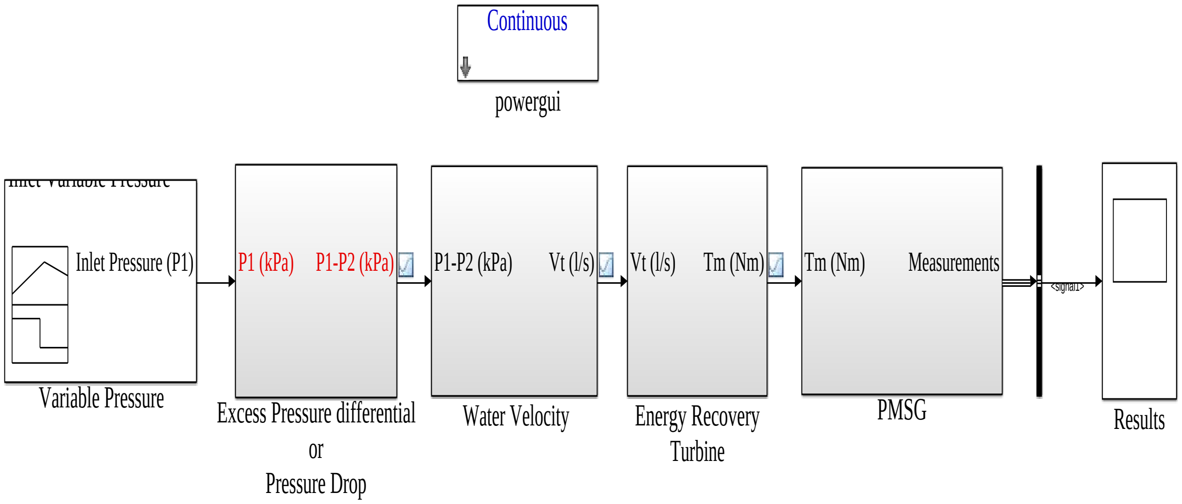

Figure III:6- Final Conduit hydropower generation model

3.7 COMPONENT SIZE AND SIMULATION PARAMETERS

The size and parameters used in the simulation are described. Three major components of the Conduit Hydropower Generation system are listed in Table IV:1.

Table IV:1- Simulation parameters

COMPONENT	PARAMETERS	
Conduit Bypass pipe	Friction coefficient	0.02
	Length	1 m
	Radius	4.8 cm
	Entrance losses	0.35
	Elbow losses	1.7
	Exit losses	1
Turbine	Efficiency	85%
PMSG (Salient pole)	Ld	0.02547
	Lq	0.02816
	Rs	2 ohms

	Pole pairs	3
Load	Nominal Power	1 kW
	Frequency	50 Hz

3.8 MODEL SIMULATION RESULTS

To study the dynamic response of the conduit hydropower generation system under variable pressure, the step input that represents excess pressure has been used strictly for simulation purposes. The performance results are shown in Figure III:7 to III:11. The system pressure was 340 kPa for the first 2 seconds, whilst the excess pressure was 40 kPa. The system water reached a minimum of 150 kPa after 2 seconds and reached a maximum of 430 kPa after 4 seconds. The available excess pressure followed the same graphical trend, given by the system pressure. After 2 seconds the excess pressure was at minimum zero Pa and then reached a maximum of 119 kPa after 4 seconds, as shown in Figure III:7.

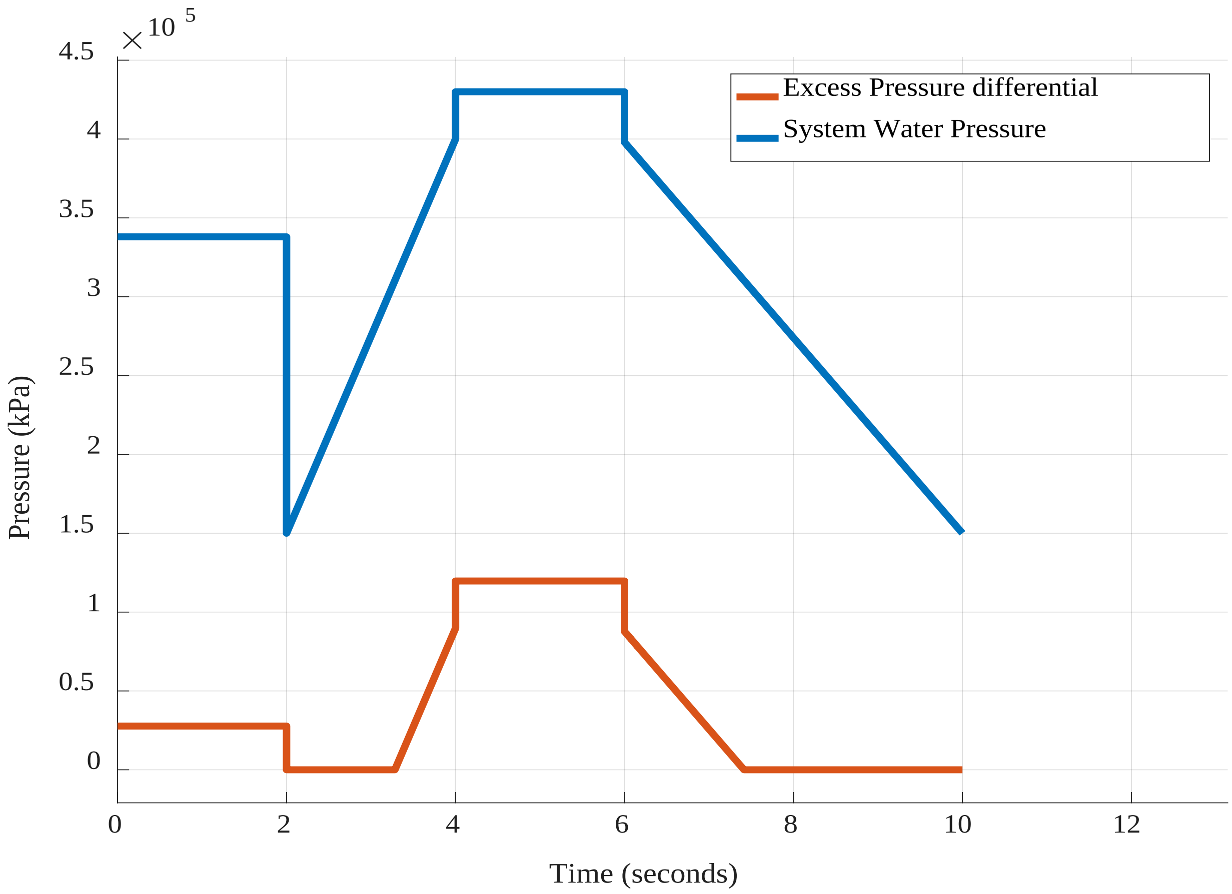

Figure III:7- System Water Pressure Vs Excess Pressure

The water velocity is directly proportional to the available excess pressure in the system. After 2 seconds, the water velocity was zero and then reached maximum of 8,573 l/s after 4 seconds, as shown in Figure III:8.

