FLATNESS BASED CONTROL OF MICRO-HYDROKINETIC RIVER ELECTRIFICATION SYSTEM

By

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Declaration

I, Ngancha Bonja Patrick 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 own independent work, 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, and has not been submitted before by any person in fulfilment (or partial fulfilment) of the requirements for the attainment of any qualification.

Student Signature:

Date: 2017-07-01

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Abstract

In areas where adequate water resource is available, hydrokinetic energy conversion systems are currently gaining recognition, as opposed to other renewable energy sources such as solar or wind energy. The operational principle of hydrokinetic energy is not similar to traditional hydropower generation that explores use of the potential energy of falling water, which has drawbacks such as the expensive construction of dams and the disturbance of aquatic ecosystems. Hence, hydrokinetic energy generates electricity by making use of underwater turbines to extract the kinetic energy of flowing water, with no construction of dams or diversions. A hydrokinetic turbine uses flowing water, which varies with climatic conditions throughout the year, to power the shaft of a generator, hence, generating an unstable energy output. The aim of this dissertation is to develop a controller that will be used to stabilize the output voltage and frequency generated in a hydrokinetic energy system.

An overview of various methods used to minimize the fluctuating impacts of power generated from renewable energy sources is included in the current conducted research. Several renewable energy sources such as biomass, wind, solar, hydro and geothermal have been discussed in the literature review. Different control methods and topologies have been cited. Hence, the study elaborates on the adoptive control principles, which include the load ballast control, dummy load control, proportional integral and derivative (PID) controller system, proportional integral (PI) controller system, pulse-width modulation (PWM) control, pitch angle control, valve control, the rate of river flow at the turbine, bidirectional diffuser-augmented control and differential flatness based controller. These control operations in renewable energy power generation are mainly based on a linear control approach.

In the case whereby a PI power controller system has been developed for a variable speed hydrokinetic turbine system, a DC-DC boost converter is used to keep constant DC link

voltage. The input DC current is regulated to follow the optimized current reference for maximum power point operation of the turbine system. The DC link voltage is controlled to feed the current in the grid through the line side PWM inverter. The active power is regulated by q-axis current while the reactive power is regulated by d-axis current. The phase angle of utility voltage is detected using PLL (phased locked loop) in a d-q synchronous reference frame. The proposed scheme is modelled and simulated using MATLAB/ Simulink, and the results give a high quality power conversion solution for a variable speed hydrokinetic system.

In the second case, whereby the differential flatness concept is applied to a controller, the idea of this concept is to generate an imaginary trajectory that will take the system from an initial condition to a desired output generating power. This control concept has the ability to resolve complex control problems such as output voltage and frequency fluctuations of renewable energy systems, while exploiting their linear properties. The results show that the generated outputs are dynamically adjusted during the voltage regulation process.

The advantage of the proposed differential flatness based controller over the traditional PI control resides in the fact that decoupling is not necessary and the system is much more robust as demonstrated by the modelling and simulation studies under different operating conditions, such as changes in water flow rate.

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Nomenclature

A	Swept area of a turbine [m^2]
B_m	Damping coefficient [N.m/s]
β	Finite integer [degrees]
ρ	Water density (1000kg/m3),
C_{1-6}	Empirical power coefficient parameter of a turbine
C_p	Power coefficient of a turbine
$C_{p.max}$	Maximum power coefficient
D	Turbine diameter [m]
E	Induced voltage in a stator [Volts]
e	Error signal [pu]
E_{hk}	Energy generated by a hydrokinetic system [Wh]
f	Electrical frequency [Hz]
G	Gear ratio
H	Turbine height [m]
i_d, i_q, i_0	d, q and zero axes reference frame stator currents [Amperes]
I_h	Hourly irradiance [kWh/m^2]
J_{ed}	Equivalent rotational inertia of a generator and a turbine [$kg.m^2$]
J_g	Rotational inertial of a generator [$kg.m^2$]
L_d, L_q	d, q axes reference frame inductances [H]
m	Water mass [kg]
N	Lifespan of the system [years]
Θ_g	Rotor angular position of a generator [degrees]

ρ	Water density [1000 kg/m^3]
P	Number of pole pairs
P_m	Mechanical power of a turbine [W]
P_w	Power of the moving water [W]
p_f	Packing factor
ρ_w	Air density [1.225 kg/m^3]
R	Turbine radius [m]
R_s	Stator resistance of a generator [Ω]
t	Time [sec]
τ_i	Time constant
T_e	Electromagnetic torque of a generator [N.m]
T_m	Mechanical torque of a turbine rotor shaft [N.m]
$T_{w.g}$	Mechanical torque from a water turbine to a generator [N.m]
v	Wind/Water speed [m/s]
v_d,v_q,v_0	d, q and zero axes reference frame stator terminal voltages [Volts]
m_d and m_q	Direct and quadrature axis modulation signals
K_p and k_i	Proportional and integral gains
ψ_d, ψ_q	Stator flux linkage components in the d-q frame
ψ_{pm}	Magnetic flux of the rotor magnets [Wb]
V_s	DC system voltage
ω_e	Electrical angular velocity of a generator [rad/sec]
ω_g	Angular velocity of a generator [rad/sec]
ω_m	Mechanical angular velocity of a turbine [rad/sec]
U(t)	System input [pu]
$y_{(t)}$	System output [pu]

yref	Reference signal [pu]
$g_{(x)}$	Input matrix
λ	Tip-speed ratio
η_{CONV}	Converter efficiency
η_g	Generator efficiency
η_t	Turbine efficiency
L_d	d axis reference frame inductances (H)
L_q	q axis reference frame inductances (H)
Θ	Magnetic flux of the rotor magnets [Wb]

Abbreviations

AC	Alternating Current
PI	Proportional Integral
PID	Proportional Integral and Derivative
FC	Fuel Cell
WT	Wind
SC	Supercapacitor
DC	Direct Current
DG	Diesel Generator
DHT	Darrieus Hydrokinetic Turbine
DME	Department of Minerals and Energy
DoE	Department of Energy
GHGs	Concentration of Greenhouse Gases
MHR	Micro-Hydrokinetic River
MHRC	Micro-Hydrokinetic River and Control
MPPT	Maximum Power Point Tracking
PWM	Pulse Width Modulation
PEC	Power Electronic Control
VToL	Vertical Takeoff and Landing
O&M	Operation and Maintenance
PMSG	Permanent Magnet Synchronous Generator
PV	Photovoltaic
RCT	River Current Turbines
LTV	Linear Time Varying

SCB	Supercapacitor-Bank
VDC	Direct Current Voltage
WRSG	Wound Rotor Synchronous Generator

CHAPTER 1: INTRODUCTION

1.1 Background

The growing migration of population has led to a high need for electrical energy in remote areas. However, a good number of developing countries are now focusing on renewable energy sources for electricity generation. This growing demand for power generated using renewable energy sources has taken over the global stage [1]. Renewable technologies (biomass, wind, solar, hydro and geothermal) offer clean sources of energy that can provide other means of electricity to small rural areas situated far from utility grid lines [2, 3]. The main challenge of renewable power generation is the fact that their produced powers depend on the meteorological conditions (e.g. water flow rate, solar intensity and wind speed) which are non-linear and vary with the hours of the day and the seasons of the year. Due to these intermittent and variable characteristics, serious problems such as voltage variations and frequency fluctuations are posed when these sources are utilized for the generation of electrical energy [4]. Frequency fluctuations and voltage instability are considered as threats for secure and economical operation of standalone and grid application systems. Hence, there is a need for controlling the output voltage and frequency to maintain a secure operation.

Among different renewable energy technologies, the hydrokinetic energy system is gaining recognition for the specific amount of energy produced [5]. Hydrokinetic energy differs from hydropower generation that explores the use of the potential energy of falling water and has drawbacks such as the expensive construction of dams and disturbance of aquatic ecosystems [6]. Hydrokinetic energy generates electricity by making use of underwater turbines to extract the kinetic energy of flowing water. Hence, no construction of dams or diversions is necessary.

There are quite a number of studies dealing with the techno-economic analysis of hydrokinetic systems. However, there is very little literature available on the performance analysis of the hydrokinetic system submitted to variable water flow input. The authors of [7, 8] studied the performance characteristic of a hydrokinetic system under variable water speeds culminating in generated energy. The major limitation of their studies was that the output voltage and frequency obtained was not stable. Therefore, this study focuses on how electricity generated by the hydrokinetic energy sources is controlled with the aim of producing the specified voltage and frequency to be supplied to consumers.

1.2 Problem Statement

In traditional hydropower systems, most of the control is done upstream with the aim of supplying the turbine with a constant input. However, the techniques are expensive and pose challenges if selected to be implemented for hydrokinetic systems. River water velocity is highly reliant on climatic conditions and this causes the uncontrolled turbine to rotate at different speeds which implies fluctuation in generated output power. The power fluctuation causes frequency fluctuation and voltage flicker.

Most of the available software packages/tools for modelling renewable energy systems do not have hydrokinetic components. Hence, it is difficult to study/analyse the electrical output power of the system submitted to variable water flow of the off-grid MHR system.

1.3 Objectives of the Study

This work looks at finding a solution to the problem outlined in section 1.2. Starting by converting the variable generated output power from a hydrokinetic river system due to the seasonal variation in flow rate, into a constant voltage and frequency, that can be used to supply power to isolated loads, or in the long run be fed into the national grid [7]. This is in view of the stipulated conditions permitting the injection of power into a national grid network, namely: same voltage level, same frequency, same phase and same phase sequence [9].

The tool that will be use to offer the above solution is a converter that uses a concept of differential flatness. Flatness involves, linearizing the system to provide a complete knowledge of all variables, choosing the flat output and using the flat output to determine the flat trajectories, in order to control the generated voltage and frequency.

1.4 Research Methodology

The following methodologies were used for this research:

- Control methods literature review: The literature related to different control methods of power are reviewed; previous researches on the control strategies based on differential flatness principle are reviewed, and conclusions drawn on the different technologies involved.
- Control system model development: This includes the development of mathematical models of a PI controller and a differential flatness based controller of a MHR controller system, as well as implementation of the developed models in the MATLAB software.
- Simulation: The behaviour of the PI controller and the differential flatness based controller systems submitted to variable flow is analysed and the results discussed on the impact of

adding a converter to the hydrokinetic generating system to achieve a stable voltage and frequency at the output.

1.5 Hypothesis

The modelled power converter will produce constant voltage and frequency even if a variable flow is applied to the turbine's upstream.

The application of flatness will enable a complex nonlinear dynamic system to be made equivalent to a linear system, and the trajectories of all system variables can be directly and easily controlled by controlling the flat output and its derivatives, without solving differential equations.

1.6 Limitation of the Study

This study will be limited to modelling a boost converter employing a PI controller as well as a boost converter employing a differential flatness based control scheme. Other control options will only be reviewed, but not modelled.

The study will focus on simulations.

Experiments on a prototype are beyond the scope of this work.

1.7 Contribution to Knowledge

The study presented a global review of relevant renewable energy power generating control method, based on the differential flatness principle. Suggested control mechanisms, relevant technologies, differential flatness principles, and applications for rural electrification are discussed. This will enable researchers to identify more research gaps and the correct equipment for a specific application.

The simulated results obtained from a PI controller are compared to those of a differential flatness based adoptive controller. This enables the correct selection of the most affordable and reliable electrification control option from among the existing ones.

The development of a MATLAB/Simulink model to assist with performance evaluation of the MHR controller system during the planning stage is presented.

1.8 Research Output

Journal Publications:

P.B. Ngancha, K. Kusakana, and E. Markus. "Performance analysis of a hydrokinetic system with power converter submitted to variable water flow." Advanced Science Letters (Accepted in August 2017).

P.B. Ngancha, K. Kusakana, and E. Markus. "Flatness based control of variable speed micro hydrokinetic generation systems with power converters." Advanced Science Letters (Accepted in August 2017).

Conference Papers:

P.B. Ngancha, K. Kusakana, and E. Markus. "Modelling and simulation of a power converter for variable speed hydrokinetic systems", Domestic Use of Energy (DUE), International Conference on. IEEE, 2017.

P.B. Ngancha, K. Kusakana, and E. Markus. “A survey of differential flatness-based control applied to renewable energy sources”, PowerAfrica, IEEE PES (pp. 371-379), 2017.

P.B. Ngancha, K. Kusakana, and E. Markus. “Flatness based control of a variable speed micro hydrokinetic generation system." Industrial and Commercial use of Energy (ICUE), 2017.

1.9 Outline of the Dissertation

Chapter 1 is an introduction to the dissertation, which presents background on the research study flatness based control of a Micro-Hydrokinetic River Electrification System. It lists the problem statement, objectives, methodology, hypothesis, delimitation of the study, as well as the research outputs.

Chapter 2 provides a comprehensive overview of the current control techniques in renewable energy technology, its general advantages and disadvantages, with typical application for renewable energy systems, as well as differential flatness based control applied to renewable energy. The primary focus is on a global review of differential flatness principles. A review of current differential flatness technologies, developments, suggestions, evaluations, as well as improvements, is also included.

Chapter 3 covers the development of the mathematical model for the off-grid MHR controller systems. The developed model has been implemented in MATLAB/Simulink software.

Chapter 4 discusses the simulation results of the developed model. Performance of the proposed proportional integral (PI) MHR control system is compared to that of a flatness based control system in order to reveal the consistently achieved fast and dynamic controlled performance in areas with flowing water resources.

Chapter 5 presents the conclusions and suggests future areas of research to be carried out in the area of MHR control technology.

CHAPTER 2: LITERATURE REVIEW

2.1 Introduction

This chapter presents a review of the current status and potential of renewable energy power generation and control. It reviews the status of other control systems in electrical energy generation applications. It also presents recent development studies focusing on efficiency improvement.

Different control techniques have been applied to enhance the stabilization of energy generated in renewable power systems, and primarily these can be separated into different categories such as:

- Mechanical control (at the input of prime mover (turbine) valves or mechanical breaks) [10, 11].
- Control using linear controller systems (PID control, PI control, PWM control) [12 – 15].
- Control at the load side (load ballast, dummy load, and electronic load controllers) [16 – 20].

The adoption of differential flatness based control to renewable energy sources for the stability and management of the output power is becoming an increasing reality. Differential flatness is a mathematical property of a system described by a set of differential equations [21]. The main advantage of this control method is the possibility to express the dynamic behaviour of a system in terms of a fictitious output that defines the system's characteristics. This control approach has often been used in a variety of nonlinear systems across various engineering disciplines, including robotics [22, 23], induction motors [24], vertical takeoff and landing (VTOL) aircraft, polymerization reactors [25], Van de Vusse reactor [26] and a continuous bioreactor [27]. The differential flatness property of a large class of chemical reactors has been shown by [28].

The term 'differential flatness' or 'flatness' does not describe a specific control algorithm, it is rather a general approach in the analysis and design of dynamical systems. Flatness can be viewed as a form of feedback linearization, as its control technique combines the trajectory generation and trajectory tracking. The term 'flatness based control' can further be expatiated as: in at least one step in the design of a control algorithm, the explicit algebraic relation between full states (x) or inputs (u) and the flat outputs (y) and a number of its derivatives (y,$\dot{y}$,$\ddot{y}$,..) are being applied [29, 30]. This review chapter presents an overview of various methods that can be used to minimize the fluctuating impacts of power generated from renewable sources with a view to outlining the benefits of differential flatness based control. This study aims to provide information on better control techniques towards establishing a reasonable grid (or standalone) power generation connection that can make an immense contribution to the operation and maintenance costs of renewable energy systems.

2.2 Methods of electrical generation control

This section has categorized the control methods with regard to the mechanism of the energy conversion. Different control methods of the conversion system applied in typical applications of renewable energy power generation system are cited with their advantages and disadvantages in Table 2.1.

TABLE 2.1: METHODS USED TO CONTROL RENEWABLE SOURCES OF POWER GENERATION.

Method	**Description**	**General advantages**	**General disadvantages**	**Typical application for renewable energy**
Control at the load side	load ballast	1. Simplicity of design. 2. Lower parts count. 3. Low noise. 4. Fast transient response.	1. Low efficiency if input-output difference is large. 2. Low efficiency (significant heat dissipation). 3. May require a head sink. 4. Capable exclusively of step-down operation.	It gives the possibility to control voltage and frequency of the self-excited induction generator operated as a standalone under varying load conditions [10].
Control at the load side	Dummy load	1. Overall low cost. 2. Low noise. 3. Simplicity of design. 4. Low output voltage ripple.	1. Size depending on the voltage level. 2. High heat loss. 3. Lower efficiency levels.	Can be used for power balancing at varying consumer load as required for stand-alone micro-hydel generators driven by uncontrolled turbines [11].
Power electronic Control	PID control	1. Smaller maximum overshoot as opposed to a PI controller. 2. A high possibility of no steady state error. 3. Better system resolution.	1. Limitation in parameter large time delay process settings. 2. Limitation in integrating process.	This control method can be used to switch correctly and automatically between different wind turbine work states according to the weather condition, load and battery status [12].

