Flatness based control of a variable speed micro hydrokinetic generation system

P.B. Ngancha, K. Kusakana*, E. Markus

Abstract— In this paper, the concept of differential flatness is applied to a controller with the aim of producing constant voltage and frequency from a hydrokinetic with permanent synchronous generator submitted to variable water flow. The idea of this concept being to generate an imaginary trajectory that will take the system from an initial condition to a desired output generating power. The results show that, the generated output is dynamically adjusted during the voltage regulation process. The advantage of the proposed differential flatness based controller over the traditional proportional integral (PI) control is that decoupling is not necessary, as demonstrated by the modelling and simulation studies under different operating conditions, such as changes in water flow rate.

***Index Terms*— Hydrokinetic, Differential Flatness based, power controller, modelling, performance analysis**

1 INTRODUCTION

Renewable technologies offer clean sources of energy and provide an economical means of electrical energy generation which can be used to supply small households in far areas and also the utility grid lines [1]. Among different renewable energy technologies, hydrokinetic energy system is gaining recognition for its ease in construction and availability, as opposed to wind, solar or traditional hydropower energy [2]. Hydrokinetic energy generates electricity by making use of underwater wind turbines to extract the kinetic energy of flowing water [3].

The main setback of renewable energy sources of power generation is the fact that their produced powers depend on meteorological conditions which are highly nonlinear. Due to these intermittent and uncertain characteristics, serious problems are then posed when these sources are utilized for the generation of electrical energy, such as voltage variations and frequency fluctuations [4]. Frequency fluctuations and voltage instability are considered as threats for secure and economical operation in standalone and grid application systems [5]. Therefore, this paper will focus on controlling the variable output generated by hydrokinetic systems submitted to fluctuating water flow.

Several control strategies have been developed and applied in the energy generation industry over the years, and they involved decoupling of the alternating current component and in some cases reference values are needed.

In this paper, a differential flatness based adaptive control method is proposed and applied to a 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 which can be used to calculate all other system variables using differentiation [6]. 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 [7, 8]. 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 [9].

2 MICRO-HYDROKINETIC CONTROL SYSTEM OVERVIEW

This system can be better understood using the flow diagram in figure 1, numbered from 1 to 4 below:

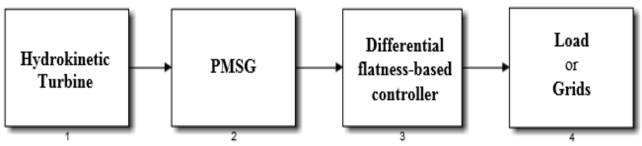

Figure 1: Flow diagram of control system

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.

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2.1 **Hydrokinetic turbine model**

The mechanical power extracted by a hydrokinetic turbine is expressed as follows [10]:

$$P_m = \frac{1}{2}\rho A V^3 C_p \quad (1)$$

Where: ρ is the water density (1000kg/m^3), A is the swept area of the turbine rotor blades (m^2), v is the flowing water velocity and C_p is turbine power coefficient.

The turbine power coefficient (C_p) 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 Eq. 2 [11]:

$$C_p(\lambda,\beta) = 0.5176\left(116\frac{1}{\lambda_i} - 0.4\beta - 5\right)e^{\left(\frac{-21}{\lambda_i}\right)} + 0.0068\lambda \quad (2)$$

The parameter λi is determined using the following equation:

$$\lambda_i = 1/\left(\frac{1}{\lambda+0.08\beta} - \frac{0.035}{1+\beta^3}\right) \quad (3)$$

A direct drive one-mass drive-train model has been bypassed in this system by applying a 1:1 ratio between the turbine and the PMSG.

2.2 **Permanent magnet synchronous generator (PMSG) model**

The PMSG generates three-phase AC components in the form:

$$v_a = R_s i_a + L_a\frac{di_a}{dt} - \omega_e L_a i_a \quad (4)$$

$$v_b = R_s i_b + L_b\frac{di_b}{dt} - \omega_e L_b i_b \quad (5)$$

$$v_c = R_s i_c + L_c\frac{di_c}{dt} - \omega_e L_c i_c \quad (6)$$

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 (9); more details on this concept can be found in ref. [12].