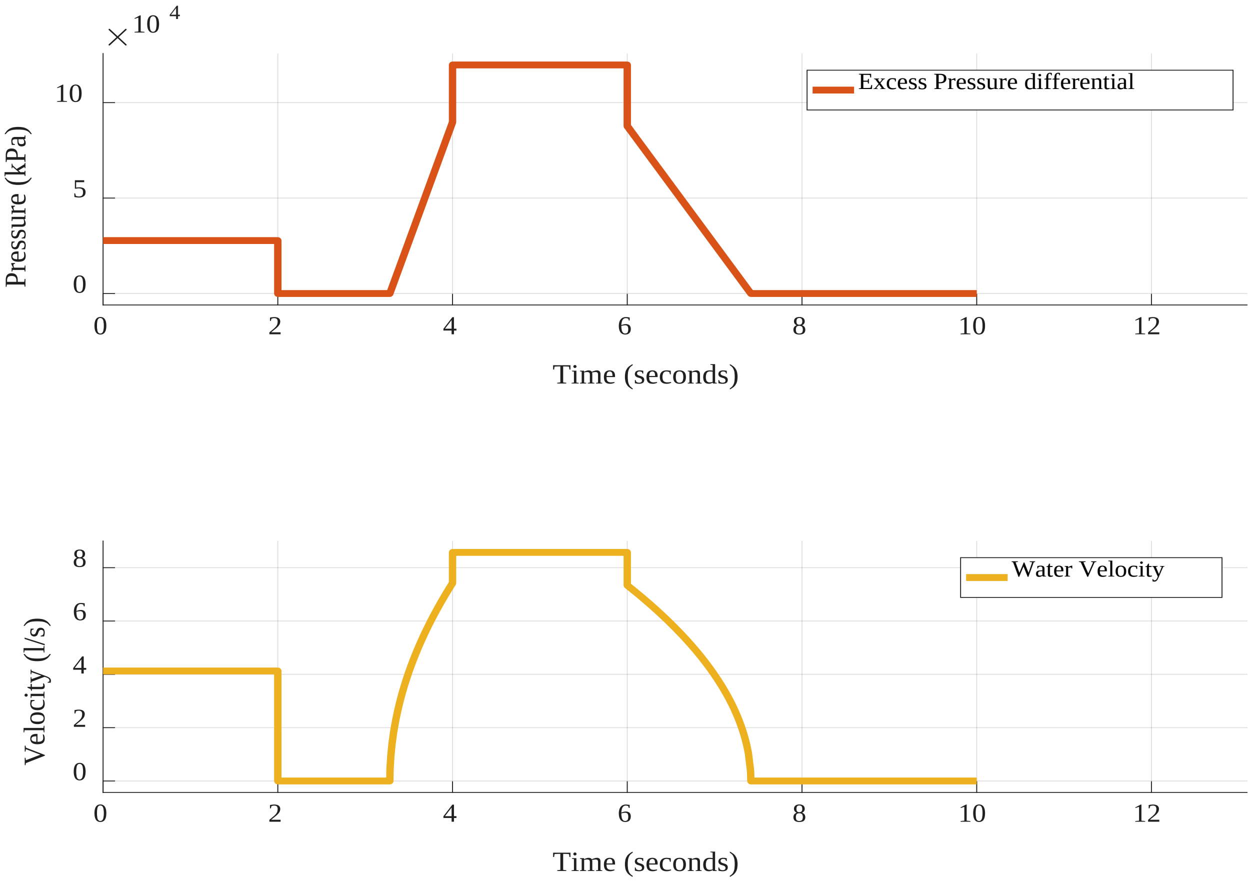

Figure III:8- Excess Pressure Vs Water Velocity

The mechanical torque of the energy recovery system is inversely proportional to the available excess pressure. As excess pressure reached its minimum, the mechanical torque was at maximum -0.00 N.m after 2 seconds, as the excess pressure reached its maximum, the mechanical torque was at a maximum of -0.3139 N.m, as shown in Figure III:9.