		4. Easily available.		
Power electronic Control	PI control	1. Small steady-state error, depending on its given application. 2. Smooth power and torque fluctuations.	1. Maximum overshoot, given a particular application. 2. Long settling time, given an application. 3. Sluggish response to sudden disturbances. 4. Sensitivity to controller gains.	This proposed system can be used to improve the poor dynamic response of the system during islanding with the help of battery energy storage system [13].
Power electronic Control	Optimal control	1 Fully exploits scientific quantitative. 2. improved energy conversion efficiency. 3. Extract a maximum of power under fluctuating input condition.	1. A need for multiple power source. 2. High cost.	This system can be used to control multi-mode operations and ensure the dynamic balance of driving power and electric load demand [14].
Power electronic Controller scheme	buck converter for control of the speed and a boost converter controlling the load voltage	1. High efficiency in stepping up (boost), step down (buck), and invert voltages. 2. Available from multiple suppliers.	1. Complexity in their chips. 2. Increases chip size due to switching regulators. 3. Noisy due to high-frequency switching.	This system can be used to track a speed profile, generated by an MPPT algorithm, to operate a laboratory wind energy system based on a DC generator [15].

Mechanical control	River flow rate at turbine.	1. Design of turbine. 2. Surrounding fluid behaviour. 3. Water density.	1. Fluid wave movement. 2. Flow direction. 3. Seasonal effect on water level.	This study can be used to control the height and the frequency of the upcoming waves, to amplify the rotational speed of the turbine [16].
Mechanical control	Bidirectional diffuser-augmented (nozzles in the flow)	1. Increase the power conversion efficiency. 2. Controlling one direction flow.	1. If the rotational axis is perpendicular to the current, the turbine operates whatever the flow direction. 2. Effect on water level.	Proposes a novel system configuration that can be used to capture as much of kinetic energy as possble from in stream current water [17].
Mechanical control	Pitch angle of wind turbine).	1. Maintain the aerodynamic power produced by the wind turbine. 2. Relatively fast. 3. Avoid a runaway turbine in case of high wind speed.	1. Limited by the pitch rate. 2. Control algorithm limitation. 3. Limited by the shape of the CP curve as a function of pitch angle.	Presented some work which can be applied on turbine positioning and detailed assessment of various turbine systems (horizontal and vertical axes) [18].
Mechanical control	The ballast load control.	1. Simplicity of design. 2. Lower parts count. 3. Low noise.	1. Loss of energy due to the bypass. 2. High depreciation factor. 3. High transient risk. 4. Increased cost due to load.	Proposes a load controller that can be used to increase or decrease a ballast load connected across the generator as the user load varies [19].

Mechanical control	Input of resource using valves on hydropower	1. Availability. 2. Clean fuel source. 3. No pollution of the air. 4. Affordability. 5. Long life span.	1. Environmental Consequences (damming of water). 2. Expensive. 3. Droughts. 4. Limited Reservoirs.	This design can be used for the development of a micro hydro power plant [20].

Table 2.1 above has presented an overview of various methods that have been used to minimize the negative impacts experienced when generating energy using renewable energy sources, and it further indicates the advantages and disadvantages experienced by each approach. From Table 2.1 above, it is observed that the control of energy generation has long been a serious concern, based on traditional power generating technologies. However, the huge demand for renewable energy generating technology, which has taken the centre stage in most countries' energy generating systems and given the form of inventive equipment used for this method of energy generation. One therefore realises that energy generated through renewable power sources, is in most cases connected in a cascaded nature of construction form in order to produce an adequate power output. In view of this, an innovative and rapidly responding controller's technology of power generated using renewable energy sources is eliciting particular concern.

2.3 Principle of flatness based control.

The initial idea of differential flatness was introduced in the early 90's [29]. This brings an alternate representation of the system in which trajectory planning and nonlinear controller design are straightforward. This control theory is an interdisciplinary branch of engineering and mathematics that deals with the behaviour of dynamic systems and how they can be modified by the use of a feedback signal. The usual objective of a control theory is to control a system, often called the plant, so that its output follows a desired control signal, called the reference, which may be a fixed or changing value [21]. To achieve this, a controller is designed as in Figure 2.1 below.

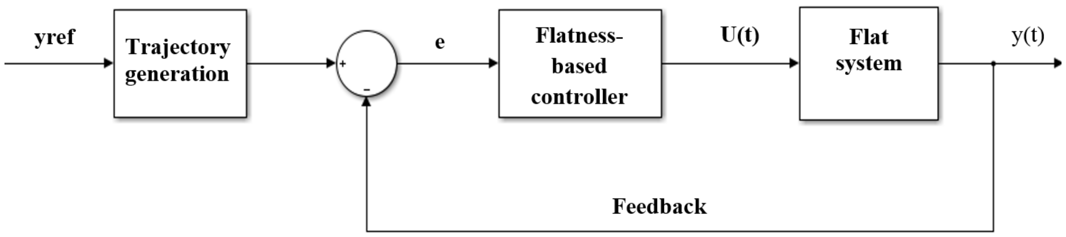

Figure 2.1: Flatness based control system.

Where: yref is the reference signal,

e is the error signal,

U(t) is the system input,

y(t) is the system output.

To begin with, according to this principle, a system should initially prove to be flat by selecting an appropriate flat output. Then, the reference trajectory should be planned on the chosen output so that the maximum power may be extracted from the source. The main advantage of this control method is the ability of solving a complex nonlinear system such as that of renewable energy in the transient state as well as the steady state, allowing an optimal design of the system components [30, 31]. In addition, the proposed control strategy can improve performance of the system in the transient state as opposed to the traditional control approaches [32]. It should be noted that this control technique has been proposed to manage the energy in an electrical hybrid system [33], in systems of reactive energy compensation [34]. Additionally, it has been proposed to control a permanent magnet synchronous motor [35, 36] and to control induction motors [37].

Consider a general nonlinear system of the form:

$$x' = f(x) + g(x)u \tag{2.1}$$

$$x = [x_1, x_2, \ldots x_n]T \quad x \in \mathbb{R}^n \tag{2.2}$$

$$u = [u_1, u_2, \ldots u_m]T \quad u \in \mathbb{R}^m \tag{2.3}$$

If the state variable x can be parameterized by flat output y and its derivatives, the system is said to be differentially flat and admits the flat output $y = [y_1, y_2, \ldots, y_m]T$ [29, 30]. Then, the state variables and control variables can be written as follows:

$$x = \varphi_1\left(y, \; y', \ldots, \; y^{\beta}\right) \tag{2.4}$$

$$u = \varphi_2\left(y, \; y', \ldots, y^{(\beta+1)}\right) \tag{2.5}$$

In which β is the finite integer.

A set of equations (2.4) and (2.5) denotes as differential parameterization of the system variables used in the controller design. By this process, a nonlinear flat system can be equivalent to a linear controllable system as described in reference [29, 30].

2.4 Review of flatness based control technique applied to renewable energy.

A number of researchers have applied the flatness based theory in the field of renewable energy technology. This section is divided into different categories of renewable energy sources in which the flatness based control has been applied, namely:

- Fuel cell (FC),
- Wind (WT),
- Solar (PV),
- Hydro,
- Biomass,
- Tides,
- Oceans,
- Hydrogen,
- Geothermal energy.

Recent research studies are reviewed and summarized in Table 2.2, which provides the source authors, a summary of the research focus, renewable energy technologies covered and comment on the key results of the work reviewed.

TABLE 2.2: REVIEW OF FLATNESS BASED CONTROL TECHNOLOGY APPLIED TO RENEWABLE ENERGY SOURCES.

Authors	Technology	Focus of the Review	Comments on key results
A. Gensior, T. P. Nguyen, J.	Wind (WT)	Research on loss optimization and control of a doubly fed induction generator and two power	Using the flatness principle, a trajectory-

Rudolph, H. Guldner, [38]		electronic converters is considered. A mathematical model is given and the flatness of the model is shown. The freedom in the choice of one component of the chosen flat output is used in order to reduce the power losses in the system.	tracking controller for the machine and the grid side converter are developed (Back-stepping approach).
A. Payman, S. Pierfederici, F. Meibody-Tabar, [39]	Fuel cell (FC) and Supercapacitor (SC)	Proposed to control a multi-source alongside a multi-load electrical hybrid system (EHS). Supercapacitor-bank (SCB) and fuel cell are the main auxiliary sources. They supply two independent loads, connected to a direct current (DC) bus through unidirectional buck converters. An observer is also proposed and designed to estimate either the fuel cell voltage against power (V-P) output characteristic or voltage against current (V-I) output.	The use of flatness based proposed observer allows the achievement of an efficient control of the system, hence avoiding overcharging or discharging of an SCB.
A. Shahin, S. Eskander, H. Moussa, J. -P. Martin, B. Nahid-Mobarakeh, S. Pierfederici, [40]	Solar (PV)	Applied a new method based on flatness based control to advance reliability of parallel-connected inverters. At one loop with high bandwidth and low voltage, a total harmonic distortion (THD) controller based on the flatness technique is proposed in a non-isolated power supply composed of N units.	With flatness based control by aligning in parallel quite a few units, the power supply system is able to meet high power requirements and the prospect of maintenance operation without interrupting the supply.
C. Join, G. Robert, M. Fliess, [41]	Hydro	Applied a concept known as Model-Free Control to hydroelectric run-of-the river power plants. In this, a level trajectory is	The flatness based principle is used to control the set-point,

		planned for cascaded power plants. Numerous dynamic simulations results confirm this with a modest and robust control algorithm. There are only three control parameters, which are easy to tune, and performances are robust for a large range of operating points.	even in severe operating conditions. The advantages are that a mathematical model of the process is no longer necessary, consequently complicated identification procedures are avoided.
D. He & X. Cai, [42]	Solar (PV)	Applies a novel feed-forward control based on flatness to a high voltage direct current (HVDC) source converter system. To track the reference trajectory such as active power, DC voltage, the transition limitation of current are being taken into account in the discrete time reference trajectory. The feed-forward part of input comes from the function of input and flat output, and the other feedback controllers are used to eliminate errors.	Feed-forward makes flatness based controller provides a faster dynamic response as opposed to conventional dead-beat controls. Feed-forward is its main advantage for its enhancement of the dynamic performance.
D. Schlipf, D. Cheng, P. Wen, [43]	Wind (WT)	Evaluated a flatness based feed forward control approach of wind turbines using Lidar. This permits the calculation of the control action based on the trajectories of the rotor speed and tower motion using wind measurements. In this study, the planning of the trajectory is done online and takes into consideration the constraints due to the actuator regulating the rotor speed and minimize tower movements.	Using the technique of flatness, the feed forward signals of the collective pitch and generator torque update can be combined with conventional feedback controllers to obtain a considerable reduction of the tower and shaft loads.

D. Wang, C. Liu and G. Li, [44]	Wind (WT)	Proposes an "optimal integrated control scheme" for the grid side voltage source converter (VSC). The control approach includes a main controller and an additional controller, in the main controller. A double loop controller based on the differential flatness based theory is designed for grid side VSC, and an auxiliary second harmonic compensation control loop based on an improved calculation method for grid side instantaneous transmission power is designed by the quasi proportional resonant (Quasi PR) control principle, which is able to simultaneously restrain the second harmonic components in active power and reactive power injected into the grid without considering the current control calculation for the respective references.	Flatness based principle enables a reduction of the direct current link overvoltage during grid faults, by adding a modified control factor to the traditional direct current voltage control loop in grid side VSC.
F. Michaud and G. Robert, [45]	Hydro	Presented a robust control law based on the nonlinear differential flatness principle for the speed governor of a hydraulic turbine control system participating in power frequency control.	The comparison of flatness base nonlinear structure with a linear proportional integral (PI) feed forward controller gives better results; less sensitive to process variations and lower overshoot.
G. Rigatos, P. Siano, P. Wira, V. L o i a, [46]	Fuel cell (FC)	Presents an approach to nonlinear control of fuel cells using the differential flatness theory and Kalman filtering (KF). The design of a	This flatness based control arrangement is robust to model

		state-feedback controller is achieved and extended by considering the additional state variables for the derivatives of the aggregate disturbance input. Subsequently, a Kalman filter based disturbance observer is applied to the linearized extended model of the fuel cells.	uncertainties and external perturbations, and the Kalman filter based estimator is able to identify the perturbation term and to compensate by including an additional element in the feedback control law.
H. C.Enriquez, J.C.Romero, and G.A. Ramos, [47]	Wind (WT)	Proposes an alternative robust observer based linear control technique to maximize energy capture in a 4.8MW horizontal axis variable speed wind turbine. The strategy is to use a generalized proportional integral (GPI) observer to reconstruct the aerodynamic torque in order to obtain a generator speed optimal trajectory. Then, a robust GPI observer based controller supported by an active disturbance rejection (ADR) approach allows asymptotic tracking of the generator speed optimal trajectory.	The proposed flatness based approach controls the power coefficient through the generator angular speed and near to an optimum point at which power coefficient is maximized. The results show that the proposed control strategy is effective in terms of power capture and robustness.
H. Fürst, D. Schlipf1, M. I. Latour, and P. W. Cheng, [48]	Wind (WT)	The application of the promising methodology of feed forward control using nacelle-based lidar sensor measurements on a 10 MW wind turbine concept. The feed forward controller is designed so that disturbances from the changing wind speed to the generator speed are compensated by adding an update to the collective pitch rate	Flatness based principle leads to a conclusion that the benefits of lidar assisted control might be even more attractive for 10 MW turbines, since the cost of a lidar system will be the same while

		signal of the normal feedback controller. The evaluation of the feed forward controller is done in two steps: Firstly, simulations using perfect lidar data measurements are applied to check the robustness of the controller against model uncertainties. Secondly the uncertainties against the robustness are analysed.	the load reduction might lead to larger cost reduction due to the high overall cost compared to 5 MW wind turbines.
H. Xue, H. Li and Y. Wang, [49]	Solar (PV)	Work on a novel nonlinear differential flatness based control method for a distributed photovoltaic energy storage (PV-ES) direct current (DC) generation system. For high power applications, four phase parallel boost converters and four phase parallel bi-directional converters are implemented as a solar (PV) converter and a storage device, respectively.	Using flatness for the PV four phase parallel boost converters, an improved algorithm is designed to achieve maximum power point tracking (MPPT) control, to lessen current ripple and widen the range of PV module output voltage.
H.A. Aldwaihi and E. Delaleau [50]	Wind (WT)	Presented a novel control law for a permanent magnet synchronous generator (PMSG) driven by a wind turbine (WT) and connected to a battery bank via an AC/DC converter. The novel algorithm gives a simple method, based on trajectory planning, that reduces the copper losses in the PMSG stator, hence, achieving the maximum power captured by the WT.	The key finding of the paper is to show that flatness based control (FBC) is compatible with any maximum power point tracking (MPPT) strategy.
I. Tegani, A. Aboubou, R. Saadi, M. Y.	Solar (PV), Wind (WT)	Presented a control design of a renewable energy hybrid power system, in which the energy generated is managed through a non-	The results show that the proposed flatness PNN is able to manage the

Ayad, M. Becherif, [51]	and Fuel cell (FC)	linear method based on the differential flatness property to improve on the control law. A predictive neural network (PNN) is used to ensure a better tracing for the reference trajectory signals.	power flow in a hybrid system with multi renewable sources, and provides more stability by decreasing the perturbation in the controlled DC bus voltage.
J.T. Agee and A. A. Jimoh, [52]	Solar (PV)	Demonstrates that the concept of differential flatness could be used to design controllers for a polar axis solar tracker that would enable a reduction in hardware costs. Three control objectives are realized using one controller structure, while sensorless solar tracking is achieved using trajectories of motion.	It is deduced that the implementation of (or flatness based) trajectories of motion with the controller can reduce the drive power requirement and associated photovoltaic (PV) cost by about 31%. Sensorless tracking offers the possibility of hardware cost reductions.
M. Aimene, A. Payman, B. Dakyo, [53]	Wind (WT)	A novel nonlinear control method based on differential flatness is applied to a high power wind energy conversion system connected to the grid. The control is done by planning the appropriate trajectories on components of the output variable vector of the system. The studied system includes a three blade horizontal wind turbine and a permanent magnet synchronous generator (PMSG) which	The advantage of the proposed flatness based method is the control of the system in its high performance level as well as during the transient state.

		is connected to the grid through a back-back converter and a filter.	
M. Benaouadj, M. Y. Ayad, M. Becherif, A. Aboubou, M. Bahri, O. Akhrif, [54]	Wind (WT)/ Solar (PV)/ Batteries and Supercapacitor (SC)	Looks at the energy flow control of Wind/PV/Batteries/Super capacitors. The system is managed using a nonlinear control based on the flatness concept; the lead acid batteries are used to compensate the power demand that cannot be provided by the PV and wind generators. Supercapacitors are employed to relieve the batteries of repeated charging and discharging, ensuring longer hybrid source lifetime.	The outcome in using the flatness based principle is to obtain an autonomous hybrid power source to supply a residential load, coming from exchanging power among different components.
M. Benaouadj, A. Aboubou, M.Y. Ayad, M. Becherif, [55]	Solar (PV) and Batteries	Presented a work on standalone application, and to demonstrate the role of a supercapacitor as a transient power source, a non-linear control strategy based on the differential flatness approach is applied to manage energy flows in two systems. The first includes a photovoltaic (PV) source considered as a main source and lead acid batteries used as a storage unit, while the second is obtained with the hybridization of the PV source, lead acid batteries, and supercapacitors.	The simulation results have demonstrated that, with the principle of flatness based control, the direct current (DC) link voltage is controlled and regulated to its reference. The batteries and supercapacitors' voltages and states of charge are maintained in their admissible intervals under conditions of high discharges, thus, the storage unit and hybrid sources lifetime increases.