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

$$\omega_e = p.\omega_g \quad (7)$$

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

$$\frac{d\theta_e}{dt} = \omega_e \quad (8)$$

The conversion of three-phase voltage variables into DC voltage variables is done as follows:

$$\begin{vmatrix} v_d \\ v_q \\ v_0 \end{vmatrix} = \frac{2}{3}\begin{vmatrix} \cos\theta_e & \cos(\theta_e - \frac{2\pi}{3}) & \cos(\theta_e + \frac{2\pi}{3}) \\ \sin\theta_e & \sin(\theta_e - \frac{2\pi}{3}) & \sin(\theta_e + \frac{2\pi}{3}) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{vmatrix}\begin{vmatrix} V_a \\ V_b \\ V_c \end{vmatrix} \quad (9)$$

To simplify the model, the zero phase sequence component can be ignored and equation (9) then becomes:

$$\begin{vmatrix} v_d \\ v_q \end{vmatrix} = \frac{2}{3}\begin{vmatrix} \cos\theta_e & \cos(\theta_e - \frac{2\pi}{3}) & \cos(\theta_e + \frac{2\pi}{3}) \\ \sin\theta_e & \sin(\theta_e - \frac{2\pi}{3}) & \sin(\theta_e + \frac{2\pi}{3}) \end{vmatrix}\begin{vmatrix} V_a \\ V_b \\ V_c \end{vmatrix} \quad (10)$$

Converting V_{dq0} back to V_{abc} is made possible by means of reverse Park's transformation as shown in the equation (11) below.

$$\begin{vmatrix} V_d \\ V_q \\ V_c \end{vmatrix} = \frac{2}{3}\begin{vmatrix} \cos\Theta_e & \sin\Theta_e & 1 \\ \cos(\Theta_e - \frac{2\pi}{3}) & \sin(\Theta_e - \frac{2\pi}{3}) & 1 \\ \cos(\Theta_e + \frac{2\pi}{3}) & \cos(\Theta_e + \frac{2\pi}{3}) & 1 \end{vmatrix}\begin{vmatrix} V_d \\ V_q \\ V_0 \end{vmatrix} \quad (11)$$

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 [13]:

$$V_d = R_s i_d + \frac{d\psi_d}{d_t} - \omega_e \psi_q \quad (12)$$

$$V_q = R_s i_q + \frac{d\psi_q}{d_t} - \omega_e \psi_d \quad (13)$$

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

$$\psi_d = L_d i_d + \psi_{pm} \quad (14)$$

$$\psi_q = L_q i_q \quad (15)$$

And the permanent magnet flux linkage components expressed as follows:

$$\psi_{pm} = \frac{\omega_e}{E} \quad (16)$$

Substituting ψ_d and ψ_q from equations (14) and (15) into equations (12) and (13):

$$V_d = R_s i_d + L_d\frac{di_d}{d_t} + \frac{d\psi_{pm}}{d_t} - \omega_e L_q i_q \quad (17)$$

$$V_q = R_s i_q + L_q\frac{di_q}{d_t} + L_d\omega_e i_d + \omega_e\psi_{pm} \quad (18)$$

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 (17) and (18) can be rearranged be substituting ω_e from equation (17) to obtain the output d and q voltages of the generator as follows:

$$V_d = R_s i_d + L_d \frac{di_d}{d_t} + \frac{d\psi_{pm}}{d_t} - E\psi_{PM} L_q i_q \quad (19)$$

$$V_q = R_s i_q + L_q \frac{di_q}{d_t} + L_d E\psi_{pm} i_d + E\psi_{pm}^2 \quad (20)$$

Marking $\dot{i_d}$ and $\dot{i_q}$ the subject of equation (19) and (20) gives:

$$\dot{i_d} = \frac{V_d}{L_d} - \frac{R_s}{L_d} i_d + \frac{E\Psi_{pm} L_q}{L_d} i_q - \frac{\dot{\Psi_{pm}}}{L_d} \quad (21)$$

$$\dot{i_q} = \frac{V_q}{L_q} - \frac{E\psi_{pm} L_d}{L_q} i_d - \frac{R_s}{L_q} i_q - \frac{E\psi_{pm}^2}{L_q} \quad (22)$$

2.3 Feedback linearization

Putting equation (21) and (22) 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 equation into the state space form is to enable one to carry out flatness analysis of the system and also 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.

$$\begin{vmatrix} \dot{i_d} \\ \dot{i_q} \end{vmatrix} = \begin{vmatrix} -\frac{R_s}{L_d} & \frac{E\psi_{pm} L_q}{L_d} \\ -\frac{E\psi_{pm} L_d}{L_q} & -\frac{R_s}{L_q} \end{vmatrix} \begin{vmatrix} i_d \\ i_q \end{vmatrix} + \begin{vmatrix} \frac{1}{L_d} & 0 \\ 0 & \frac{1}{L_q} \end{vmatrix} \begin{vmatrix} V_d \\ V_q \end{vmatrix} * \begin{vmatrix} -\frac{\dot{\Psi_{pm}}}{L_d} \\ -\frac{E\psi_{pm}^2}{L_q} \end{vmatrix} \quad (23)$$

$$f_{(x)} = \begin{vmatrix} f_1 \\ f_2 \end{vmatrix} = \begin{vmatrix} -\frac{R_s}{L_d} i_d & \frac{E\psi_{pm} L_q}{L_d} i_q \\ -\frac{E\psi_{pm} L_d}{L_q} i_d & -\frac{R_s}{L_q} i_q \end{vmatrix} \quad (24)$$