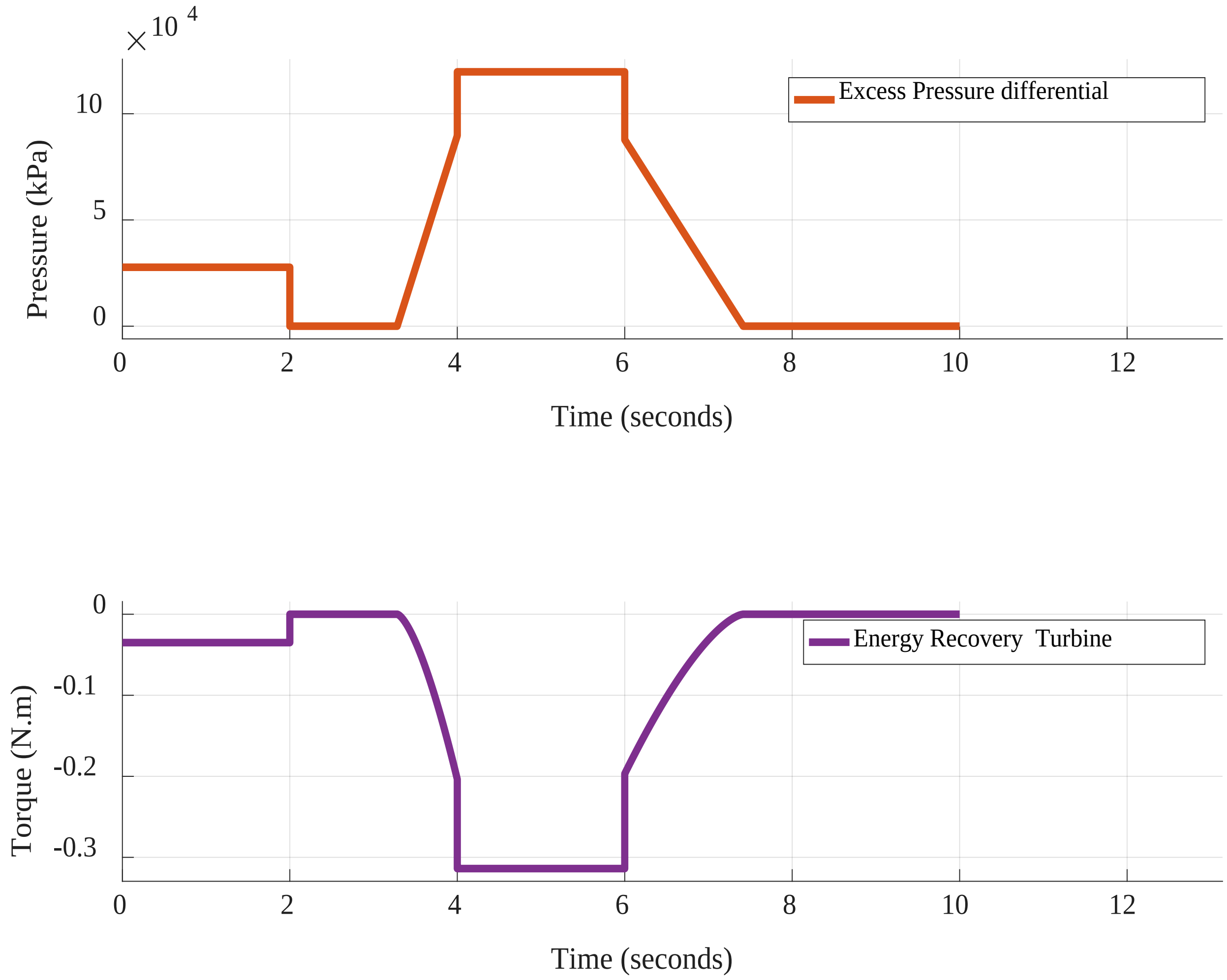

Figure III:9- Excess Pressure Vs Mechanical Torque

The generated three phase voltages and currents are dependent on the available pressure; the relationship is directly proportional. The PMSG solely generated voltages and currents, with respect to the available excess pressure in the system. The system's voltages and currents were an at minimum after 2 seconds and maximum after 4 seconds, as shown in Figure III:10.

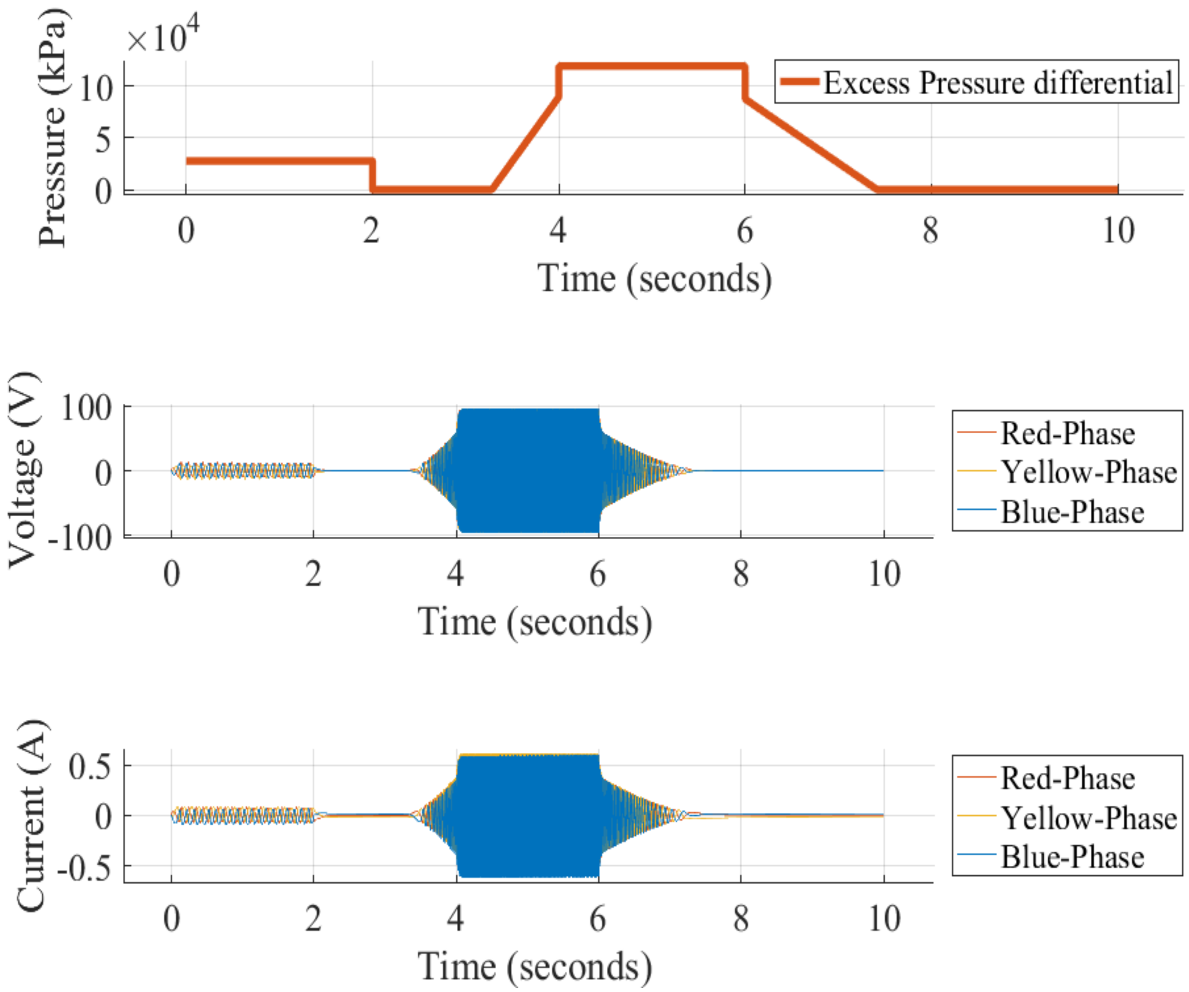

Figure III:10- Voltage and Current Relative to Excess Pressure

The electromagnetic torque of the PMSG is directly proportional to the mechanical torque of the turbine, shown in Figure III:11.