M. Benaouadj, M. Y. Ayad, M. Becherif, A. Aboubou, [56]	Solar (PV)/ Wind (WT)/ Supercapacitor (SC)/ Batteries	Work on an autonomous Wind/Photovoltaic (PV) hybrid power source using lead acid batteries and supercapacitors as storage elements. The lead acid batteries are used to compensate the power demand, which wind and PV generators cannot provide. Supercapacitors are employed to relieve the batteries of repeated charging and discharging ensuring longer hybrid source lifetime. The exchanged power among different components is managed using a non-linear control based on the flatness concept, to obtain an effective supply.	The possibility of power exchanged among different components is managed using a non-linear control based on the flatness concept to obtain an effective supply.
M. Josevski and D. Abel, [57]	Fuel cell (FC)	Proposed a flatness based model predictive control (FMPC) to address an energy management problem of hybrid electric vehicles. A predictive controller for the optimization of the hybrid electric vehicle fuel efficiency is introduced, as the idea is to use the concept of differential flatness to determine the evolution of a system's state across the prediction horizon without numerical integration. The entire nonlinear optimization problem is expressed as a function of a fictitious output, called the flat output and its first derivative. The optimal distribution of the requested torque between propulsion devices is then determined by a static optimization.	Due to the adoption of flatness based control, FMPC resulted in improved fuel economy, as opposed to the economy of LTV-MPC controller

M. Phattanasak, W. Kaewmanee, J. P. Martin, S. Pierfederici, B. Davat, [58]	Fuel cell (FC) and Solar (PV)	This paper presents an interleaved-double-dual-boost converter (IDDB) used in renewable energy application where high voltage gain is required, such as in photovoltaic or fuel cell applications. The variation of the input voltage is compensated by a trajectory planning process. Two kinds of controllers are applied to this converter: 1) a controller based on flatness properties for regulating the output voltage (outer loop); 2) a sliding mode controller for inductor current (inner loop).	The principle of flatness based control is used in converting the relatively low direct current (DC) voltage obtained from the renewable energy sources to a higher level for fulfilling the requirement of the inverter, limiting the converter losses and increasing the voltage gain.
M. Phattanasak, R. Gavagsaz-Ghoachani, J.P. Martin, S. Pierfederici, B. Davat, [59]	Fuel cell (FC) and Supercapacitor (SC)	Presented a flatness based controller for a hybrid source system. An isolated three-port bidirectional full bridge DC-DC converter is utilized to transfer energy between the load and the auxiliary source.	By using the principle of flatness based control, the fuel cell (FC) is used as a main power source and the supercapacitor (SC) is employed as an auxiliary source to deal with the slow transient response of fuel cell (FC).
M. Phattanasak, W. Kaewmanee, P. Thounthong,	Wind (WT)	Work on a nonlinear control algorithm for a current fed DC-DC converter. Based on flatness properties, a converter which can guarantee the responses during either start up or steady state is built. This converter consists of an inductor, a controllable full bridge	The advantages of this flatness based converter include galvanic isolation, low input current ripple and high voltage gain.

P. Sethakul, M. Zandi, [60]		converter, which is connected to a full bridge rectifier via a high frequency transformer.	
M. Treuer, T. Weissbach, M. Kurth, V. Hagenmeyer, [61]	Hydro	Presented a flatness based “two-degree-of-freedom control concept”. In the principle, a smooth trajectory for set point changes of the generator output are provided, which takes into account the dynamics of the plant.	Applying the flatness based control technique, the trajectory planning for the plant is thereby addressed; therefore, result in limiting the gradients of set point changes of the power output.
M.H. Variani, K. Tomsovic, [62]	Wind (WT)	Investigates the high penetration of distributed generation and alternative energy units in wind generation. The reference phase is tracked by the local control, which is obtained through economic dispatch at the global control level. As a result of applying the flatness based method, the “n” machine system is decoupled into “n” linear controllable systems in canonical form.	Flatness based control strategy results in a distributed automatic generation control (AGC) formulation that is absolutely easier to design, implement and demonstrates promising performance in mitigating frequency deviations as opposed to conventional AGC.
O. Kraa, R. Saadi, M. Becherif, M.Y. Ayad, [63]	Fuel cell (FC) and Supercapacitor (SC)	Uses the flatness and sliding mode control strategy of fuel cell and supercapacitors hybrid source. Flatness is used to decouple the system into two sources so that each sub-system has a separate control target expressed in terms of a sliding surface. Secondly, the sliding mode controller is used to ensure	The proposed flatness sliding control combination successfully manages the hybrid system energy with a stable and robust performance.

		instant power sharing between the direct current (DC) bus converters, which ensure that the SC and FC currents track well with their references that are calculated from the SC and FC powers.	
P. Song, Y. Li, L. Wang, C. Duan, [64]	Solar (PV)	Presented a controller for the modular multilevel converter. The generation of reference trajectories of state variables are planned in space according to the desired system output, and the implementation of the controller to generate the desired feed-forward input controller variable, according to system input equations, is also achieved.	The process aims to eliminate the impacts of uncertainty of the converter model and factors such as internal and external disturbances. The error feedback compensation is used to calibrate system flatness output and to track the reference trajectories rapidly.
P. Thounthong, [65]	Fuel cell (FC)	Presented a high gain boost converter (three level converter and transformer less converter) for fuel cell (FC) vehicle applications. A prototype FC power converter (1.2 kW three-level boost converter) is developed in the laboratory.	With the use of flatness, the design controller parameters are straightforward and autonomous at the operating point.
P. Thounthong, A. Luksanasakul, P. Koseeyaporn, B. Davat, [66]	Fuel cell (FC) and Solar (PV)	Presented a control system of an energy hybrid power plant, fed by fuel cell (FC) and photovoltaic (PV) sources with a supercapacitor (SC) storage device and suitable for distributed generation applications, The PV is used as the primary source and the FC acts as a backup, feeding	By adopting the principle of differential flatness-based control, a simple solution is obtained for the fast response, stabilization problems in the power system and to

		the deficient power (steady state) from the PV; and the SC functions as an auxiliary source and a short-term storage system for supplying the deficiency power (transient and steady state) from the PV and the FC, four phase parallel converters are implemented for the FC converter, PV converter, and SC converter, respectively.	validate excellent control algorithms during load cycles.
P. Thounthong, S. Pierfederici, B. Davat, [67]	Fuel cell (FC)	Adapted flatness based technique to control a group of converters supplied by a fuel cell (FC) (main-source) and supercapacitor (auxiliary-source). The design controller parameters are independent of the operating point; moreover, communications between converters are taken into account by the controllers, and very high dynamics in disturbance rejection are achieved.	The flatness based method leads to the interactions among the controls of the converters in case they are designed separately.
R. Saadi, M. Benaouadj, O. Kraa, M. Becherif, M. Y. Ayad, A. Aboubou, M. Bahri, A. Haddi, [68]	Fuel cell (FC) and Supercapacitors (SC)	Presents a flatness based control algorithm for a direct current (DC) hybrid power source used in electric vehicles (EV). The control procedure is based on the flatness properties of the system. A fuel cell (FC) is considered as the main source, and a supercapacitors (SC) pack considered as the auxiliary source. Correct planning of the trajectory of the flat output; permits control of the vehicle.	The benefit of this flatness based control procedure is that the state variable and control input are categorically estimated by the trajectories of the flat output derived from these outputs without the need to integrate any differential equation.
T. Rabbani, S. Munier, D.	Hydro	Applied a flatness based controller to an open channel hydraulic canal. In this principle, an	Based on the flatness principle, the results

Dorchies, P.O. Malaterre, A. Bayen, X. Litrico. [69]		open loop controller is thus able to compute the upstream water discharge corresponding to a desired downstream water discharge.	project that the gravitational withdrawals along the canal reach, decrease the steady state error to 1% (gravitational lateral withdrawals assumption) as opposed to 6.2% (constant lateral withdrawals assumption).

Table 2 above has presented an overview of flatness based control that has been used to minimize the negative impacts experienced when applied to renewable energy sources. It also elaborates and comments on key results.

After analysing this table, it can be concluded that any control system arrangement selected should be used to keep the generated energy output stable and steady with the aim of increasing the generating efficiency. The use of differential flatness is advantageous especially in nonlinear systems where the reduction of the number of variables to the outputs and the inherited reduction of parameters and equality constraints simplify the calculations and establish a robust control system. Because of this, they represent an interesting alternative to other control based methods, which involve the solution of complex differential equations.

2.5 Discussion on review of flatness based control methods

After investigating the various technologies, adopting the principle of flatness based control above, it is recorded that the control of power generation in renewable energy sources is focused on voltage / frequency regulation and stability improvement, and this can be further explained based on different technologies adopting the flatness based principle:

- The concept of adapting differential flatness based controls in fuel cell (FC) systems, is being applied more often with significant advantages, such as: flatness helps to improve the lifetime performance of fuel optimization, therefore improving the fuel economy and good tracking performance of the clutch position as opposed to a linear time-varying MPC (LTV-MPC) [34]; the flatness property has been used to decrease the steady-state error of a three level boost converter for vehicle application [65]; by adopting the flatness based property better interactions are achieved between controls of the converters if they are designed separately, with a stable and robust performance, while limiting the converter losses [46, 67]; flatness has also been applied in a double dual boost converter to increase the voltage gain [58], and finally the flatness property can be used to avoid overcharging or discharging of a supercapacitor-bank (SCB) applied in a multi-source / multi-load electrical hybrid system [39].
- The application of the differential flatness principle in Solar (PV) power generating systems is prominent in renewable energy with credible advantages such as: a possibility of maintenance during operation is made possible without interrupting supply in cases in which flatness based control architecture is applied to parallel voltage source inverter topology [40]. Due to the flatness feed-forward enhancement performance, it is possible to achieve faster dynamic response, than with conventional dead-beat control [42]. The flatness property can also be used to obtain maximum power point tracking (MPPT) control, when managing the power flow in multi-renewable energy sources [49, 51]. In addition, there is an increase in lifetime performance when the flatness principle is applied to manage energy flows in two hybrid storage units [52, 64], and finally the application of the flatness property reduces the drive power requirement and associated PV cost.

- The flatness based control principle in a wind power generating system is also an area of interest, with numerous advantages, such as: when designing a flatness based converter, flatness reduces the number of sensors due to its property and has the possibility to control the system even during the transient state, like the conventional converter [53]. When applying flatness based control in megawatt wind turbines, with the aim of reducing fatigue and extreme loading, it improves the fault-tolerance and dynamic response capability, as well as its cost effectiveness [44, 48]. The flatness principle has provided robustness in changing operational conditions in a wind power generating system [60]; and finally, applying flatness in wind (WT) systems can lead to better galvanic isolation, high voltage gain, low input current ripple and effective supply [62].
- The use of the flatness based control system in a hydropower generating system is the least covered technology with definite advantages, such as flatness limits the mathematical model of the process; therefore, complex identification procedures are bypassed [41]. When comparing the flatness based control principle to the traditional proportional integral (PI) control principle applied to hydro generating systems, the advantages of using flatness are as follows: lower overshoot, sensitive to process variations, limited gradients of set point changes and decreased steady-state error [45, 61].

2.6 Conclusion

This chapter has given an overview of different control methods applied in the field of renewable energy power, with much focus on differential flatness. By using the differential flatness based control method, a nonlinear dynamic system is made equivalent to a linear system, and the trajectories of all system variables can be directly and easily controlled by controlling the flat output and its derivatives, without solving differential equations.

The renewable energy power considered in the different studies reviewed, include fuel cell (FC), solar (PV), wind (WT) generators and hydropower. Moreover, these resources have different characteristics in terms of their output power stabilization, subject to the operational strategies. The investigation as separated into four technologies, indicated that:

- Fuel cell (FC) systems: flatness is used to improve fuel economy, and doing so decreases the error, and ensures better interactions with the converter that increase the voltage gain.
- Solar (PV) power generating systems enhance the possibility of maintenance during operation and obtains maximum tracking control, when managing the power flow in multi-renewable energy sources, hence, an increase in lifetime performance.
- In a wind power generating system, flatness reduces the number of sensors when controlling, therefore increases its cost effectiveness. It also reduces fatigue and extreme loading in megawatt wind turbines.
- In a hydropower generating system, flatness limits the mathematical model; therefore, complex procedures are bypassed. Hence, it is sensitive to process variations and limited set point changes.

CHAPTER 3: MODELLING OF POWER ELECTRONIC CONTROLLER SYSTEM

3.1 Introduction

In the first case, a pulse width modulator (PWM) converter, DC-DC booster and inverter is used to model the proposed control approach. The controlled DC-DC boosting converter is used to control the output power of a hydrokinetic system by sensing the rectified voltage and tracking the maximum power point. Hence, the DC link voltage is kept constant under variable water speeds. The inverter at the load side is used to supply constant output voltage in terms of amplitude and frequency. Both the active and reactive power of the stator winding are been regulated through the control of dq-axes rotor currents. The q-axis current regulates the active power while the d-axis regulates the reactive power. A maximum power point tracking (MPPT) is used to extract maximum power from the flowing water since it varies with change in water speed. A sensorless maximum power extraction method has been used. The sensorless MPPT technique is used because the ones that use mechanical speed sensors are inaccurate. They require sensors with tolerable accuracy to track the maximum output power of the hydrokinetic turbine system.

In case two, a differential flatness based adaptive control method is proposed and applied to an MHR system for voltage and frequency stabilization. Differential flatness is a process whereby all system variables are expressed in functions of derivatives of certain specific sets, thereby obtaining differentially independent variables that can be used to calculate all other system variables using differentiation [70]. In applying the principle of flatness based control, the trajectories of all system variables can be directly estimated by describing a given parameter of the flat output and its derivatives without solving differential equations [71, 72]. In doing so, the generated output can be dynamically tuned to satisfy the time varying operating requirement. In contrast to other control methods, the proposed control method avoids the coupling effects between the active current and the reactive current. In addition, this control method is robust in various system operating conditions, giving a fast and dynamic response to the system, therefore, it is simple and cheaper to construct [73].

The layout of the modelled micro-hydrokinetic river control (MHRC) system in this study consists of a turbine, mechanical drive-train, PMSG, and a control system. The turbine is connected to the generator via the mechanical drive-train through the rotor shaft. The hydrokinetic turbine converts the kinetic energy of flowing water into mechanical energy by driving the PMSG via the shaft. The mechanical drive ratio is considered to be 1:1 since no gearbox has been used. The power electronic control (PEC) system is connected to the output of the PMSG to supply AC voltage having constant amplitude and frequency, to a three phase balanced load. The generated electrical energy is fed into the PEC system to stabilize the variable voltage into a constant amplitude and frequency source before supplying the load.

3.2 Hydrokinetic turbine model

The mechanical power extracted by a hydrokinetic turbine is less than the power of the moving water. Only a fraction of the total kinetic power can be extracted, due to losses. Hence, the power coefficient is limited to 59.3% as tested by the well-known Betz law. The mechanical torque extracted by a hydrokinetic turbine is expressed as follows [74]:

$$T_m = \frac{\rho A V^3 C_p}{2\omega_m} \tag{3.1}$$

Where: ρ is the water density ($1000\mathrm{k_g/m^3}$), A is the swept area of the turbine rotor blades (m^2), v is the flowing water velocity, C_p is the turbine power coefficient and ω_m is the mechanical speed of the rotor.