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

$$g_{(x)} = \begin{vmatrix} g_1 & 0 \\ 0 & g_2 \end{vmatrix} = \begin{vmatrix} \frac{1}{L_d} & 0 \\ 0 & \frac{1}{L_q} \end{vmatrix} \quad (25)$$

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

If the transfer function is selected based on (24) and (25), the response of equation (23) is based on a first order transfer function.

2.4 Differential flatness properties

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 [14].

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 equation (20) & (21) in terms of flat output:

$$\dot{y_1} = \frac{1}{L_d} V_d - \frac{R_s}{L_d} i_d + \frac{E\Psi_{pm} L_q}{L_d} i_q - \frac{\dot{\Psi_{pm}}}{L_d} \quad (26)$$

$$\dot{y_2} = \frac{1}{L_q} V_q - \frac{E\psi_{pm} L_d}{L_q} i_d - \frac{R_s}{L_q} i_q - \frac{E\psi_{pm}^2}{L_q} \quad (27)$$

Expressing the input in terms of flat output, from equations (19) & (20):

$$V_d = R_s y_1 - E\Psi_{pm} L_q y_2 + L_d \dot{y_1} + \dot{\psi_{pm}} \quad (28)$$

$$V_q = L_d E\Psi_{pm} y_1 + R_s y_2 + L_q \dot{y_2} + E\psi_{pm}^2 \quad (29)$$

Expressing the state in terms of flat output, from equations (21) & (22):

$$i_d = \frac{1}{R_s} V_d + \frac{E\Psi_{pm} L_q}{R_s} y_2 - \frac{L_d}{R_s} \dot{y_1} - \frac{\dot{\psi_{pm}}}{R_s} \quad (30)$$

$$i_q = \frac{1}{R_s} V_q + \frac{E\Psi_{pm} L_d}{R_s} y_1 - \frac{L_q}{R_s} \dot{y_2} - \frac{E\psi_{pm}^2}{R_s} \quad (31)$$

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 indeterminate) 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 [10]. 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 full within the left of a cartesian plane, and strictly avoiding a factor at the imaginary axes [11].

Let:

$$y_1 = 0.1300t^3 - 0.0377t^4 + 0.0030t^5 \quad (32)$$

$$\dot{y_1} = 0.3900t^2 - 0.1508t^3 + 0.0150t^4 \quad (33)$$

$$y_2 = 0.0230t^3 - 0.0754t^4 + 0.0060t^5 \quad (34)$$

$\dot{y_2} = 0.0690t^2 - 0.3016t^3 + 0.0300t^4$ (35)

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 4 and generating the flat trajectory as shown in figures 2 and 3 respectively.

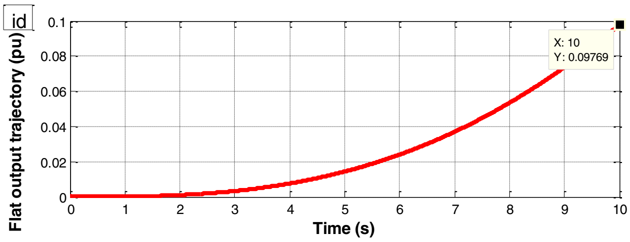

Figure 2: Flat trajectory of d-axis

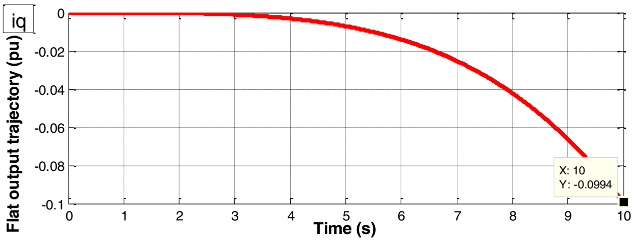

Figure 3: Flat trajectory of q-axis

2.5 Differential flatness converter

Figure 4 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 (32) to (35) respectively. The trajectory is generated using i_d and i_q in equations (30) and (31) 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.