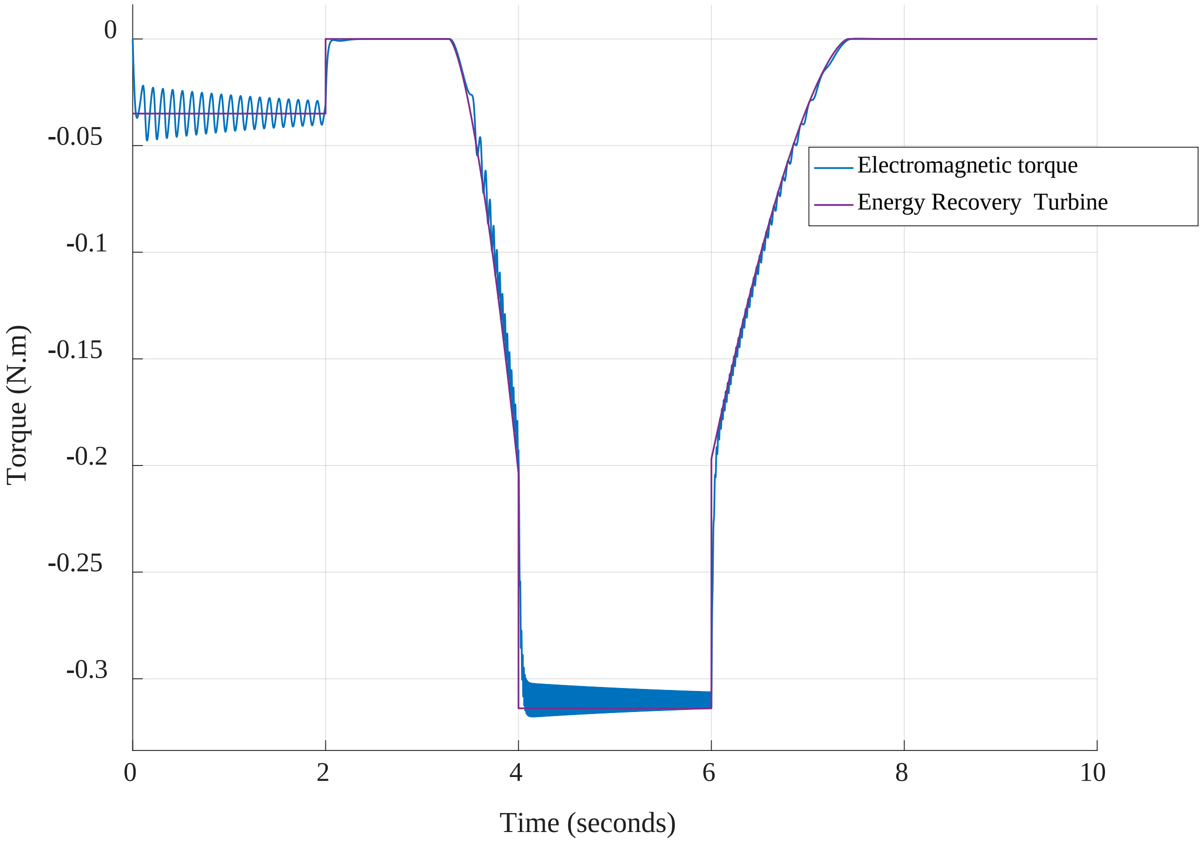

Figure III:11- Electromagnetic Torque Vs Mechanical Torque

3.9 SUMMARY

To develop a small conduit hydropower generation system, three models should be considered. This is essential for quantifying the amount of mechanical power available.

From the simulation results obtained, it is evident that the model performance is in line with the objectives of this research. Further verification, using experimental prototype results is required.

CHAPTER IV: EXPERIMENTAL RESULTS AND DISCUSSION

4.1 INTRODUCTION

This chapter demonstrates the prototype results based on the energy recovery model developed in Chapter III, using MATLAB/Simulink software. For experimental analysis, a Brushless Permanent Magnet DC Generator (BPMDCG), was used. This generator was chosen, due to price and availability. The BPMDCG is basically a synchronous machine, which makes it suitable for model verification. The objective is to experiment or interpret the correctness and success of the developed model. This is done by studying the dynamic behaviour of a conduit hydropower generation system, under variable water pressure.

The performance of the modelled conduit hydropower system is further compared to the performance of a laboratory prototype. From the results, evaluation of the system will form the basis for conclusions in Chapter V. Inlet water pressure was measured observe how the system responds to a change in water pressure. This data was used to simulate the performance of the model in MATLAB/Simulink, in comparison to the laboratory prototype.

4.2 PROTOTYPE DESCRIPTION

The conduit hydropower generation system is designed to generate electric energy from a circulating water flow and a pressure differential. The electrical energy is generated using a Brushless Permanent Magnet DC Generator (BPMDCG). The generated energy is stored in a battery, to which various loads may be connected and the energy consumption should constantly be lower than the energy produced by the system.

The system has an aligned input and output hydraulic design and a defined flow direction. The hydraulic body and electric generator form a single compact body without the need for a mechanical close. The electrical and hydraulic parameters of the system are shown in Tables IV:1 and IV:2, respectively. The electrical installation guideline is given in Appendix A. The system adopted the assembly layout from Figure II:12 in Chapter II, to form a complete installation of the conduit hydropower generation system, as shown in Figure IV:1.

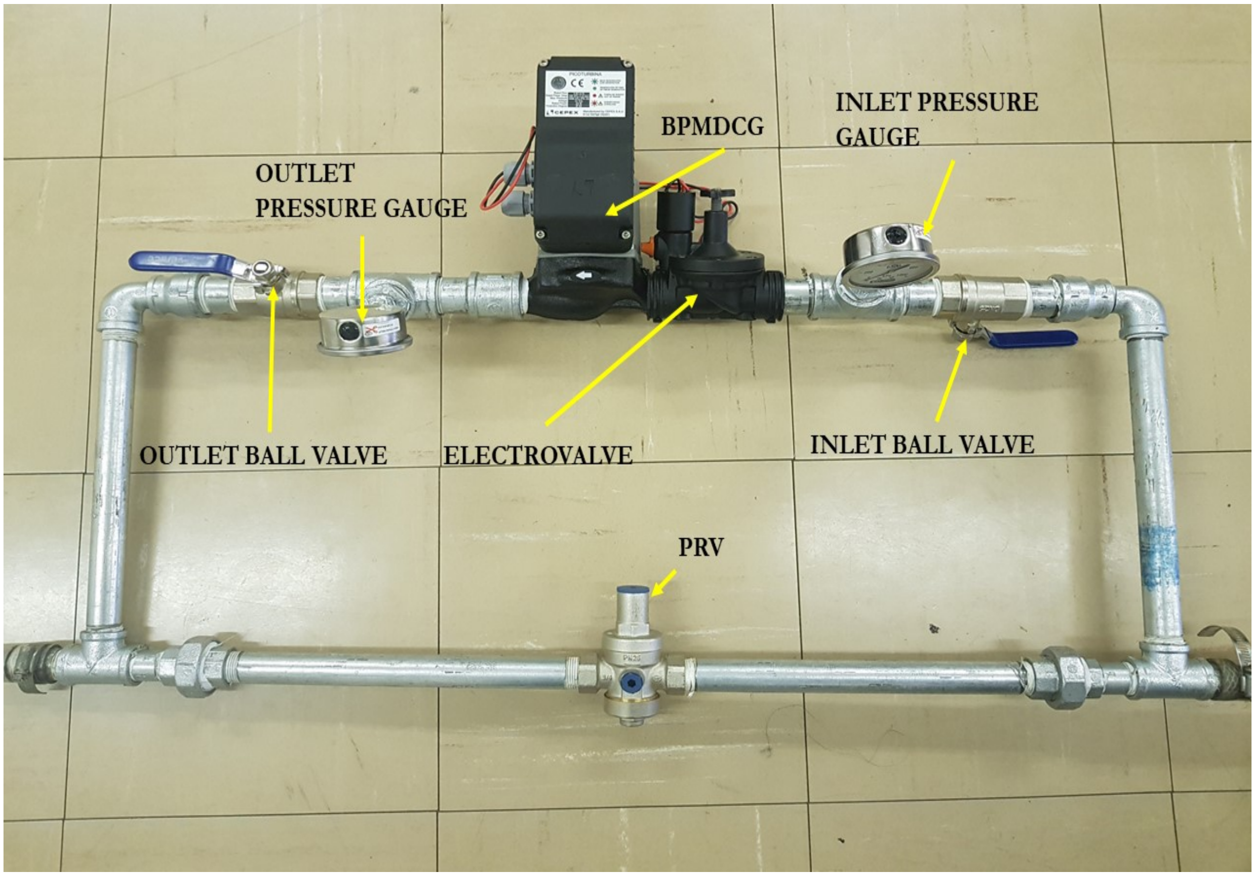

Figure IV:1- Prototype for Conduit Hydropower Generation System

Table IV:1- Electrical parameters

ELECTRICAL PARAMETERS	
Rated output voltage	12 Vdc
Maximum output current	2.2 A
Rated output power	25 W
Type of batteries allowed	Sealed lead-acid according to EN60896-11:2003
Battery capacity	[9-45] Ah