The turbine power coefficient (Cp) relies on the tip-speed ratio (λ) and the blade pitch angle (β) and can be expressed using the empirical coefficient of a typical hydrokinetic system, as shown in Equation (3.2) [75]:

$$C_p(\lambda, \beta) = 0.5176\left(116\frac{1}{\lambda_i} - 0.4\beta - 5\right)e^{(\frac{-21}{\lambda_i})} + \quad 0.0068\lambda \qquad (3.2)$$

The parameter λ_i is determined using the following equation:

$$\lambda_\mathrm{i} = 1/(\frac{1}{\lambda+0.08\beta} - \frac{0.035}{1+\beta^3}) \qquad (3.3)$$

Figure 3.1 shows the modelled underwater hydrokinetic turbine system, which involves various parameters contained in its underwater operation like: the density of water, turbine power coefficient, the blade radios, rate of flow of water and the rotor mechanical speed of the generator.

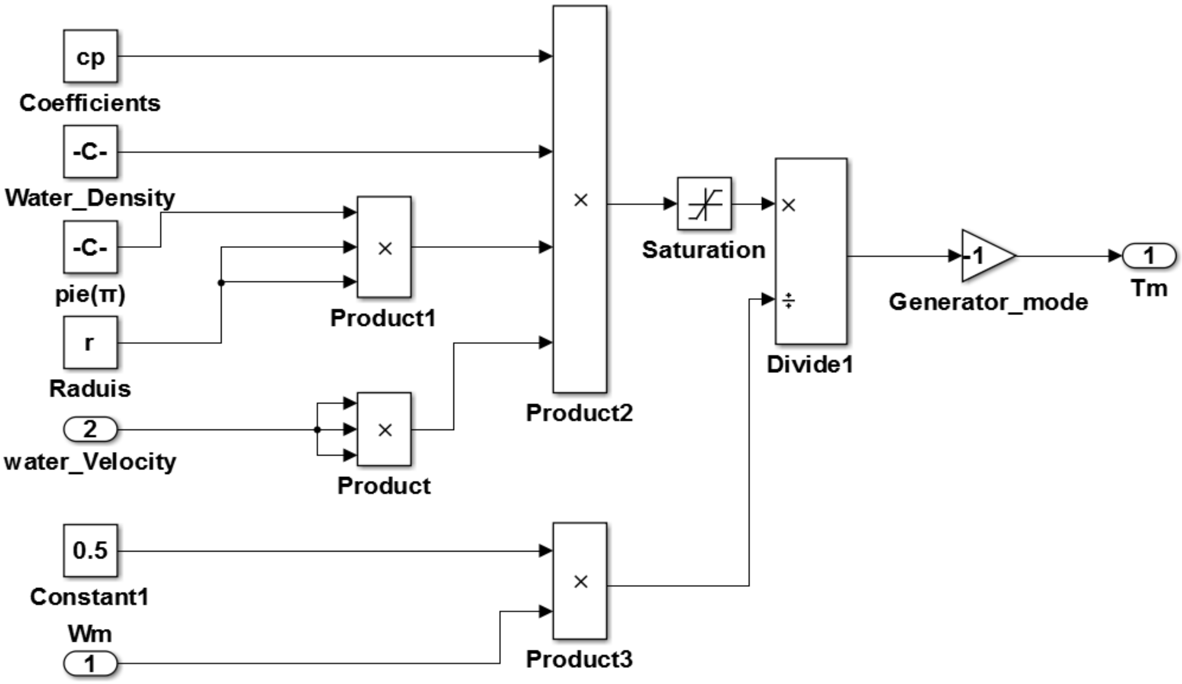

Figure 3.1: Simulink block diagram of a modelled turbine system

A direct drive one-mass drive-train model has been modelled in figuere 3.2 and used between the turbine and the PMSG.

The rotor angular speed of the generator (ω_g) is:

$$\omega_g = \frac{T_e}{B_m} - \left(\frac{J_{eq}}{B_m}\right)\frac{d_{wg}}{d_t} + \frac{T_{wg}}{B_m} \tag{3.4}$$

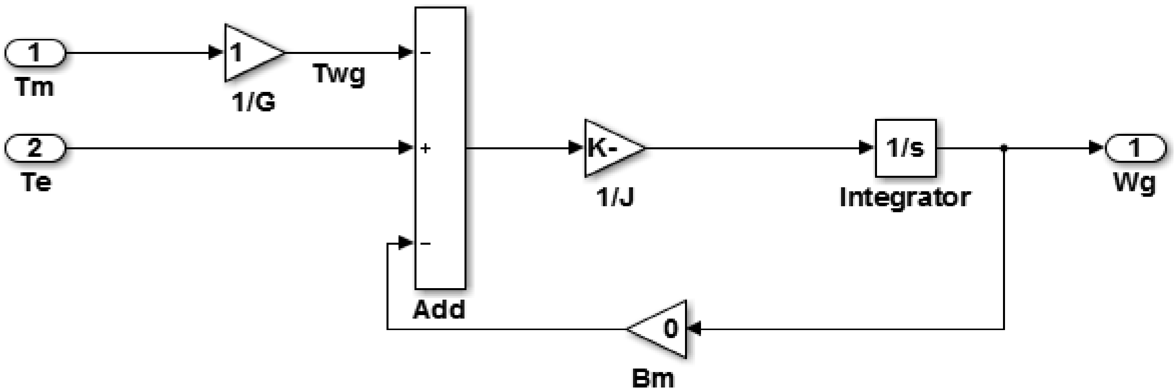

Figure 3.2: Simulink block diagram of a modelled drive system

3.3 Permanent magnet synchronous generator (PMSG) model

The PMSG generates three phase AC components in the form:

$$v_a = R_s i_a + L_a \frac{di_a}{dt} - \omega_e L_a i_a \tag{3.5}$$

$$v_b = R_s i_b + L_b \frac{di_b}{dt} - \omega_e L_b i_b \tag{3.6}$$

$$v_c = R_s i_c + L_c \frac{di_c}{dt} - \omega_e L_c i_c \tag{3.7}$$

Where V_a, V_b and V_c are the line voltages

The transformation of the three-phase alternating current or voltage quantities into direct current or voltage (d-q) quantities is made possible by means of Park's Transformation Method, as shown in Equation (3.8) [76]. This method transforms the parameters and equation from the stationary form into direct-quadrature (d-q) axes. For a salient pole permanent magnet synchronous machine, d and q axes inductances are almost equal due to a large and constant air gap. The dynamic model of a permanent magnet synchronous machine is derived from a two-phase synchronous reference frame, in which the q-axis is 90° ahead of the d-axis with respect to the direction of rotation.

The three phase AC components of the PMSG converted into direct and quadrature components (V_{abc} into dc voltage variables V_{dq0}):

$$\begin{bmatrix} V_d \\ V_q \\ V_0 \end{bmatrix} = \frac{2}{3} \begin{bmatrix} \cos\theta_e & \cos(\theta_e - \frac{2\pi}{3}) & \cos(\theta_e + \frac{2\pi}{3}) \\ \sin\theta_e & \sin(\theta_e - \frac{2\pi}{3}) & \sin(\theta_e + \frac{2\pi}{3}) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} \tag{3.8}$$

To simplify the model, the zero phase sequence component can be ignored and equation (3.8) then becomes:

$$\begin{bmatrix} V_d \\ V_q \end{bmatrix} = \frac{2}{3} \begin{bmatrix} \cos\theta_e & \cos(\theta_e - \frac{2\pi}{3}) & \cos(\theta_e + \frac{2\pi}{3}) \\ \sin\theta_e & \sin(\theta_e - \frac{2\pi}{3}) & \sin(\theta_e + \frac{2\pi}{3}) \end{bmatrix} \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} \tag{3.9}$$

Figure 3.3 shows the Simulink block diagram of the V_{abc} to V_{dq0} transformation, obtained by modelling using the MATLAB Simulink program.

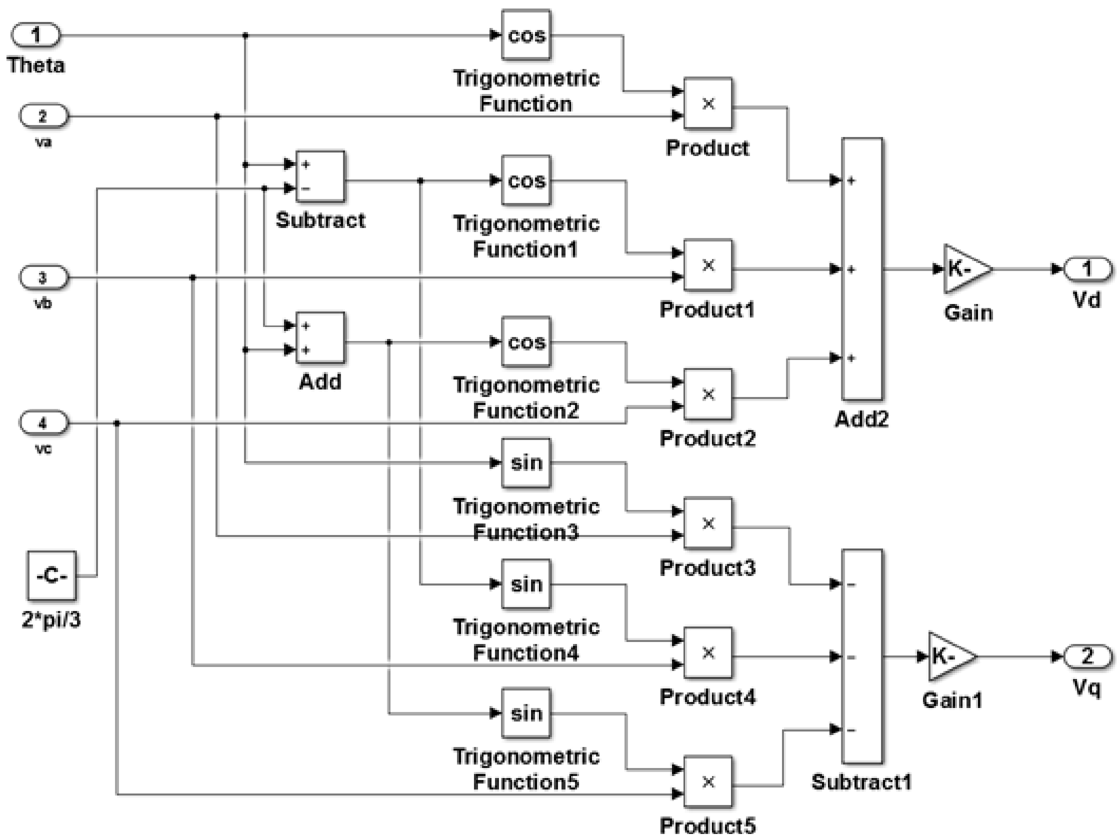

Figure 3.3: Simulink block diagram of V_{abc}_to_V_{dq}

When modelling a PMSG, the d-q synchronous reference frame components are used to derive the model. The d-axis components and q-axis components can be controlled to influence the active and reactive power, respectively. By 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 expressed as follows [77]:

$$v_d = R_s i_d + L_d \frac{di_d}{dt} - \omega_e L_q i_q \tag{3.10}$$

$$v_q = R_s i_q + L_q \frac{di_q}{dt} - \omega_e \psi_{pm} + \omega_e L_d i_d \tag{3.11}$$

Where: v_d and v_q are the stator terminal voltages in the d-q axis reference frame (V), R_S is the stator resistance (Ω), L_d and L_q are the d, q axes reference frame inductances (H), i_d and i_q are the d, q axes reference frame stator currents (A), and ω_e is the electrical angular speed (rad/sec).

Equations (3.10) and (3.11) can be rearranged to obtain the output d and q currents of the generator as follows:

$$i_d = \int \left(\frac{v_d}{L_d} - \frac{R_s}{L_d} i_d + \frac{L_q}{L_d} \omega_e i_q\right) \tag{3.12}$$

$$i_q = \int \left(\frac{v_q}{L_q} - \frac{R_s}{L_q} i_q + \frac{L_d}{L_q} \omega_e i_d - \frac{\psi_{pm}}{L_q} \omega_e\right) \tag{3.13}$$

In the d-q synchronous rotating reference frame, the electromagnetic torque (T_e) is presented as follows:

$$T_e = \frac{3}{2}(\psi_{pm}.i_q + (L_d - L_q)i_d.i_q) \quad (3.14)$$

Where: p is the number of pole pairs.

Figure 3.4 shows the (PMSG) generator system Simulink block diagram for the complete processes from the rotor speed, to the magnetizing circuit and the generated output power. The main objective is to use the generator Simulink model to generate electricity under variable water flow speeds.

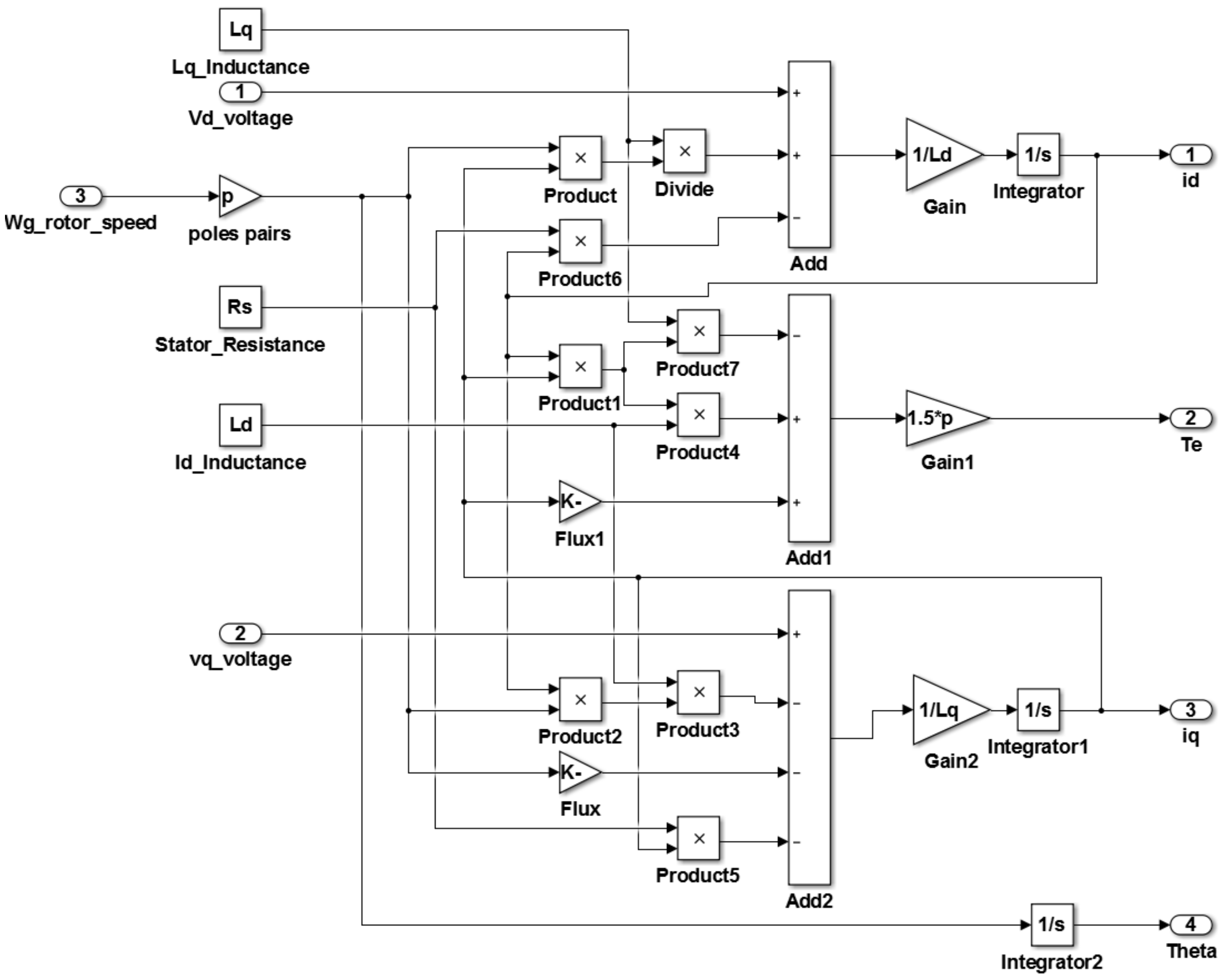

Figure 3.4: Simulink block diagram of a modelled (PMSG) generator system

The relationship between the electrical angular speed (ω_e) and rotor angular speed of the generator (ω_g) is expressed as follows:

$$\omega_e = p.\omega_g \tag{3.15}$$

The relationship between ω_e and electrical angle (θ_e) is expressed as follows:

$$\frac{d\theta_e}{dt} = \omega_e \tag{3.16}$$

3.4 PI controller model

Since the hydrokinetic power fluctuates with water speed, the PMSG output voltage and frequency vary continuously. The controller plays an important role in solving this problem. The I_{dq} current controller is responsible for affecting the reference current magnitude and angle within the stator. The design of the current controller is based on the v_d and v_q voltages.