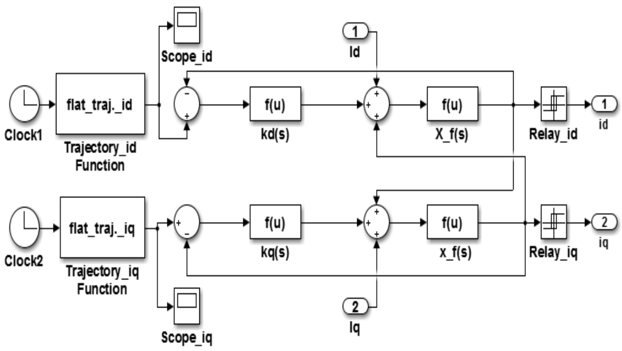

Figure 4: Simulink block diagram of a differential flatness-based controller

2.6 Overall developed converter

Figure 5 shows the overall MHRC system Simulink block diagram for the complete processes from the turbine, drive-train, generator, control and to the three-phase load. The main objective is to use the overall Simulink model to test the proposed control system's performance under variable water flow speed. The methodology followed to develop this block diagram is explained in ref. [15].

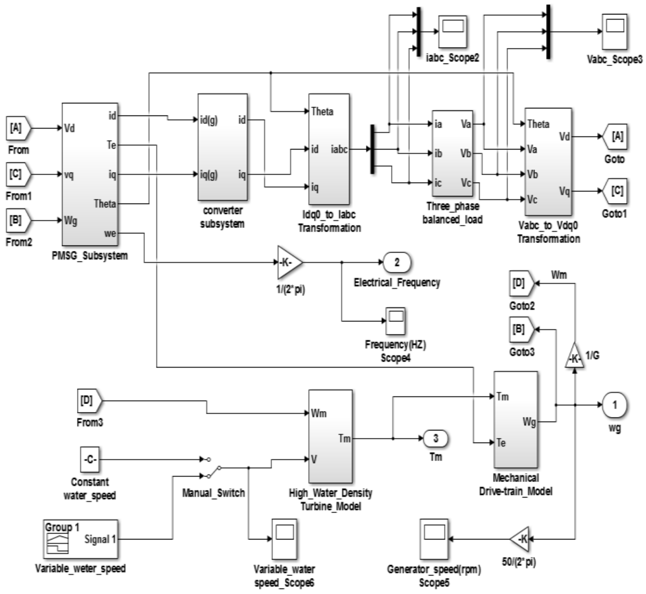

Figure 5: Simulink block diagram of an overall MHRC system model

3 RESULTS AND DISCUSSION

Two 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 simulation results of the variable speed hydrokinetic river system without the inclusion of the converter. The second case will reveal the simulation results with the inclusion of the converter in the variable speed hydrokinetic river system. Both cases were tested in a simulation with the inclusion of a permanent magnet synchronous generation (PMSG) with characteristics shown in table 1 below.

Table I: PMSG parameters [16].

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 132.37 V, 50 Hz at a rated full load speed of 377.2rpm, as shown in Table 1. During the simulations, it has been assumed that the water flow velocity rises from 0 to 2.58 m/s for the period of 3s and remains constant for 4s, and then decreases to 0 m/s for the next 3s.

3.1 Case 1: micro-hydrokinetic river system performance without the inclusion of a flatness-based converter.

This 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 speed and without the converter 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 6 and Figure 7, 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 187.4 V-peak as observed in figure 8, and at a frequency close to 50 Hz referred to in figure 10. The variations in the water flow speed also relate to the variation of the generated voltage, current and frequency magnitude, as seen in figures 8, 9 and 10 respectively.