Table IV:2- Hydraulic parameters

HYDRAULIC PARAMETERS	
Maximum pressure at the entrance P1_max	10 bar
ΔMinimum entry-exit operating pressure	0.45 bar
ΔMaximum entry-exit working pressure	1.8 bar
ΔAbsolute maximum input-output pressure ΔPmax	2.0 bar
Minimum operating flow	0.5 L/s
Maximum working flow	0.95 L/s
Absolute maximum flow Qmax	1.0 L/s

4.3 PROTOTYPE RESULTS

For experimental characterisation, the BPMDCG was connected to a domestic water pipe line (3 bar static pressure). In this set-up the flow rate may vary between 0.69 l/s and 3 l/s. The voltage and current output was measured over a 1-ohm load resistor. A rechargeable 12 V battery was connected to the generator, as per the manufacturer's manual. The generator may not operate without the battery being connected. During voltage and current measurements, the initial circuit start-up voltage was considered, for accuracy of the results. The difference in the measured and the start-up voltage is equal to the actual voltage generated; the pressure drop over the energy recovery system was further calculated. The input data for both the prototype and MATLAB/Simulink models is pressure in the inlet; the conduit hydropower generation is expected to utilise the differential/pressure drop after PRV. The measured data is summarized in Table IV:3; this data was used to plot graphic representation of the prototype results, as compared with the MATLAB/Simulink model.

Table IV:3- Experimental results

Water Flow (l/s)	Inlet Pressure (kPa)	Outlet Pressures (kPa)	Pressure Drop (kPa)	Output Voltage	Charging Current (A)
0,69	40	0	40	0	0,1
0,89	50	5	45	0	0,1
1,089	110	6	104	0.06	0,2
1,277	150	25	125	0.83	0,9
1,5	200	35	165	1.94	1,2
1,7	260	40	220	1.94	1,2
1,93	340	40	300	1.94	1,23
2,2	440	43	397	1.94	1,23

From Table IV:3 above, the inlet pressure data was imported to MATLAB, for computing a graphical data plot, as shown below in Figure IV:2. This data was also used as input to the conduit hydropower generation model.

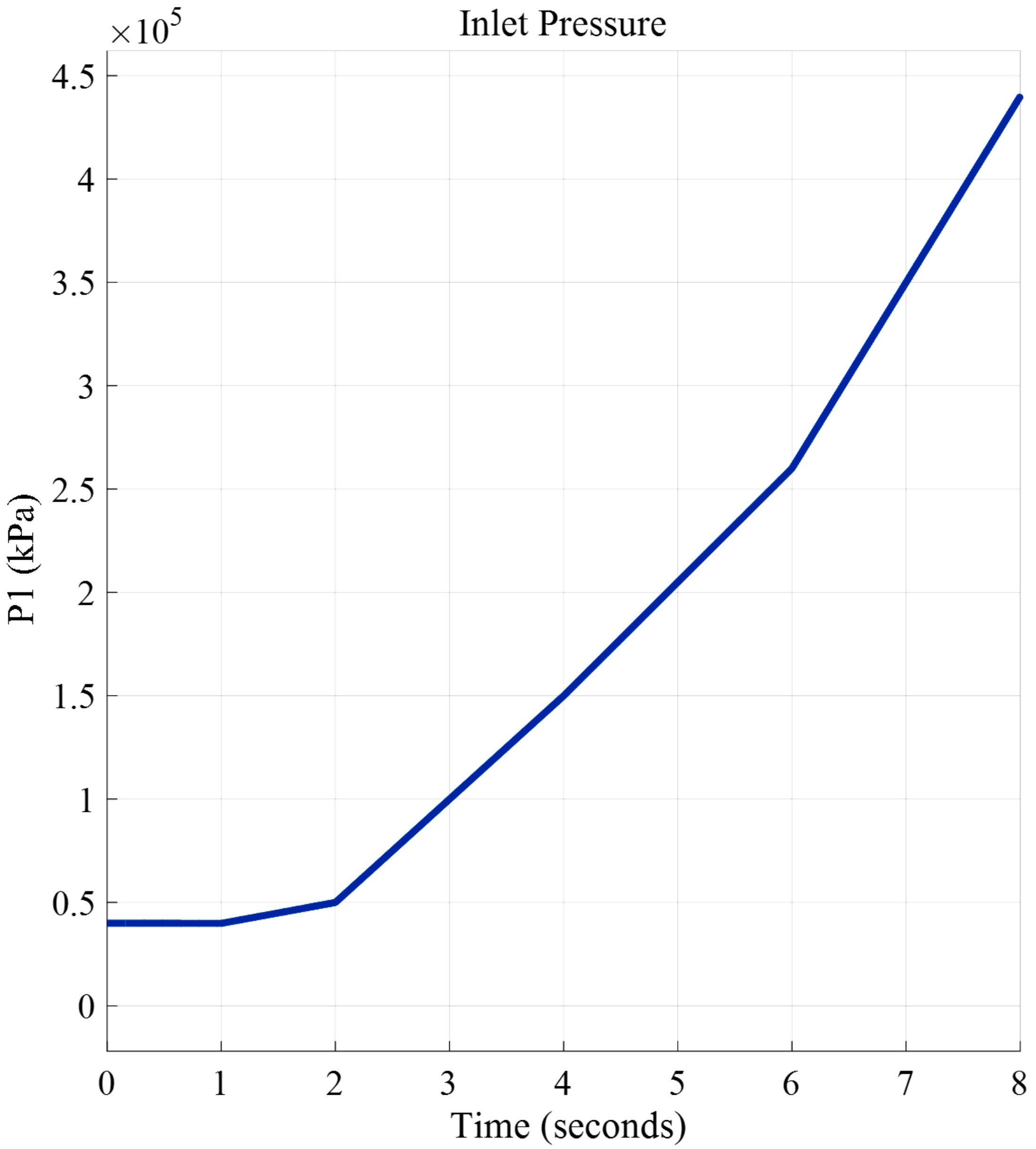

Figure IV:2- Inlet Pressure data

The inlet pressure varied from 40 kPa to 440 kPa, as indicated in Figure IV:28. This is regular as there is a variable water demand in the municipal water supply systems. Pressure fluctuates relative to the varying water demand; less demand leads to increased pressure and more demand leads to less pressure in the system.