Let:

$$v_d(t) = \frac{V_{dc}}{2} m_d(t) \tag{3.17}$$

$$v_q(t) = \frac{V_{dc}}{2} m_q(t) \tag{3.18}$$

Where: m_d and m_q represent the direct and quadrature axis modulation signals.

Due to the presence of $L\omega_0$ terms in Equations (3.19) and (3.20), the dynamics of i_d and i_q are coupled. To decouple these dynamics, we determine m_d and m_q as:

$$m_d(t) = \frac{2}{V_{dc}}(v_d - L\omega_0 i_q) \tag{3.19}$$

$$m_q(t) = \frac{2}{V_{dc}}(v_q - L\omega_0 i_d) \tag{3.20}$$

Where: L is the inductance, ω_0 is the angular frequency.

The d-axis PI-compensator transfer function is given by:

$$k_d(s) = \frac{(K_p s + k_i)}{s} \tag{3.21}$$

Where K_p and k_i are proportional and integral gains, respectively. Thus, the loop gain is expressed as:

$$l(s) = \left(\frac{k_p}{L_s}\right)\frac{s + k_i/k_p}{s + (R + r_{on})/L} \tag{3.22}$$

It is noted that due to the plant pole at $s = -(R + r_{on})/L$, which is fairly close to the origin, the magnitude and the phase of the loop gain begin to drop from a relatively low frequency. Thus, the compensator zero firstly cancels the plant pole, $s = -\frac{ki}{kp}$ and the loop gain assumes the form, $E_{(s)} = \frac{k_p}{L_s}$. Then, the closed-loop transfer function $E_{(s)}/(1 + E_{(s)})$ becomes:

$$\frac{I_d(s)}{I_{dref}(s)} = G_i(s) = \frac{1}{\tau_i s + 1} \tag{3.23}$$

With,

$$k_p = L/\tau_i \tag{3.24}$$

$$k_i = (R + r_{on})/\tau_i \quad (3.25)$$

Where τ_i is the time constant of the resultant closed-loop system.

Equation (3.23) indicates that, if kp and ki are selected based on (3.24) and (3.25), the response of i_d(t) to i_d-ref (t) is based on a first-order transfer function, whose time constant τ_i is a design choice. τ_i should be made small for a fast current-control response but adequately large so that $1/\tau_i$, that is, the bandwidth of the closed-loop control system, is considerably smaller. For example, it can be made 10 times smaller than the switching frequency of the DC-DC controller (expressed in rad/s). Depending on the requirements of a specific application and the converter switching frequency, τ_i is typically selected in the range of 0.5-5 ms. The same compensator as $k_d(s)$ is also adopted for the q-axis compensator kq(s) as in the d-q model.

Based on (3.26) and (3.27), i_d and i_q can be controlled by v_d and v_q, respectively. The d-axis compensator processes $e_d = i_d ref - i_d$ provides a V_d voltage.

$$L\frac{di_d}{dt} = V_d - (R + r_{on})i_d \quad (3.26)$$

$$L\frac{di_q}{dt} = V_q - (R + r_{on})i_q \quad (3.27)$$

Where: r_{on} is the resistance due to mutual induction.

Then, based on Equation (3.19), it can be seen that v_d contributes to m_d . Similarly, the q-axis compensator processes $e_q = iqref - iq$ and provides v_q voltage that contributes to m_q. The controller then amplifies m_d and m_q by a factor of $V_{dc}/2$ and generates V_d and V_q that, in turn, control i_d and i_q based on (3.12) and (3.13).

To make i_d and i_q the subject of the formula, Equations (3.26) and (3.27) can be rearranged as follows:

$$i_d = \int \left(\frac{v_d}{L} - \frac{(R + r_{on})}{L} i_d\right) \quad (3.28)$$

$$i_q = \int \left(\frac{v_q}{L} - \frac{(R + r_{on})}{L} i_q\right) \quad (3.29)$$

3.4.1 Proportional integral (PI) DC-DC boost power converter

The figure below shows a Simulink block diagram of the developed feedback I_{dq} controller, the converter involved element of the reference set point, the gain factor and the transfer function coupled to realize the objective of power stabilization.

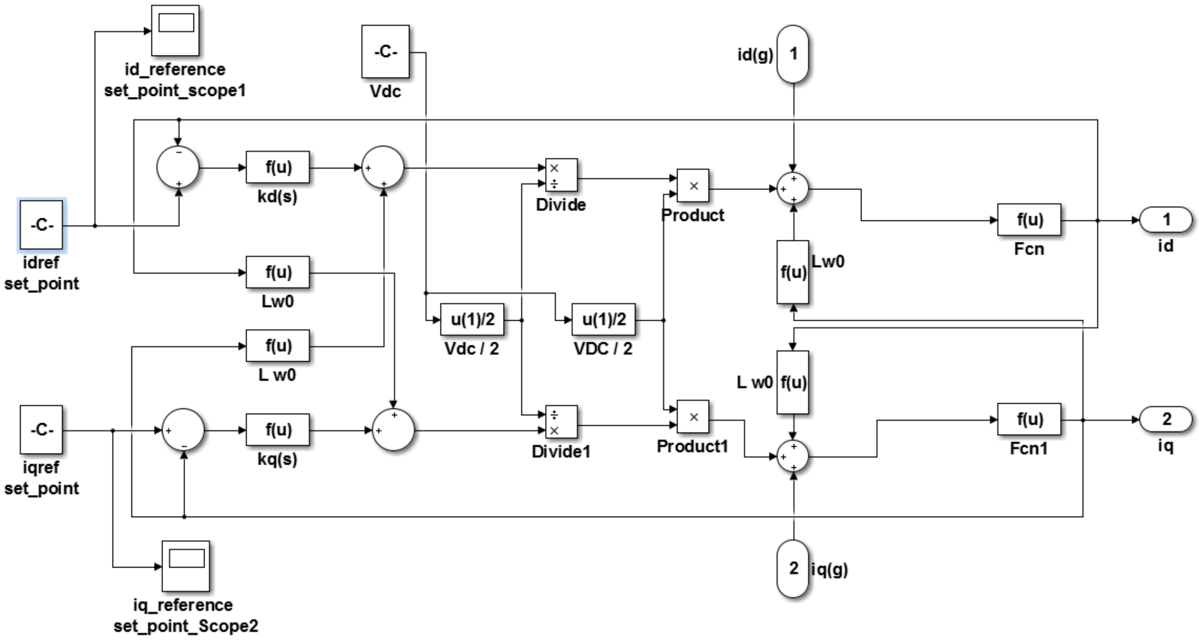

Figure 3.5: Simulink block diagram of a modelled converter system

This work presented the modelling and control technique of a variable speed hydrokinetic turbine system comprised of a PMSG. The main purpose of the investigation was to make use of the power electronic control system to prevent voltage deviation in a hydrokinetic turbine system due to variable flowing water speed constraints. The proposed AC-DC-AC control model has been developed using the MATLAB/Simulink program. Through the inclusion of the converter between the generator and the load, constant voltage in terms of the amplitude and frequency was achieved at variable water flow speeds. This was made possible through maintenance of a constant control reference setting. Hence, the proposed control algorithm is suitable for the hydrokinetic turbine generation system as revealed by the simulation results.

3.5 Differential flatness based controller model

The layout of the system can be better understood using the flow diagram in figure 3.6, numbered from 1 to 4 below:

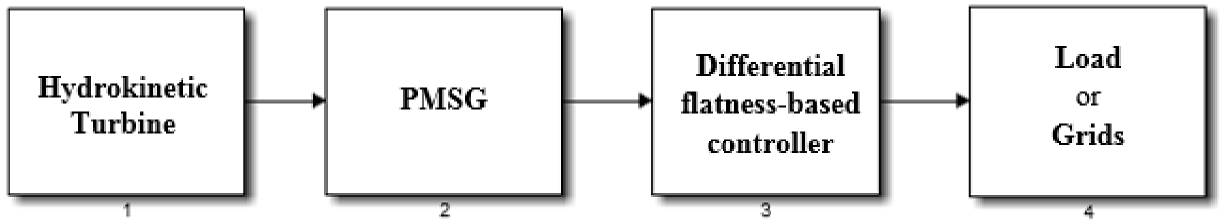

Figure 3.6: Flow diagram of control system

The turbine converts the mechanical energy of flowing water to drive the shaft of the permanent magnet synchronous generator (PMSG). The electrical energy that is generated by the PMSG is then controlled by using the differential flatness based controller to obtain a stable output voltage and frequency to supply the load.

The d-q reference stator voltages in equation (3.10) and (3.11) can be expressed as follows:

$$V_d = R_s i_d + \frac{d\psi_d}{d_t} - \omega_e \psi_q \tag{3.30}$$

$$V_q = R_s i_q + \frac{d\psi_q}{d_t} - \omega_e \psi_d \tag{3.31}$$

Knowing that the stator flux linkage components in the d-q frame are expressed as follows:

$$\psi_d = L_d i_d + \psi_{pm} \quad (3.32)$$

$$\psi_q = L_q i_q \quad (3.33)$$

Moreover, the permanent magnet flux linkage components are expressed as follows:

$$\psi_{pm} = \frac{\omega_e}{E} \quad (3.34)$$

Substituting ψ_d and ψ_q from equations (3.32) and (3.33) into equations (3.30) and (3.31)

$$V_d = R_s i_d + L_d \frac{di_d}{d_t} + \frac{d\psi_{pm}}{d_t} - \omega_e L_q i_q \quad (3.35)$$

$$V_q = R_s i_q + L_q \frac{di_q}{d_t} + L_d \omega_e i_d + \omega_e \psi_{pm} \quad (3.36)$$

Where: v_d and v_q are the stator terminal voltages in the d-q axes reference frame voltages measured in volts (V), R_S is the stator resistance measured in ohm (Ω), L_d and L_q are the d-q axes reference frame inductances measured in henry (H), i_d and i_q are the d-q axis reference frame stator currents measured in amperes (A), ψ_{pm} is the permanent magnet flux and ω_e is the electrical angular speed (rad/sec).

Equations (3.35) and (3.36) can be rearranged be substituting ω_e from equation (3.35) to obtain the output d and q voltages of the generator as follows:

$$V_d = R_s i_d + L_d \frac{di_d}{d_t} + \frac{d\psi_{pm}}{d_t} - E\psi_{PM} L_q i_q \tag{3.37}$$

$$V_q = R_s i_q + L_q \frac{di_q}{d_t} + L_d E\psi_{pm} i_d + E\psi_{pm}^2 \tag{3.38}$$

Marking $\dot{i_d}$ and $\dot{i_q}$ the subject of equations (3.37) and (3.38) gives

$$\dot{i_d} = \frac{V_d}{L_d} - \frac{R_s}{L_d} i_d + \frac{E\Psi_{pm} L_q}{L_d} i_q - \frac{\dot{\Psi_{pm}}}{L_d} \tag{3.39}$$

$$\dot{i_q} = \frac{V_q}{L_q} - \frac{E\psi_{pm} L_d}{L_q} i_d - \frac{R_s}{L_q} i_q - \frac{E\psi_{pm}^2}{L_q} \tag{3.40}$$

3.5.1 Feedback linearization

Putting equations (3.39) and (3.40) into the state space form: $\dot{x} = f_{(x)} + g_{(x)} u$

This equation is used to calculate any other system variable. The purpose of putting the above equations into the state space form is to enable one to carry out flatness analysis of the system and to be able to separate the state vectors. The representation provides complete knowledge of all variables of the system such as that of the transfer function and system gain; hence, it will work well when dealing with a system of huge sizes.

$$\begin{vmatrix} \dot{i_d} \\ \dot{i_q} \end{vmatrix} = \begin{vmatrix} -\frac{R_s}{L_d} & \frac{E\psi_{pm} L_q}{L_d} \\ -\frac{E\psi_{pm} L_d}{L_q} & -\frac{R_s}{L_q} \end{vmatrix} \begin{matrix} i_d \\ i_q \end{matrix} + \begin{vmatrix} \frac{1}{L_d} & 0 \\ 0 & \frac{1}{L_q} \end{vmatrix} \begin{matrix} V_d \\ V_q \end{matrix} * \begin{vmatrix} -\frac{\dot{\Psi_{pm}}}{L_d} \\ -\frac{E\psi_{pm}^2}{L_q} \end{vmatrix} \tag{3.41}$$

$$f_{(x)} = \begin{vmatrix} f_1 \\ f_2 \end{vmatrix} = \begin{vmatrix} -\frac{R_s}{L_d} i_d & \frac{E\psi_{pm} L_q}{L_d} i_q \\ -\frac{E\psi_{pm} L_d}{L_q} i_d & -\frac{R_s}{L_q} i_q \end{vmatrix} \quad (3.42)$$

$f_{(x)}$ is the system matrix

$$g_{(x)} = \begin{vmatrix} g_1 & 0 \\ 0 & g_2 \end{vmatrix} = \begin{vmatrix} \frac{1}{L_d} & 0 \\ 0 & \frac{1}{L_q} \end{vmatrix} \quad (3.43)$$

$g_{(x)}$ is the input matrix

if the transfer function is selected based on (3.42) and (3.43), the response of equation (3.41) is based on a first order transfer function.

3.5.2 Differential flatness properties

To analyse differential flatness properties and flatness based control, the exact dynamic model of equation (3.41) is considered. The generalized system dynamics is written as [21]:

$$\dot{x} = f(\theta, x_{(t)}, u_{(t)}) \quad (3.44)$$

In the generic case, the system's coefficients θ are subject to uncertainty, i.e

$$\theta = \theta_0 + \bar{\theta}, \bar{\theta_\iota} \in [\theta_i, \bar{\theta_\iota}], \ i=1,\ldots,p \quad (3.45)$$

Where θ_0 is the nominal value of the parameter vector. Denoting the flat output $y_{(t)} \in \mathbb{R}$ and parameters vector θ, the definition of differential flatness given in chapter two is rewritten as follows [78]:

$$Y = h(\theta, x, u, \dot{u}, \ldots, u^{(r)}) \quad (3.46)$$

$$x = \emptyset(\theta, y, \dot{y}, \ldots, y^{(r-1)}) \quad (3.47)$$

$$u = \psi(\theta, x, y, \dot{y}, \ldots, y^{(r)}) \quad (3.48)$$

Where h,ϕ, *and* ψ are smooth functions defining mappings h respectively. It is also assumed that the flat output $y_{(t)}$ is independent of the coefficients (parameters) vector θ. Equations (3.46), (3.47) and (3.48) show that for every given trajectory of the flat output $t \rightarrow x_{(t)}$ and $t \rightarrow u_{(t)}$ are given without integration of any differential equation. Moreover, for a sufficiently smooth desired trajectory of the flat output $t \rightarrow y_{(t)}$, equations (3.46), (3.47) and (3.48) can be used to design the corresponding control, $u_{(t)}$ directly for the nominal system parameters θ_0. The trajectory y is called the nominal trajectory, while the trajectory u is called the nominal control. Thus, knowing the desirable system's output, one can also find the associated flat output y and subsequently the control input that makes the system track the desirable trajectory. Let i_d and i_q be chosen as the flat output, which actually is the state variable. The choice of the state variables for a given system is not unique. The requirement when choosing the state variables is that they be linearly independent and that a minimum number of them be chosen [80].

Representing $y_1 = i_d$ and $y_2 = i_q$

Expressing the state variable in terms of the flat output:

Let: $y_1 = i_d$

$\dot{y}_1 = \dot{i}_d$

$y_2 = i_q$

$\dot{y}_2 = \dot{i}_q$

Expressing equations (3.37) and (3.38) in terms of flat output:

$$\dot{y}_1 = \frac{1}{L_d}V_d - \frac{R_s}{L_d}i_d + \frac{E\Psi_{pm}L_q}{L_d}i_q - \frac{\dot{\Psi}_{pm}}{L_d} \quad (3.49)$$

$$\dot{y}_2 = \frac{1}{L_q}V_q - \frac{E\psi_{pm}L_d}{L_q}i_d - \frac{R_s}{L_q}i_q - \frac{E\psi_{pm}^2}{L_q} \quad (3.50)$$

Expressing the input in terms of flat output, from equations (3.37) and (3.38):

$$V_d = R_s y_1 - E\Psi_{pm}L_q y_2 + L_d\dot{y}_1 + \dot{\psi}_{pm} \quad (3.51)$$

$$V_q = L_d E\Psi_{pm} y_1 + R_s y_2 + L_q\dot{y}_2 + E\psi_{pm}^2 \quad (3.52)$$

Expressing the state in terms of flat output, from equations (3.39) and (3.40):

$$i_d = \frac{1}{R_s}V_d + \frac{E\Psi_{pm}L_q}{R_s}y_2 - \frac{L_d}{R_s}\dot{y}_1 - \frac{\dot{\psi}_{pm}}{R_s} \quad (3.53)$$

$$i_q = \frac{1}{R_s} V_q + \frac{E\Psi_{pm} L_d}{R_s} y_1 - \frac{L_q}{R_s} \dot{y}_2 - \frac{E\psi_{pm}^2}{R_s} \quad (3.54)$$

Once the system variables and inputs are expressed in terms of the flat output, the flat trajectories are then designed for the control.

3.5.3 Generating the flat trajectory

A flat trajectory is a set of polynomial functions that can take the system from a desired initial condition, which is the deviation caused by the fluctuating generating input power, to a desired final value. Polynomial is a mathematical expression consisting of variables (or indeterminates) and coefficients, and they involve only the operation of addition, subtraction and multiplication. The beauty of the application of polynomial function in control systems is its tendency to turn to unity when subjected to the principle of differentiation [79]. Polynomial coefficients in this case are chosen using the "Routh- Hurwitz criterion", which speaks to the stability of a system only when all its factors fall within the left of a Cartesian plane, and strictly avoiding a factor at the imaginary axes [80].

Let the set of polynomial functions generated in MATLAB software program be given as follows [81]:

$$y_1 = 0.1300t^3 - 0.0377t^4 + 0.0030t^5 \quad (3.55)$$

$$\dot{y}_1 = 0.3900t^2 - 0.1508t^3 + 0.0150t^4 \quad (3.56)$$

$$y_2 = 0.0230t^3 - 0.0754t^4 + 0.0060t^5 \quad (3.57)$$

$$\dot{y}_2 = 0.0690t^2 - 0.3016t^3 + 0.0300t^4 \quad (3.58)$$

Given the initial conditions and their derivatives at the initial states, with the final values for the states and the inputs, the trajectory of the flat output can be determined at the initial and final times. The proposed flat trajectory is used to lead the generated power of the PMSG by applying the state variable i_d and i_q in figure 3.9 and generating the flat trajectory as shown in figures 3.7 and 3.8 respectively.

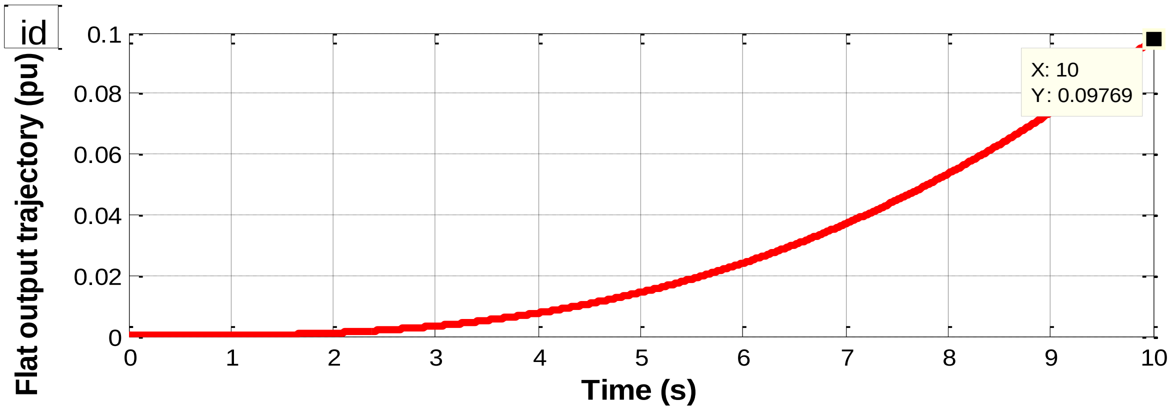

Figure 3.7: Flat trajectory of d-axis

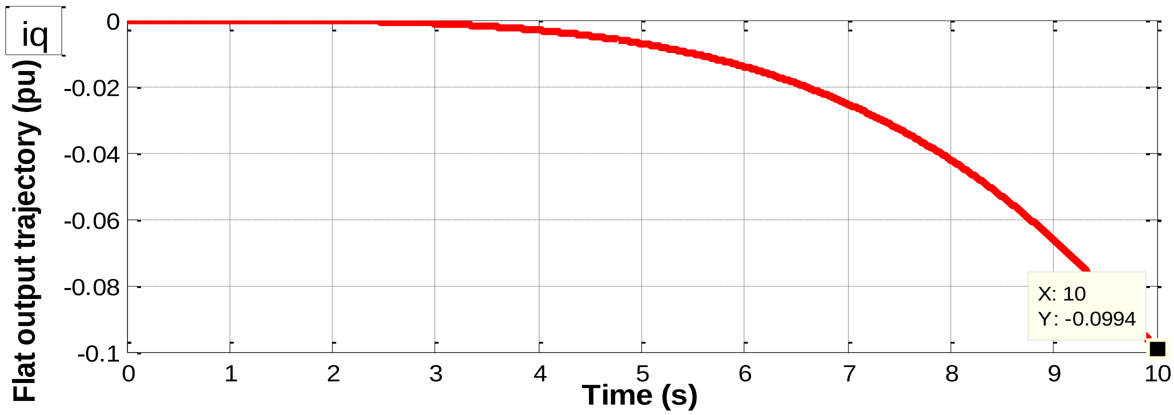

Figure 3.8: Flat trajectory of q-axis

3.5.4 Differential flatness converter

Figure 3.9 includes the clock for the timing of the flat input $y_1, \dot{y}_1, y_2$ and $\dot{y}_2$ as seen in equations (3.55) to (3.58) respectively. The trajectory is generated using i_d and i_q in equations (3.53) and (3.54) respectively: the gain is multiplied to obtain the maximum power of the system, while the system uses the transfer function to communicate between the input and output for effective control, and finally uses a relay to determine the lower limit of operation.

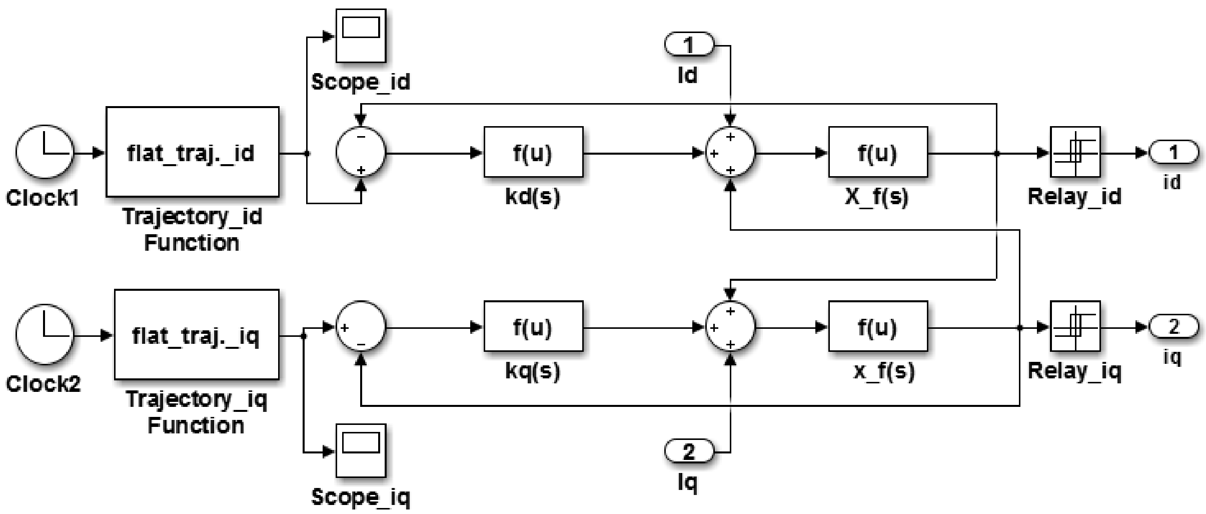

Figure 3.9: Simulink block diagram of a differential flatness based controller

A differential flatness based controller of this nature is used to manage the variable speed hydrokinetic turbine energy generation system, which includes a three-phase variable speed permanent magnet synchronous generator (PMSG) connected to the load through a controller. The idea is to consider a flat system. Then, trajectories are generated which are planned to take the input generated variable to ensure a desired final value, and in doing so, extracting the maximum generated power.

3.5 Converting from I_{dq0} to I_{abc}

The conversion of i_{dq0} back to i_{abc} after the control block is made possible by means of reverse Park's transformation, as shown in equation (3.59) below:

$$\begin{vmatrix} i_d \\ i_q \\ i_c \end{vmatrix} = \frac{2}{3} \begin{vmatrix} \cos\Theta_e & \sin\Theta_e & 1 \\ \cos(\Theta_e - \frac{2\pi}{3}) & \sin(\Theta_e - \frac{2\pi}{3}) & 1 \\ \cos(\Theta_e + \frac{2\pi}{3}) & \cos(\Theta_e + \frac{2\pi}{3}) & 1 \end{vmatrix} \begin{vmatrix} i_d \\ i_q \\ i_0 \end{vmatrix} \quad (3.59)$$

When zero phase sequence component is ignored, equation (3.60) becomes:

$$\begin{vmatrix} i_d \\ i_q \\ i_c \end{vmatrix} = \frac{2}{3} \begin{vmatrix} \cos\Theta_e & \sin\Theta_e & 1 \\ \cos(\Theta_e - \frac{2\pi}{3}) & \sin(\Theta_e - \frac{2\pi}{3}) & 1 \\ \cos(\Theta_e + \frac{2\pi}{3}) & \cos(\Theta_e + \frac{2\pi}{3}) & 1 \end{vmatrix} \begin{vmatrix} i_d \\ i_q \end{vmatrix} \quad (3.60)$$

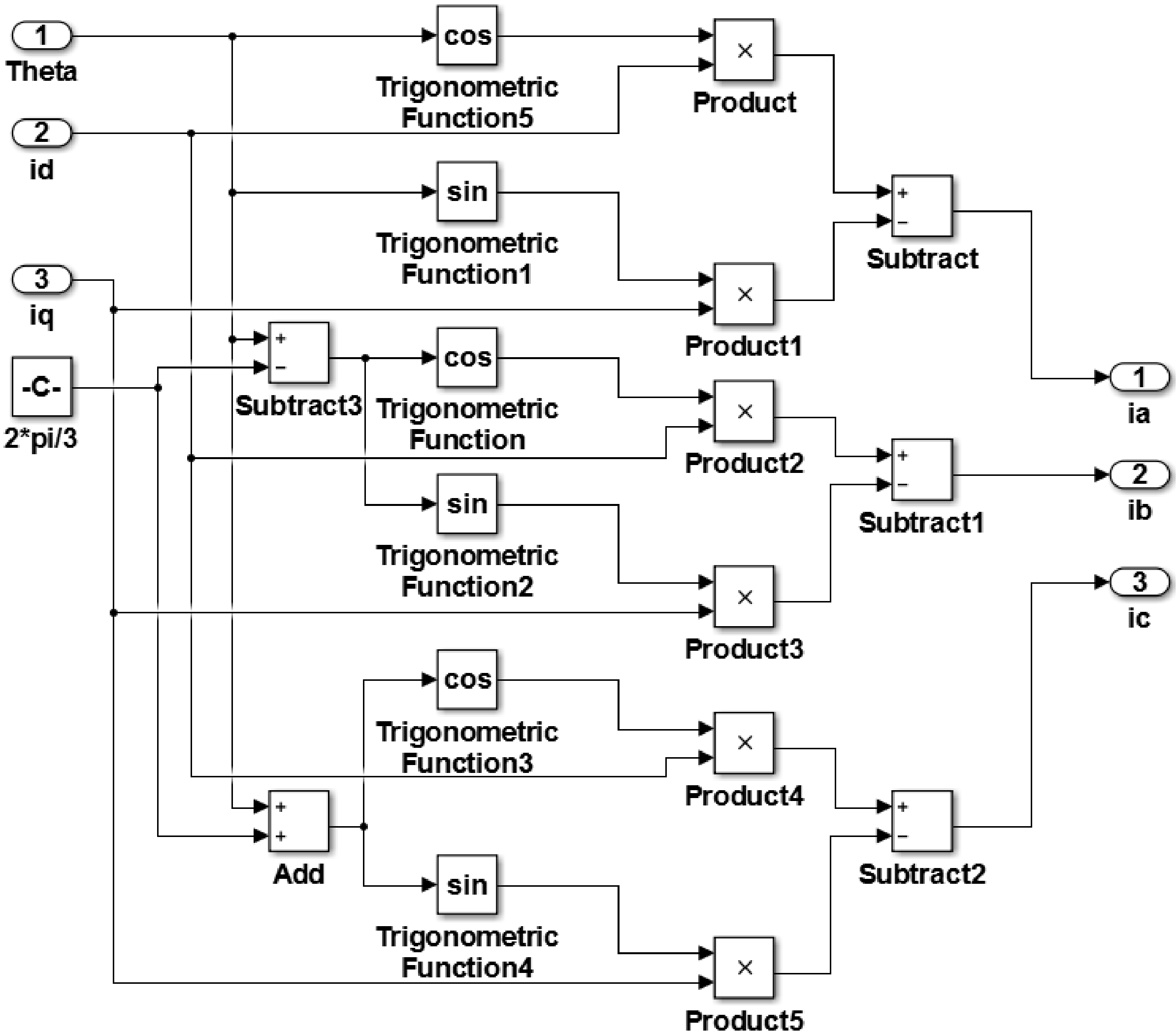

Figure 3.10: Simulink block diagram of $V_{dq0}\_to\_V_{abc}$

Finally, the three phase output currents (i_{abc}) in equations (3.61), (3.62) and (3.63) are then used to supply a three phase load, or can be injected into an electrical power grid system for utilization.

$$\frac{di_a}{dt} = \frac{1}{L}(v_a(t) + i_a R_s + v_a) \quad (3.61)$$

$$\frac{di_b}{dt} = \frac{1}{L}(v_b(t) + i_b R_s + v_b) \quad (3.62)$$

$$\frac{di_c}{dt} = \frac{1}{L}(v_c(t) + i_c R_s + v_c) \qquad (3.63)$$

3.6 Final Simulink block diagram of the developed converter

Figure 3.11 shows the overall MHRC system Simulink block diagram for the complete processes from the turbine, drivetrain, generator, control and to the three-phase load. The main objective is to use the overall Simulink model to test the proposed control system performance under variable water flow speed.

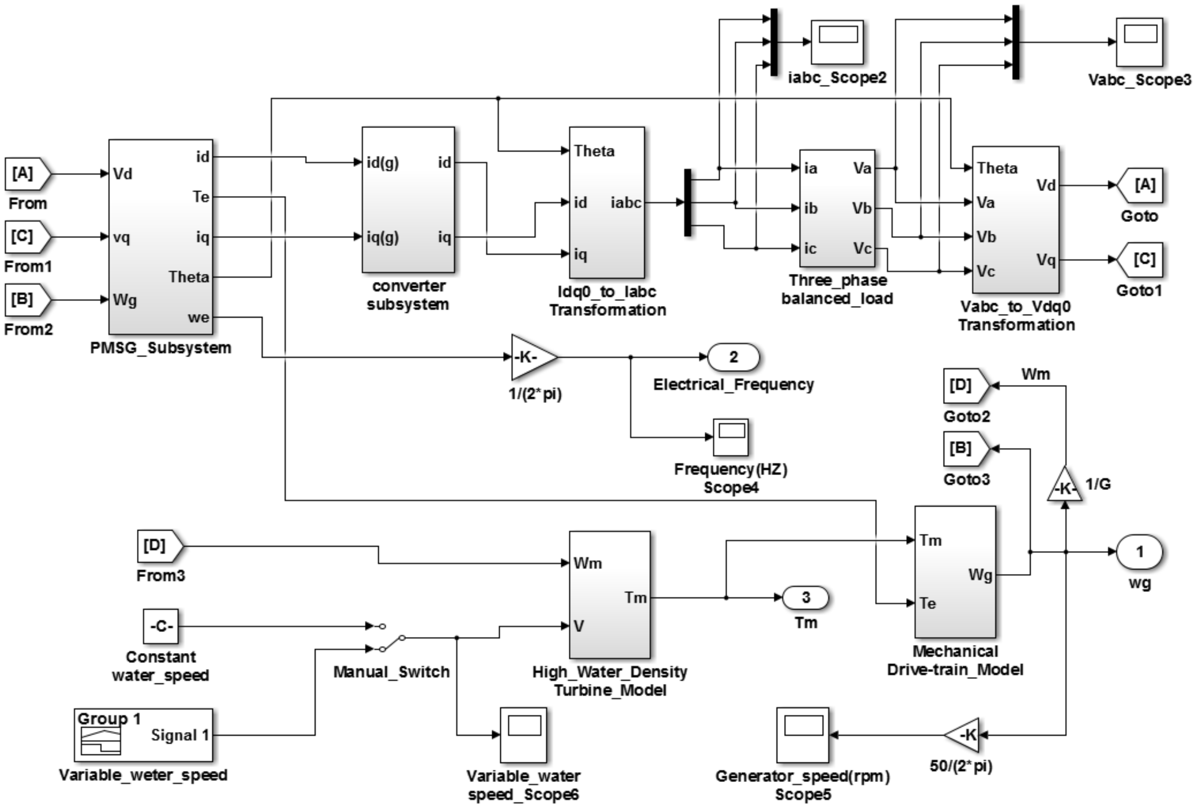

Figure 3.11: Simulink block diagram of an overall MHRC system model

3.7 Conclusion

In this chapter, the mathematical model for an off-grid micro-hydrokinetic river control system has been presented, one using proportional integral (PI) and the other employing a differential flatness based principle. This mathematical model has been used to develop a Simulink model for the overall system. The model is comprised of a turbine, drivetrain, a direct driven permanent magnet synchronous generator (PMSG) and a controller modelling. This model can be used by designers to model a micro- hydrokinetic river control system during the planning stage by simply inserting the parameters of the water flow speed, selected horizontal turbine, PMSG and a controller to be used. The performance of an off-grid MHR control system and effects of variable water speed on the system's behaviour can be analysed. This model can be used to simulate any renewable energy system employing a PMSG with either a salient pole or non-salient pole rotor.

CHAPTER 4: SIMULATION RESULTS AND DISCUSSION

4.1 Introduction

This chapter demonstrates the simulation results based on the hydrokinetic model developed in chapter 3 using a MATLAB/Simulink software program. The aim is to test/reveal the correctness/effectiveness of the developed model. This is done by studying the dynamic behaviour of the MHR control system under variable water speed. Three different cases were investigated in order to reveal the quality of the proposed power conversion solution for the variable speed hydrokinetic river system. The first case shows the performance of a hydrokinetic underwater generator without the inclusion of the controller exposed to a variable speed river system. The second case will reveal the simulation results with the inclusion of the PI controller in the hydrokinetic underwater generator system, and the third case will reveal the simulation results with the inclusion of the adaptive differential flatness based controller in the hydrokinetic underwater generator (or turbine). The validation of the modelling result is fulfilled through simulation carried out using the MATLAB/Simulink program. The results will reveal the system that is more efficient in delivering the same amount of electrical power. The simulation results proved that the control strategy works very well for the proposed hydrokinetic turbine system under variable flowing water speeds.

Table 3 gives the parameters of a permanent magnet synchronous generator (PMSG). The reason for selecting a PMSG over other types of generators is its ability to operate at low speed and also to improve the reliability of the variable speed hydrokinetic system [82]. Low speed operation capability eliminates the requirement for a gearbox that often suffers from mechanical faults and thus reduces the efficiency of the overall system. Therefore, a direct driven PMSG has been selected in this study.

TABLE 4.1: PMSG PARAMETERS [74].

Categories	Values
Stator phase resistance	2
Number of pole pairs	8
d–q axis inductance	1 mH
Permanent magnet flux	0.46 Wb
Rated rotor speed	375 rpm
Rated power	2 kW
Rated phase voltage	120 V
Rated phase current	17 A
Rated frequency	50 Hz
Balance three phase load	20kw

The selected PMSG is capable of generating 132.5 V, 50 Hz at a rated full load speed of 313.3rpm, as shown in Table 4.1. During the simulations, a Simulink signal builder has been used for variable step input in order to see how the system responds to a change in water speed. It has been assumed that the water flow velocity varies from 0.45 to 2.58 m/s. The step input signal and the selected time are only used for simulation purposes in order to show how the developed model is responding.

4.2 Simulation results

4.2.1 Case 1: Performance of a PMSG based hydrokinetic underwater turbine without AC-DC-AC converter.

This section shows the simulation results based on the performance of a micro-hydrokinetic turbine system equipped with a permanent magnet synchronous generator (PMSG) under variable water speeds and without the converter (control) system.

Based on the operational principle of synchronous generators, the rotational speed of the generator together with the number of poles determines the frequency of the induced voltage. From Figure 4.1 and Figure 4.2, it can be noticed that, at any point in time, the angular speed of the generator changes directly in proportion to the change in water flow speed. When the speed of the water increases to 2.58 m/s (from t = 3 s to 7 s), the generated voltage reaches a 187.2 V-peak as observed in figure 4.3 and at a frequency close to the 50 Hz referred to in figure 4.5. The variations of the water flow speed also relate to the variation of the generated voltage, current and frequency magnitude, as seen in figures 4.3, 4.4 and 4.5 respectively.

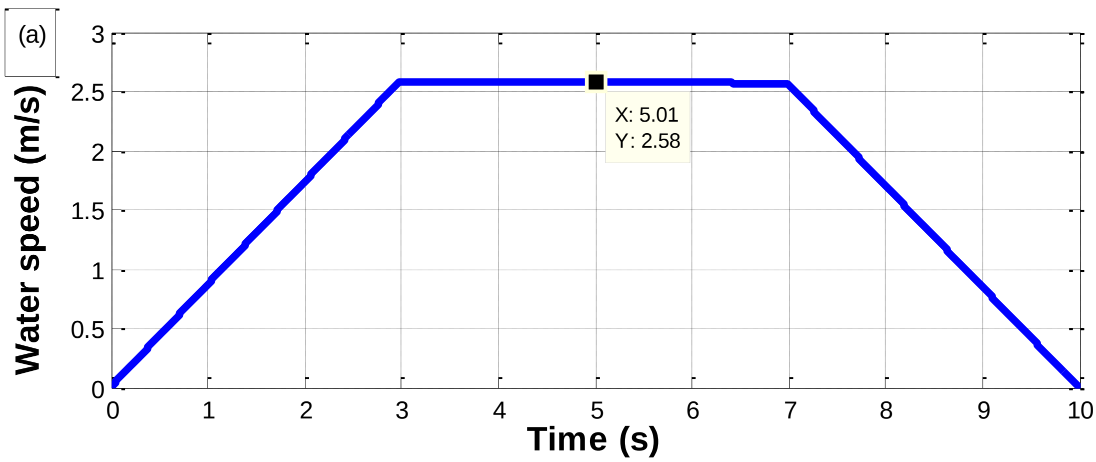

Figure 4.1: Water speed (without a controller)

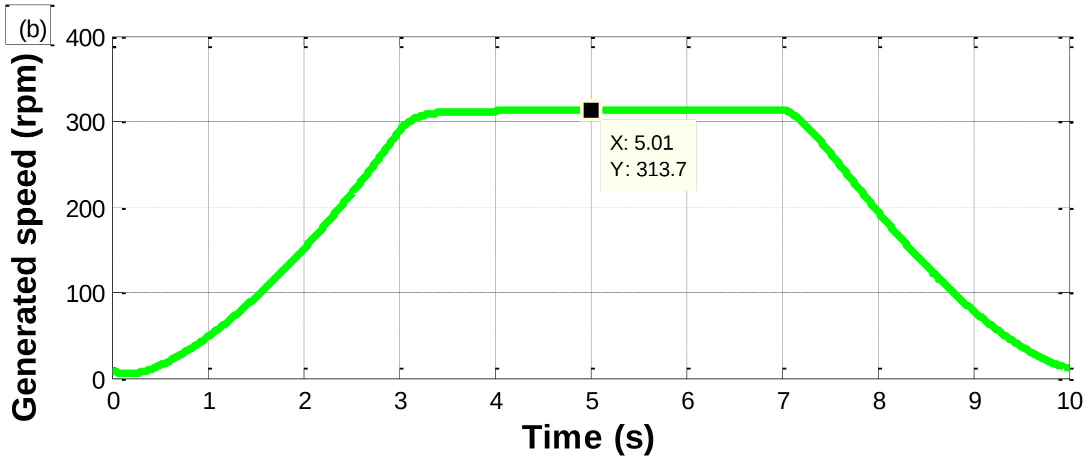

Figure 4.2: Generator speed (without a controller)

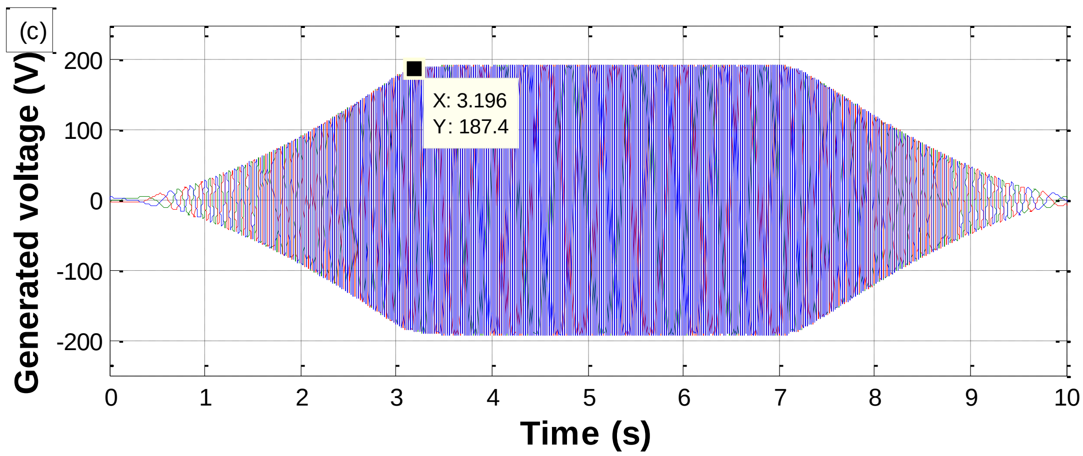

Figure 4.3: Generated Voltage (without a controller)

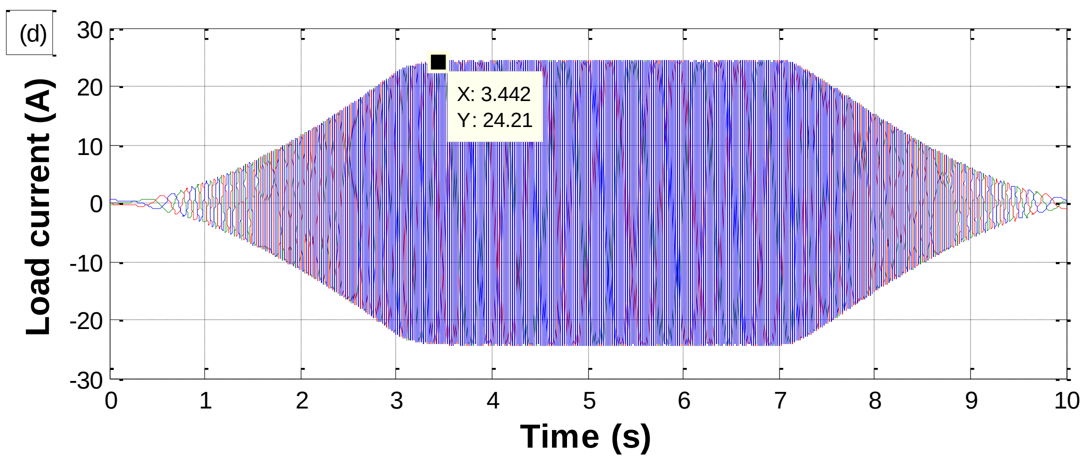

Figure 4.4: Load Current (without a controller)

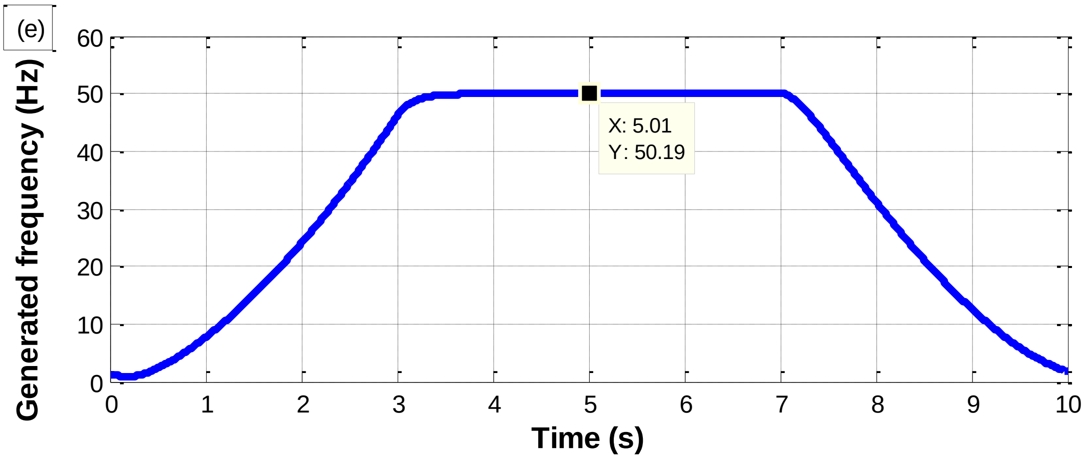

Figure 4.5: Electrical frequency (without a controller)

The simulation results proved that the generated energy obtained from a hydrokinetic river system, is non-linear, as it changes proportionally with the flow velocity of the water. This presents a necessity for a controller, to help in keeping the output power constant, so that hydrokinetic generation systems can be implemented to supply electricity to consumer loads or to sell energy to the national grid.

4.2.2 Case 2: Performance of a micro-hydrokinetic underwater generator system with the inclusion of an AC-DC-AC converter.

This section shows the simulation results based on the performance of a micro-hydrokinetic turbine system under variable water speeds and with the inclusion of the converter (control) system. The converter is a built electronic circuit that transforms different voltage magnitudes to a constant voltage level.

As explained in chapter 3, the Park's Transformation theorem in this case is used to transform the variable AC input I_{abc} into a DC I_{dq0} by using equations (3.8) and (3.9). The DC to DC current-mode control pulse-width modulation controller (PWM) is adopted, resulting in the variation of the average value of the waveform. Figure 4.6 shows that, between t=0s to t=2s, a growth in frequency due to the weak input signal, at the time when its approaches t=1.5s to t=8.5s, it's reaches 50Hz, and finally the DC I_{dq0} signal is transformed back to I_{abc} quantity with the help of equations (3.59) and (3.60).

Figure 4.7 shows that, with the inclusion of the converter into the system, a constant voltage level is obtained at the output of the converter to a value of 182.8V-peak to supply the load, while Figure 4.8 gives a clearer view of the results displayed in Figure 4.7 for the period between 3s and 3.1s.

Figure 4.9 shows that the converter output current of 22.86A-peak is witnessed across the load. Figure 4.10 gives a clearer view of Figure 4.9 taken for a period between 3 and 3.1 seconds.

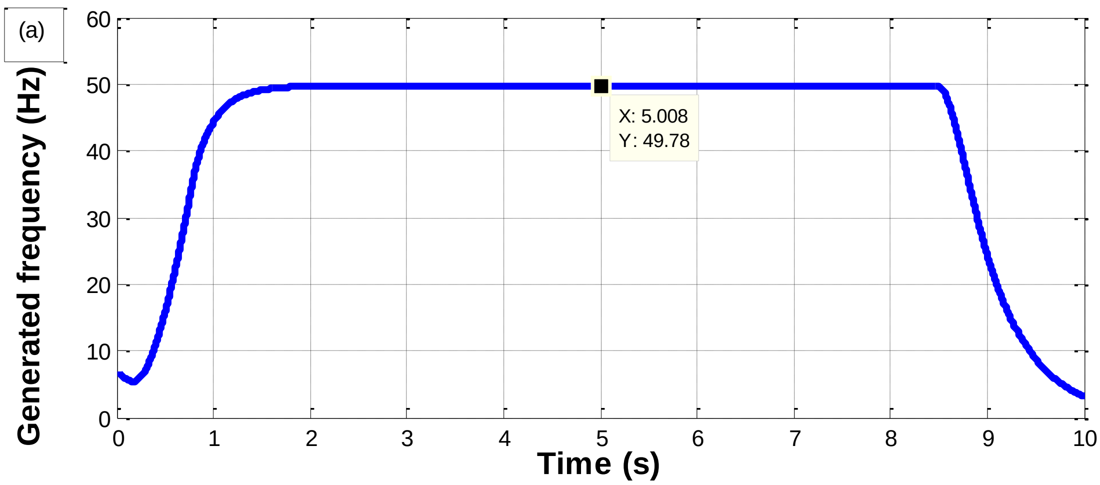

Figure 4.6: Electrical frequency (with PI converter)

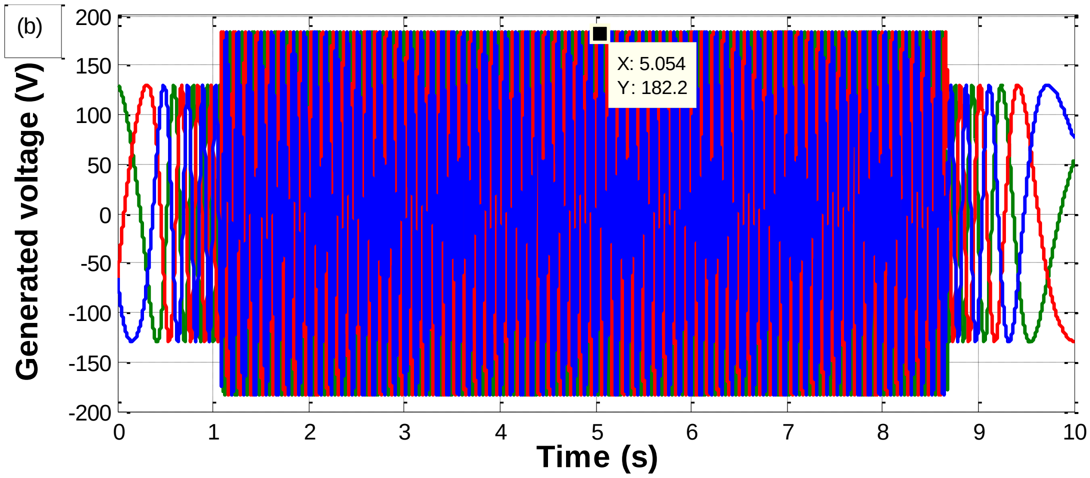

Figure 4.7: Load Voltage (with PI converter)

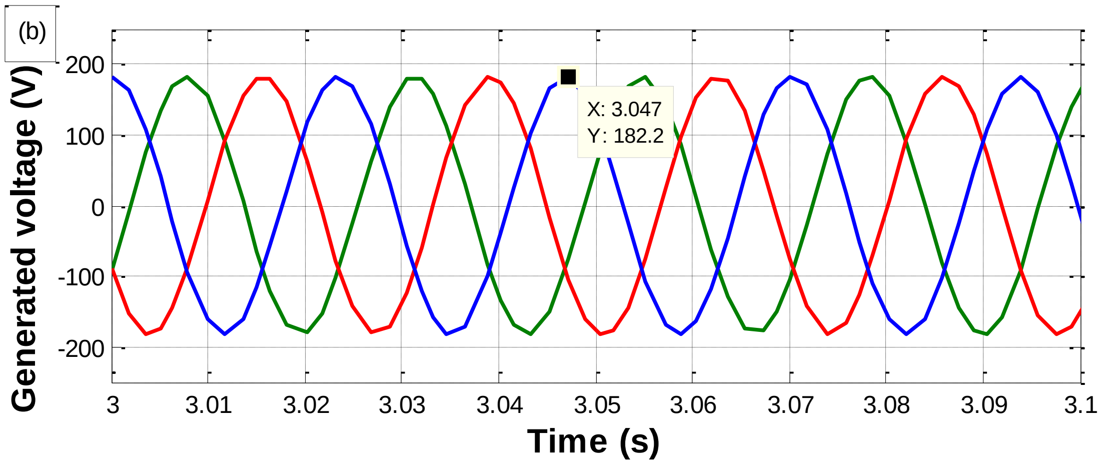

Figure 4.8: Load Voltage (extended with PI controller)

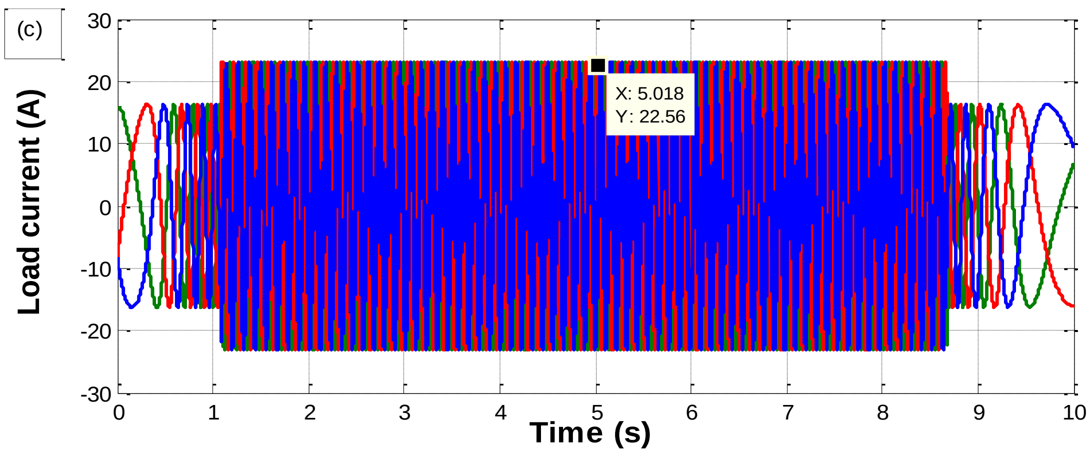

Figure 4.9: Load Current (with PI converter)

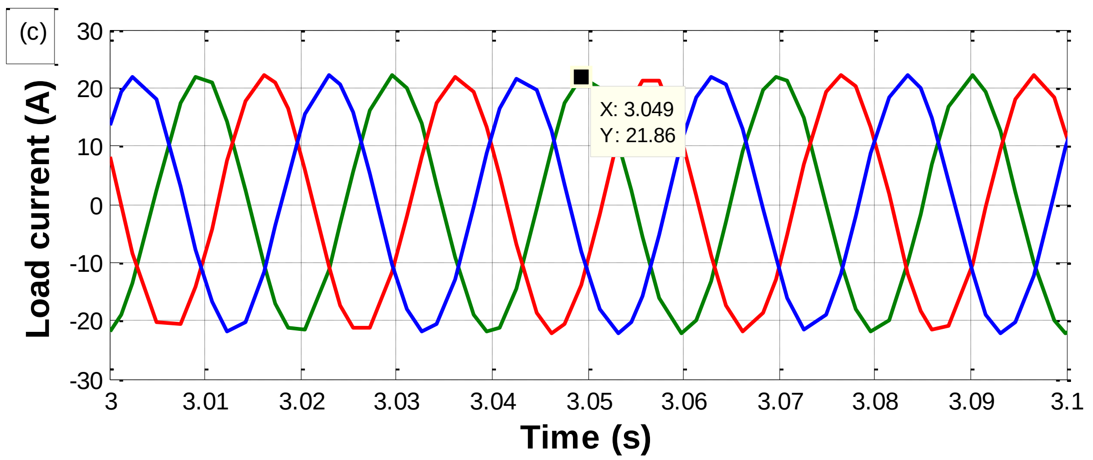

Figure 4.10: Load Current (extended with PI controller)

The simulation results proved that the control strategy works very well for the proposed hydrokinetic turbine system under variable flowing water speeds. This presents a necessity for future implementation of hydrokinetic generation systems to supply electricity to isolated rural loads or to sell energy to the national grid.

4.2.3 Case 3: micro-hydrokinetic river system performance with the inclusion of a flatness based converter.

This section shows the simulation results based on the performance of a micro-hydrokinetic turbine system under variable water speed and with the inclusion of a controller system. The converter is a built electronic circuit that transforms a different voltage magnitude to a constant voltage level. A relay is included in the converter circuit to allow the correct voltage level to be controlled.

The differential flatness DC to DC current-mode control is adopted resulting in the variation of the average value of the waveform. Figure 4.11 shows that between t=0s to t=2s, a zero frequency is experienced due to the weak input signal; at the time when it approaches t=2s to t=8.4s, it reached a stable value of 50Hz, and finally the DC I_{dq0} signal is transformed back to I_{abc} quantity by applying the reverse transformation method in equation (3.60).

Figure 4.12 shows that, between the periods 2s and 8.2s, with the inclusion of the converter into the system, a constant voltage level is obtained at the output of the converter to a value of 182.2V-peak to supply the load.

Figure 4.13 shows that the converter output current of 22.05A-peak is witnessed across the load.

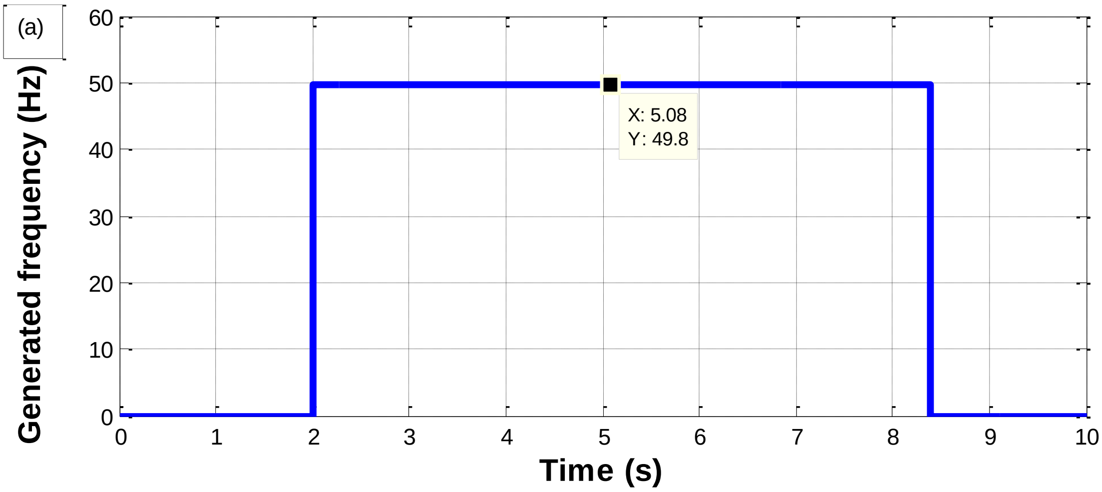

Figure 4.11: Electrical frequency (with flatness based controller)

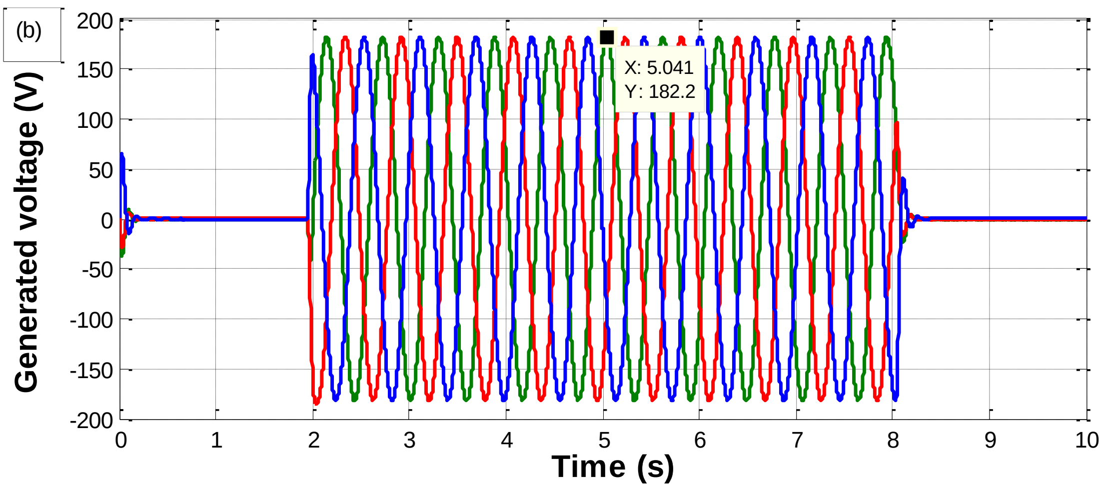

Figure 4.12: Load Voltage (with flatness based controller)

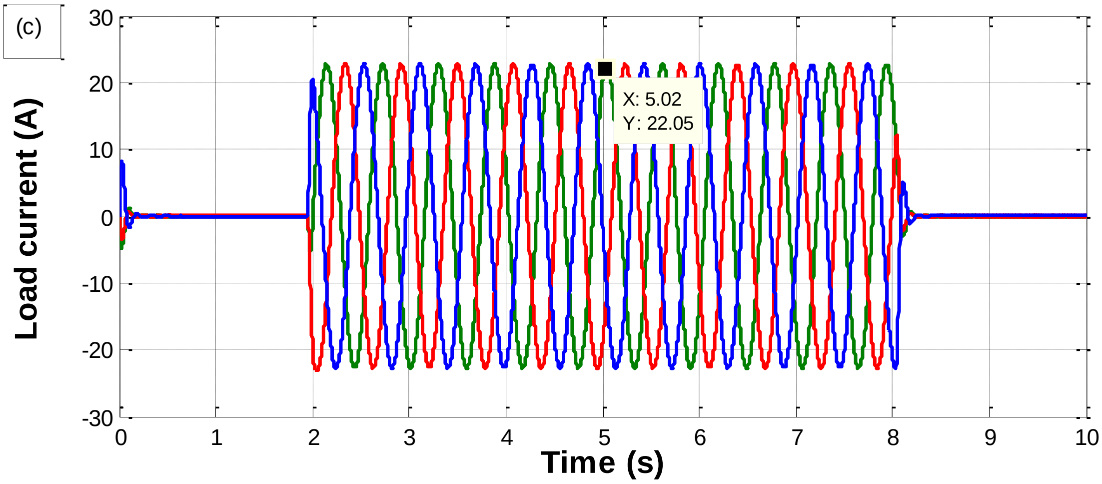

Figure 4.13: Load Current (with flatness based controller)

The results show that differential flatness based controller output voltage and frequency follow their reference flat trajectory and keep the output power constant. This principle is one effective way of controlling a system and can be readily applied to controllers used for generation of electrical energy, with additional advantages such as its simplicity in construction and the robustness of its operation. The proposed differential flatness based controller is developed using the MATLAB/Simulink program.

4.3 Conclusion

This chapter has demonstrated three sets of simulation results. The results illustrate the different level of generated output power obtained when a hydrokinetic turbine river system is used together with the PMSG. It also highlights the need for a converter in renewable energy power generation systems, and shows the stability of output voltage magnitude and frequency obtained from the converter, as per the standardised requirement.

CHAPTER 5: CONCLUSION AND FUTURE STUDIES

5.1 Conclusion

This chapter provides conclusions on controlling the generated output voltage and frequency from the generator resulting from the variable water input on the turbine side of an off-grid micro- hydrokinetic river system, as compared to a system without a controller, a system using a PI controller and a system with a differential flatness based controller.

A broader knowledge is applied to other forms of control, as a means of revealing a proper selection of technologies and creating awareness based on the potential control resource.

The principle of differential flatness has been presented in Chapter 2, which outlines the fact that flatness is centered on trajectory generation and trajectory tracking. The emphasis was on reviewing controlling methods applied in renewable energy studies. This chapter also exposed the fact that there is an opportunity to apply the differential flatness principle in controlling renewable energy power generation.

In Chapter 3, the development of a mathematical model for the controller of the converter topology was performed in order to demonstrate the potential level of power stabilization at the study site when using a flowing water resource. The modelling of a power converter was performed, which involved a PI converter as well as a differential flatness based converter. The simulation analysis was performed to compare the controller power output in the hydrokinetic system without a converter, to a system with the inclusion of a PI converter and a system that uses a differential flatness based converter. From the controller based case results, a differential flatness based system proved to be the most sensitive-effective, sustainable and environmentally friendly means of electric power control to the renewable study site. It controls electricity more reasonably than PI controller systems. Due to its reliability, it can switch-off when generation is below set limits.

Using the presented model, the dynamic behaviour of an MHR control system under variable water speed was simulated in Chapter 4 by making use of a MATLAB/Simulink software package. The simulation results proved that energy generation when using a variable flow hydrokinetic system and with the inclusion of a deferential flatness based power controller, the generated output voltage and frequency would meet the standard of the consumer load or grid specification. The off-grid MHR controller system is the best small-scale option to consider for remote rural electrification. The developed model and simulation cases have also been used to:

- Analyse the relationship between the variation of input water resource and desired output voltage.
- Analyse the relationship between the variation of input water resource and desired output frequency.
- Analyse the relationship between the number of poles and gearbox ratio.
- Demonstrate the importance of water flow rate (m/s) in relation to the speed of the synchronous rotor speed (rpm).

5.2 Suggestions for Further Studies

For future research, the developed flatness based model can be implemented in real time on a physical prototype to validate the developed model and the simulation results.

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