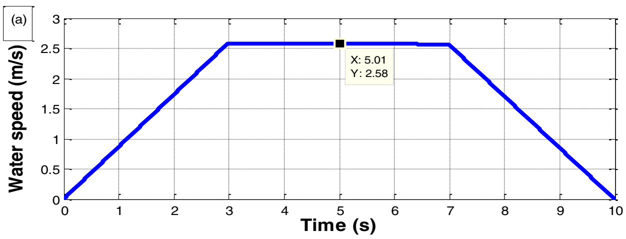

Figure 6: Water speed

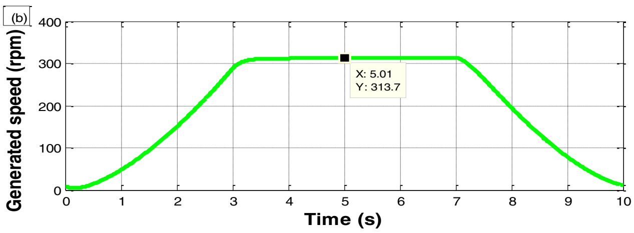

Figure 7: Generator speed

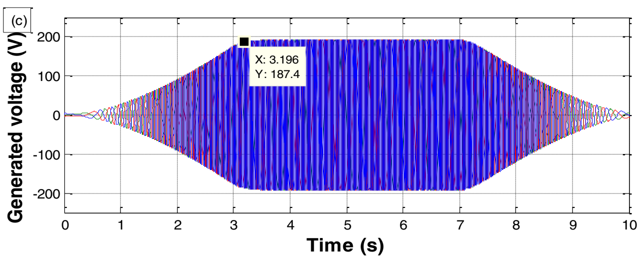

Figure 8: Generated Voltage

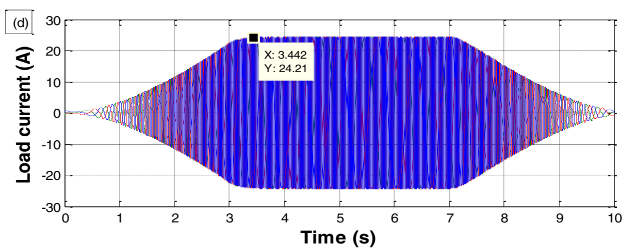

Figure 9: Load Current

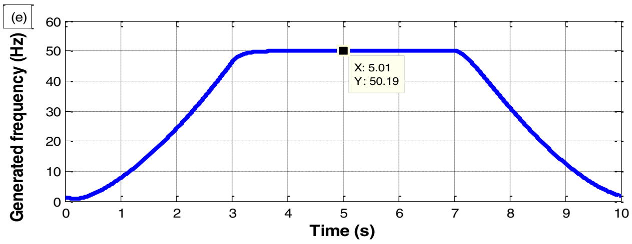

Figure 10: Electrical frequency

3.2 Case 2: 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 the controller system. The converter is a built electronic circuit that transform different voltage magnitudes to a constant voltage level. A relay is included in the converter circuit to allow the correct voltage level to be controlled.

As explained in section 2, the converter in this case is used to transform the variable alternating current (AC) input I_{abc} into a direct current (DC) I_{dq0} by using equations 9 and 10. The differential flatness DC to DC current-mode control is adopted resulting in the variation of the average value of the waveform. Figure 11 shows that between t=0s to t=2s, a zero frequency is experienced due to the weak input signal; at the time when its approaches t=2s to t=8.4s, the frequency reaches 50Hz, and finally the DC Idq0 signal is transformed back to I_{abc} quantity by applying the reverse transformation method in equation (11).

Figure 12 shows that, between the time 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 13 shows that, the converter output current of 22.05A-peak is witnessed across the load.

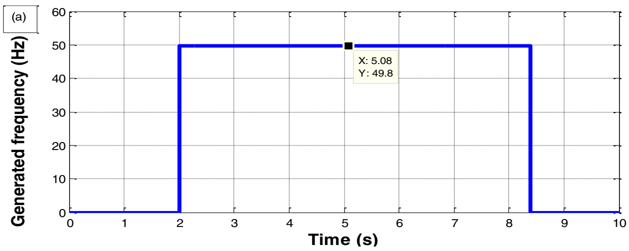

Figure 11: Electrical frequency (with converter)

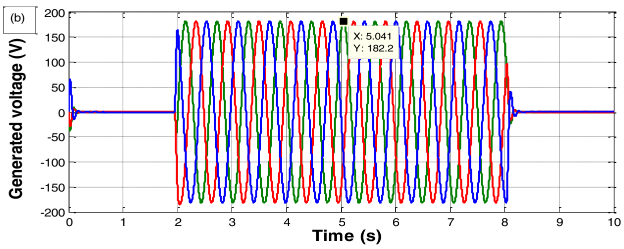

Figure 12: Load Voltage (with converter)

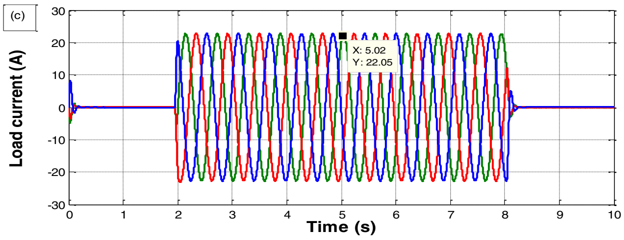

Figure 13: Load Current (with converter)

4 CONCLUSION

A differential flatness based controller 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. The results show that differential flatness based controller output voltage and frequency follow their reference trajectory and keep the output power constant. This principle is one effective way of controlling a system and can readily be 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.

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