Pressure fluctuations open a door to possible excess pressure recovery, as indicated by Figure IV:3 below:

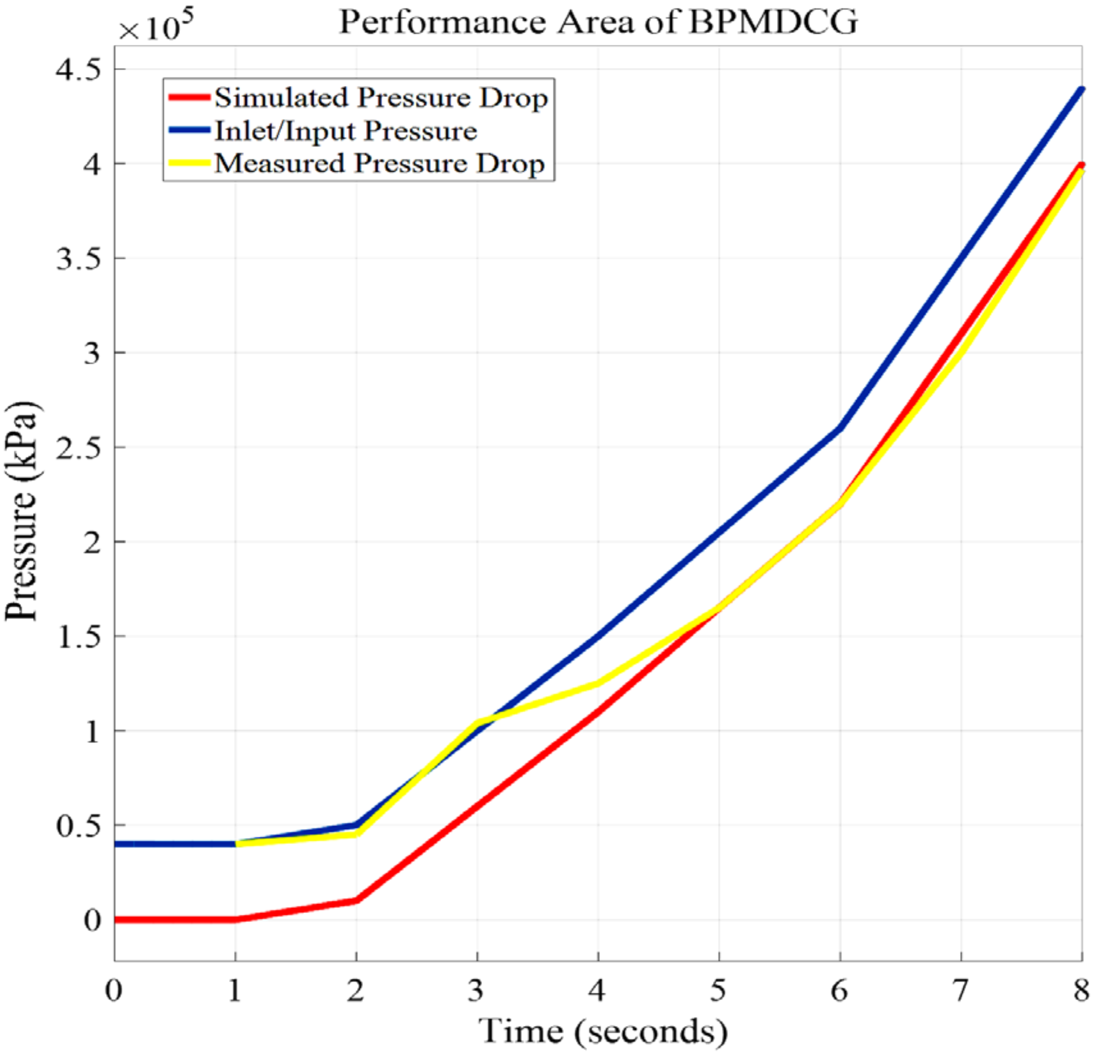

Figure IV:3- Performance area of BPMDCG

In this figure, inlet pressure forms basis for comparison of the measured pressure drop, versus the simulated pressure drop. The comparison is done in order to analyse the performance or operating area of the conduit hydropower generation system. In the first 5 seconds, there is a significant variation between the measured and the simulated pressure drop. The simulation model has a greater operating area than that of the prototype. After 5 seconds, both graphs revealed approximately identical pressure drops. This implies that both systems utilised/extracted approximately identical pressure, needed for conduit hydropower generation.

The generated voltages of the measured and the simulated data are shown in the Figure IV:4 below:

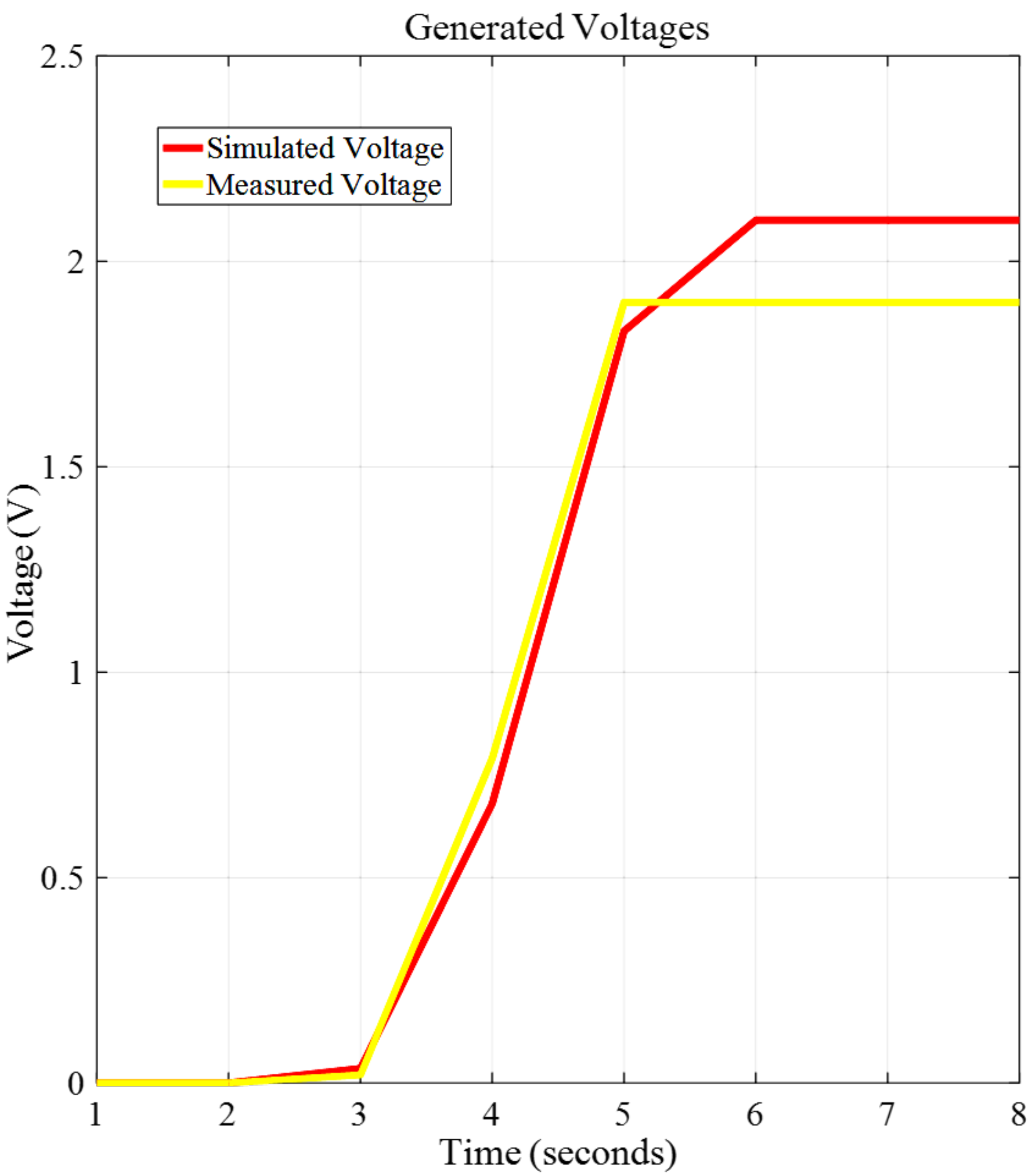

Figure IV:4- Generated Voltages

The measured voltage is less than the simulated voltage. This is due to the operating area of the actual prototype being smaller than the area of the simulated model. The prototype is allowed to reach saturation at around 1.94 V, in order to protect the generator from damage, whilst charging the battery. The saturation voltage is equal to the difference between the initial start-up voltage and the maximum output voltage of the BPMDCG. For the same reason, one may expect the same relationship between the currents. Figure IV:5 below presents charging currents of the battery:

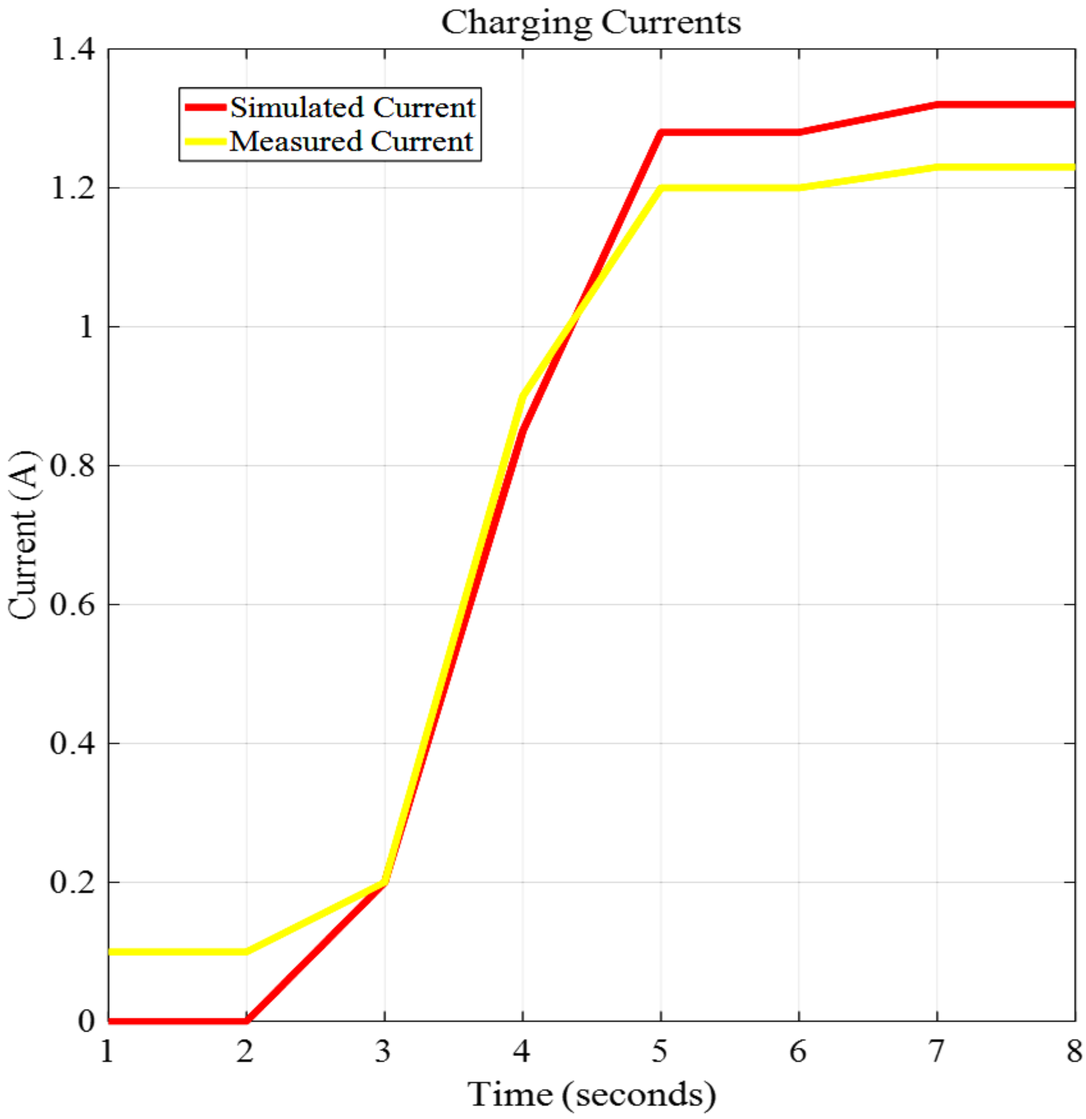

Figure IV:5- Charging Currents

The relationship is approximately identical to that of the voltages; the difference is that the measured current is slightly less.

4.4 SUMMARY

The BPMDCG responded effectively under variable pressure. The system was solely active whilst the excess pressure was available. This is due to the pressure difference between PRV pre-set pressure and the system pressure. When the system pressure was greater than the pressure setting at PRV, the energy recovery turbine utilized the pressure difference to drive the BPMDCG. Various output voltages and currents were obtained; the generator did not operate when the Pressure drop was zero. The mechanical energy required to be supplied to the generator, to satisfy the principal operation of electricity generation.

The developed model may be used by conduit hydropower developers, to study the system performance under variable pressures. The performance may be studied using any generator, including BPMDCG, although improvements for the model are still required. Since there is relativeness between the increase in excess pressure and the generated outputs, it is important to limit the energy recovered by the turbine, in order to preserve the generator's life span.

CHAPTER V: CONCLUSION

5.1 FINAL CONCLUSIONS

This chapter provides conclusions of the conducted research. This research is conducted to show how potential energy from domestic water supply systems can be used as an alternative renewable energy source. A Pico scale prototype was developed and implemented into the domestic water supply system. This prototype was tested and the results were recorded. The experimental results were analysed to verify correlation between simulation and the actual energy recovery system.

Utilization of conduit hydropower in water supply systems is a proven alternative electricity source. The potential for further expansion is large, although a few improvements of the turbine and generator may yield better results. There is a need for a more accurate simulation tool that may be utilized to quantify the available potential energy. Research and prototype testing is essential.

To reveal research gabs in the subject, a deeper review has been presented in Chapter II, analysing the production levels, the economic and the environmental points of view, as well as the description and classification of the hydraulic machines used in pressurised conduits. It should be noted that there are many components involved in the small conduit hydropower generation system. Understanding the working mechanisms of the small conduit hydropower generation system is essential for selecting the key component, in order to obtain a high efficient small conduit hydropower generation system.

To develop a small conduit hydropower generation system, three models were considered, as presented in Chapter III. The models include: Turbine, Drivetrain and PMSG generator.

The developed mathematical model was analysed and evaluated in comparison with the measured results of the laboratory prototype. The results are presented in Chapter IV; the comparison of the results revealed significant relations. The developed model responded effectively under variable pressure. The system was solely active when the excess pressure was available. This is due to the pressure difference between PRV pre-set pressure and the inlet pressure. When the inlet pressure was greater than the pressure setting at PRV, the energy recovery turbine utilized the pressure drop to drive the PMSG. Various output voltages and currents were obtained; the generator did not operate when the Pressure drop was zero. The mechanical energy needed to be supplied to the generator, to satisfy the principal operation of electricity generation.

The developed model may be used by conduit hydropower developers to study the system performance under variable pressure. The performance may be studied using any PMSG. Since there is relativity between the increase in excess pressure and the generated outputs of the PMSG, it iscrucial to limit the energy recovered by the turbine, in order to preserve the generator’s life span.

5.2 SUGGESTIONS FOR FURTHER RESEARCH

The study revealed undertaking research in the following subject matter is of importance:

- Evaluation of various turbine and generator technologies, to validate the model as a universal conduit hydropower model.
- Application of various configurations of the pipeline system and incorporating it into the simulation model.
- A thorough analysis of the physical losses in the pipeline, in order to accurately match the measured and simulated outputs.

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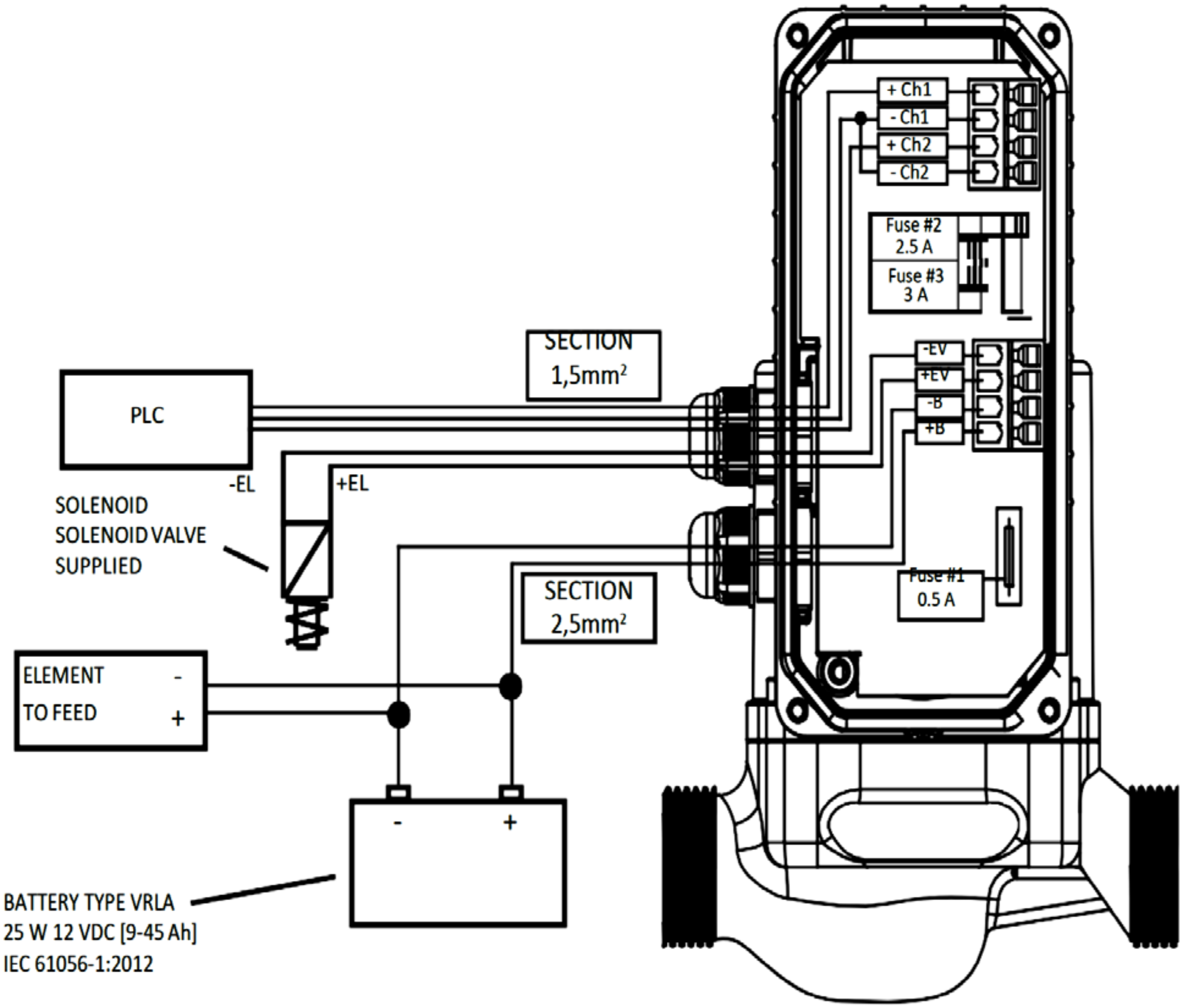
APPENDICES

APPENDIX A: Electrical Installation



- Solenoid valve (+EV, -EV) terminals: to connect the latch type solenoid the solenoid valve. Use the cables from the latch solenoid valve.

- Battery terminals (+B, -B): for connection of battery terminals. Use cables with a section of 2.5 mm^2 and ensure that the voltage drop does not exceed 3%.
- The conduit hydropower turbine has a Ch1 digital output. This (digital status output) indicates whether the Pico turbine is in operation or not, using a voltage free open collector type signal for its reading; using an external PLC or Data logger
- The Pico turbine further has a Ch2 digital output. This output emits a pulse per 1 litre of flow, circulating through the pico- turbine, using a voltage free open collector type signal of 0,5 seconds duration. This signal may be connected to a PLC or data logger, to monitor the flow circulating though the equipment.
- Use wiring with a section of at least 1.5 mm,^{2} to wire up the digital outputs. Connect the wiring in the following manner: