

Development of a Dynamic Model Based On the PID Control and Optimization Theories to Evaluate the Integrated Performance of the Energy Generation and Storage System

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ABSTRACT

This paper aims to present a study of the development of a dynamic model based on theories of PID control (proportional, integral and derivative) and optimization to evaluate the integrated performance of the energy generation and storage system. The hybrid system consists of photovoltaic (PV) generator, water generator (GH) and fuel cell (FC), connected to a DC (direct current) bus. A converter (DC / AC) is used between the bus and the load to transform the energy into acceptable levels of consumption. Minimum conditions of interruption and voltage level within the specified range are indispensable conditions for the supply of electric energy. In order to overcome the inadequacies of the architecture such as the low irradiation incident on the modules and / or reduction of the hydraulic flow, a closed loop controller is connected to the fuel cell, guaranteeing the performance of the assembly.

The analysis of the results will be presented using the SCILAB / SCICOS computational tool. The functional procedure used to describe the behavior of the process consists of the simulation of the input variables (generating power ratings) in the DC bus and the output variable (total power supplied to the load).

Keywords

Renewable energies, hybrid system, modeling and control, PID controller.

1. INTRODUCTION

Currently, efforts are underway to change the global energy supply process in order to avoid climate change caused mainly by energy consumption and consequently greenhouse gas emissions [2].

The inclusion of renewable energy sources in the energy matrix contributes significantly to reducing the harmful effects on the environment.

A large number of the Brazilian population is not yet connected to electricity supply networks, so they use equipment driven by fossil fuels as an autonomous diesel or gasoline generator. According to the [17] report, the world scenario presents alarming data, approximately 1.2 billion people are without access to electricity. Table 1 shows the rate of people without access to electricity in developing countries.

According to [3], global electricity generation has grown sharply over the last decade, reaching 22,200 TWh, of which 70% comes

from non-renewable sources such as coal, natural gas and oil. These sources are largely responsible for emissions of greenhouse gases. The generation, transmission and distribution system face major challenges to meet unpredictable daily demands and seasonal variations. One of the solutions with the potential to respond to these challenges is renewable energy sources.

The sources of renewable energies are those that have the capacity to regenerate the natural resources used in their process, that is, they are considered inexhaustible [4].

According to [1], the main sources of renewable energy are: i) hydropower, ii) biomass, iii) wind, iv) solar and v) ocean.

As most renewable energy sources are intermittent in their nature, one option to ensure stability and balance of the system is the use of equipment for its storage [3].

According to [5] water use goes beyond a renewable and sustainable source, it is a flexible option with storage possibility and ability to support the deployment of other intermittent sources such as solar and wind, besides the benefit of aid to the stability of the electrical networks.

According to [6] photovoltaic energy is being widely used in recent years due to the development of the technology employed, reducing its cost of acquisition. Another motivating point is the fact that it is friendly to the environment.

An important variable is the fact that both hydropower and photovoltaics are affected by meteorological factors such as the incidence of solar radiation and hydrological seasonality. In order to improve performance, continuity and availability, some works

Table 1: Rate of people without access to electricity

SOURCE: IEA, World Energy Outlook 2016				
Electricity access in 2014 - Regional aggregates				
Region	Population without electricity millions	Electrification rate %	Urban electrification rate %	Rural electrification rate %
Developing countries	1.185	79%	92%	67%
Africa	634	45%	71%	28%

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North Africa	1	99%	100%	99%
Sub-Saharan Africa	6 32	35%	63%	19%
Developing Asia	512	86%	96%	79%
China	0	100%	100%	100%
India	2 44	81%	96%	74%
Latin America	22	95%	98%	85%
Middle East	18	92%	98%	78%
Transition economies & OECD	1	100%	100%	100%
WORLD	1.186	84%	95%	71%

integrate a system of accumulation to the sources generating electric energy, promoting the storage of energy and later reuse. The generation and storage system consists of photovoltaic module (VF), water module (GH), fuel cell (FC), converter (CE) and load (SC), with their respective power sources: solar energy, hydraulic flow and hydrogen, shown in Figure 1.

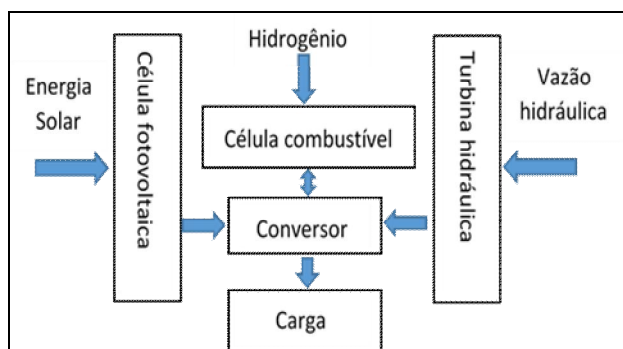


Figure 1: Power sources- solar energy, hydraulic flow and hydrogen

According to D. Mahesh Naik, D. Sreenivasulu Reddy, Dr. T. Devaraju (2014) photovoltaic energy is being widely used in recent years due to the development of the technology employed, reducing its cost of acquisition. Another motivating point is the fact that it is friendly to the environment.

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The insertion of a fuel cell as a storage medium in hybrid systems allows for greater design flexibility, accumulating excess energy from other sources and using it when it is insufficient.

The dynamic model is developed to manage the energy flow of the components, diverting surplus energy to the electrolyser (EL), responsible for generating hydrogen and ensuring the continuity of the electric power supply. The PID base of the model has the design to control the fuel cell, providing the energy in its terminals whenever requested and keeping the energy variation within the quality standards.

2. OBJECTIVES OF THE WORK

To propose a control model for integration of power generation and storage system with controlled output power.

Improve and evaluate the power generation and storage system through a dynamic model based on PID control theories.

To present the first results obtained in the dynamic system evaluation tests, which were performed using the SCILAB / SCICOS [8] computational tool.

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3. DEVELOPMENT

For a proposal of a suitable hybrid system model, it starts with the preliminary steps as: architecture and its main blocks, mathematical modeling and simulation.

3.1 System Overview

Concerns about global warming caused by burning fossil fuels have created new opportunities for the insertion of renewable and sustainable sources, such as: solar, photovoltaic, hydro, biomass, geothermal and others [9].

The main logical components predicted in the dynamic model based on PID control theories and optimization to evaluate the integrated performance of the power generation and storage system are shown in Figure 2.

The main function of the generation module presented is the generation of electric energy, connected to the DC bus. The main items are: a) photovoltaic panel (PV), a system that converts solar radiation into electrical energy [7], b) water generator (GH), has the objective of generating electric energy from mechanical energy (C) fuel cell (FC), converts the chemical energy stored in the form of fuel directly into electric energy [11], d) converter, equipment that transforms The DC power generated in AC power at the output for consumption, connecting the DC bus to the load module.

The load module represents the consumer loads and their circuits connected to the hybrid system.

The control block is the part of the system that has as purpose the management of all the activities developed by the hybrid generation system. It consists of: a) computer (CH), allows the interface between the operator and the generation system, b) controller, executes the PID program of the proposal to control the energies generated, stored and consumed by the load, c) (LCP), interconnection medium between the host computer (CH) and the controller, d) deterministic communication line (LCD), means established to conduct signals between the control module and the remote units as sensors and actuators.

Storage module, responsible for transforming and accumulating surplus energy from generators. Its components are: a) electrolyser: produces hydrogen from electricity and stores it in the reservoir [12], b) fuel tank (CCOMB), receives the hydrogen from the electrolyser and stores it for use on demand Of the system, c) flow valve (VF), dedicated to feeding the fuel cell according to the signal received by the control module.

The modules are representative, but the control is simulated and processed by software to analyze the operational behavior and validate the results.

3.2 System Overview

The SHHFFC (Hybrid water / photovoltaic / fuel cell system) is composed of hydropower, photovoltaic and fuel cell combined by a closed loop, with PID control with storage.

The main function of storage is to supply power in adverse climatic conditions for photovoltaic and hydroelectric generation, guaranteeing the reliability of the system. When photovoltaic and hydroelectric sources have energy balance, the model accumulates energy in the form of gas, using an electrolyzer. The PID control loop assumes the logic of supplying fuel to the cell and consequently to the bus according to the input error signal, indicating the need to supply the deficiency of the photovoltaic and water sources.

3.3 Photovoltaic Model

PV is a physical process where solar energy is the primary source that is subsequently converted directly into electrical energy. The equivalent electric circuit of a photovoltaic cell consists basically of a current source, a diode, series and parallel resistance as shown in Figure 2 [13].

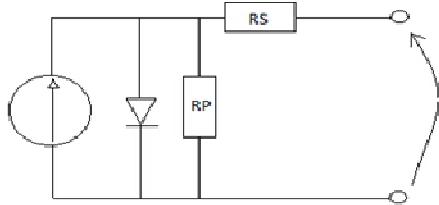


Figure 2: Electrical model of the photovoltaic panel

Equation 1 shows the characteristic of the model according to current circuit analysis.

$$I = I_L - I_D - I_{ft} = I_L - I_0 \left\{ \exp \left[\frac{V + IR_s}{a} \right] - 1 \right\} - \frac{(V + IR_s)}{R_P} \quad (1)$$

At where:

I_L - Current generated by the incidence of radiation;

I_D, I_0 - Diode saturation current;

I_{ft} - Earth leakage current;

I - Current at the output terminals;

R_p - Shunt resistance;

R_s - Resistance series;

A - Curve correction parameter;

V_t - Thermal tension;

I_{sc} - Short-circuit current.

The power can be calculated directly as the product of current I by the open circuit voltage V_{oc} . The transfer function used in the simulation has a resistive characteristic, it uses a current divider according to equation 2.

$$I_{pv} = \frac{R_S}{R_S + R_P} I \quad (2)$$

3.4 Hydroelectric Model

The power generated by the single-phase hydroelectric generator depends on the induced voltage (E), which consequently depends on the capacity of the flow, density, drop height and efficiency of the generator. equipment. The output power at its terminals is presented in equation 4, relating the output voltage (U), current and the angular phase difference between I and U .

$$I = \left[\frac{P}{U \cdot \cos \phi} \right] \cdot 1,25 \quad (3)$$

$$P(t) = U \cdot I \cos \alpha \quad (4)$$

P - Electric power of the generator (kW);

U - Voltage at the generator terminals.

The monitoring with elevation and voltage reduction (U) will be used to control the flow of power provided by the hydroelectric generator. Your equation will be inserted into the transfer function of the block diagram of the control system in the SCICOS / SCILAB software. The simplified model shown in Figure 3 will be represented by the series RL circuit, containing the resistance (R) and the reactance (X) of the equipment.

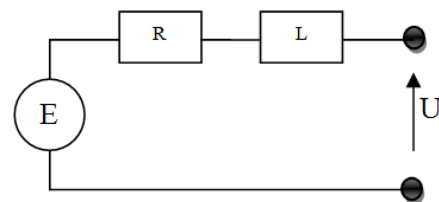


Figure 3: Electric model of the hydroelectric generator

The transfer function used in the study, indicated in equation 5, has a first order characteristic, it simulates the behavior of the hydroelectric generator when excited by a step input.

$$U(t) = \frac{R/L}{S + R/L} E \quad (5)$$

3.5 Fuel Cell Model

The fuel cell functions as a stationary type power generator. Its application has the objective of providing energy with reliability, quality and without emission of pollutants such as nitrogen oxide, carbon or sulfur. Its advantage in the application is the rapid response with changes in load, reduced maintenance and high life

[14]. Figure 4 illustrates the fuel cell with the electrode assembly connected to the load with its chemical conversions.

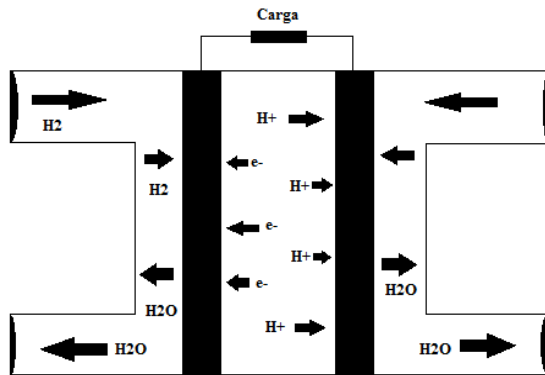


Figure 4: Fuel cell and its chemical reactions

The output voltage presented in equation 6 is the effect of thermodynamics, mass transport, kinetics and ohmic resistance [14].

$$C_{cell} = E - V_{act} - \eta_{ohmic} \quad (6)$$

C_{cell} - Output voltage;

E Thermodynamic potential;

η_{ohmic} - Resistance voltage drop;

V_{act} - Cell activation overvoltage.

Equation 7 represents the internal losses, where R_s is the resistance of the electrodes and membrane and i is the current supplied by the cell. The power at the equipment terminals is the product of i and C_{cell} .

$$V\Omega = R_s \cdot i \quad (7)$$

It was considered a PEM type fuel cell for the electric model and obtaining the transfer function. According to [15] the PEM type fuel cell circuit model to obtain the transfer function is shown in Figure 5.

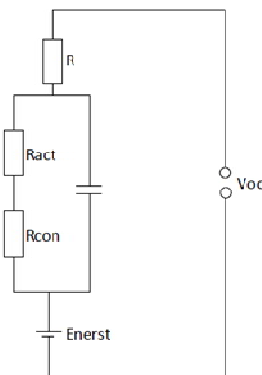


Figure 5: Fuel cell and its chemical reactions

The transfer function used in the software is first order, but of type RC. The product of its result by the current is the response in terms of power. Equation 8 shows the arrangement in the frequency domain.

$$V_{oc} = E_{erst} - \left(\frac{R_{act} + R_{con}}{sC(R_{act} + R_{con}) + 1} + R \right) \cdot i \quad (8)$$

At where:

R_{act} - Activation resistance;

R_{con} - Concentration resistance;

C -Capacitive effect of the double layer;

R - Resistance as a function of current and temperature effect;

i - Electrical current;

E_{erst} -Reversible cell voltage.

3.6 Block Diagram

The main function of the block diagram is the representation of the functions performed by the process or model of a system [18].

With the model, it is possible to pass the mathematical equations in the form of a transfer function, interconnecting the components and enabling process control [19].

This interface was developed using the toolbox contained in the SCILAB software environment called XCOS.

The main function of the window is to insert all the components provided in the architecture in an interconnected way to obtain the results of the set and later evaluation of the answers in the form of graphs. Figure 6 shows the block diagrams and response graph screen.

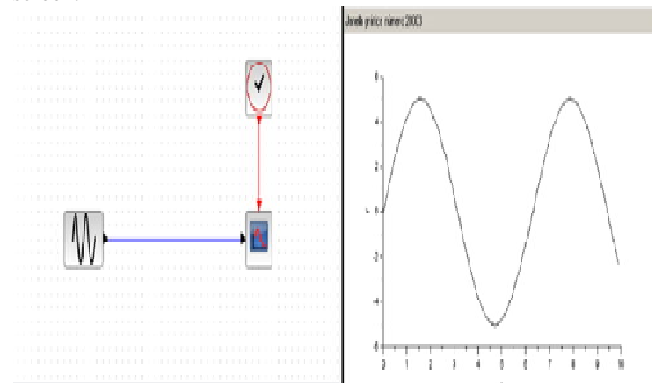


Figure 6: Block diagram and output graph

3.7 Simulation Methodology - Case study

The results initially consider a hybrid system sized with the hydropower and photovoltaic energy sources connected to the bus without the presence of the fuel cell component and the PID integrator. This first scenario simulates a parallel connection between the generating sources commonly found in some theses and articles referring to the subject addressed, here called traditional hybrid systems.

For the evaluation and comparison of the proposed dynamic system with the traditional system, without control, the input variables are restricted, simulating a possible deficiency caused by meteorological problems such as reduction of hydraulic flow and / or low incidence of full sun in the plane of the photovoltaic panel. In the second scenario, the fuel cell is inserted in the bus and the integrated PID system to the control closed loop, reproducing the same variations of the first scenario at the entrance of the system and presenting the results for comparison of the proposal.

3.7.1 First scenario

Traditional hybrid system with hydroelectric and photovoltaic generation connected to the DC bus. Figure 7 shows the set with the photovoltaic and water input variables and the output variable, available electrical power.

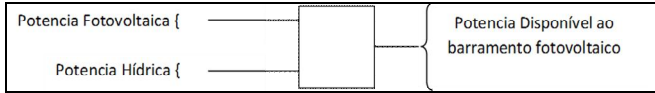


Figure 7: Hybrid, photovoltaic hybrid system model

a) Photovoltaic system

The photovoltaic modules are directly affected by the solar irradiation and temperature, changing the values of current and voltage of design and consequently the power made available by the panel, reducing the capacity of the hybrid set.

In the graph of Figure 8, the maximum power point (P_{mp}) and its respective voltage (V_{mp}) and current (I_{mp}) are shown in curve 1. The power reduction can be observed in curve 2 as it changes the V_{mp} and I_{mp} points.

The variation of solar radiation during the year is another factor that hinders the efficient sizing of photovoltaic generators. One resource used to solve this fact is to design the set of panels considering the critical point, Figure 9, the month with the lowest solar irradiation. To exemplify this difference, the city of Volta Redonda in the state of Rio de Janeiro, Brazil, was considered as a reference location. Geographic coordinates are Latitude: 22° 31' 31" South, Longitude: 44° 6' 14" Oeste° West . [20].

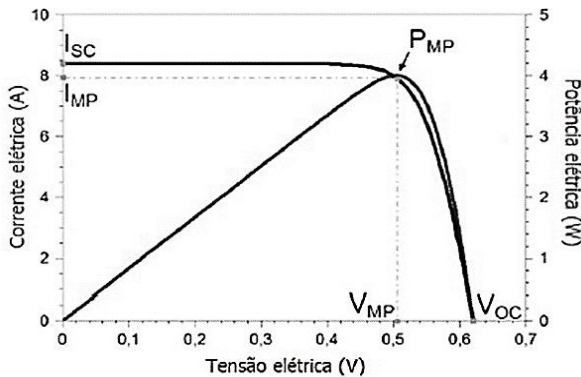


Figure 8: Hybrid, photovoltaic hybrid system model

Electrical power under test conditions of a photovoltaic cell (CRESESB, 2016).

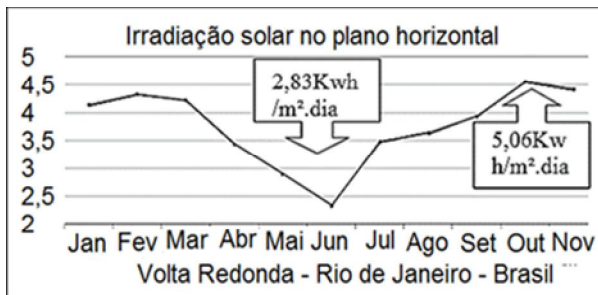


Figure 9. Monthly irradiation level (Modified - [10])

b) Hydroelectric system.

The unavailability of water results in the reduction of the flow, affecting directly in the choice of a hydroelectric generation project, that variation in the primary source may change according to the regions.

Brazil is abundant in terms of water resources, but presents a great change in spatial and temporal terms of flow [16].

As it has a great spatial variation, it is important to highlight the seasonal events caused mainly by the seasons and rainfall regimes [16].

It is possible to observe the water and solar variations in terms of amplitude and availability. It takes up the challenge in choosing the most efficient use and the technology or set that best fits for fundraising.

The following electrical properties are adopted in the test to generate the hybrid system's graphical results.

FV- 150W;

GH-100W;

Figure 10 shows the power provided by the 100W hydroelectric generator (GH). For the construction of the power characteristic curve, the SCILAB / SCICOS computational tool was used.

To simulate the power of the water generator $R / L = 1$ and the current of 1A were considered.

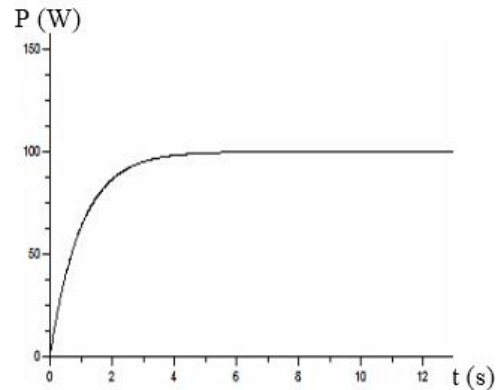


Figure 10: Active power available at the terminals of the 100W hydroelectric generator [16]

The curve shows the power supplied by the terminals of a generator, the induced voltage is represented by the step function. As the resistance value is much lower than the reactance its value has been neglected.

The power limitation shown in the graph is a characteristic of the size of each generator which is a function of the voltage depending on the armature current of the equipment.

Figure 11 shows the power provided by the 150W photovoltaic generator (PV) and the output power of the photovoltaic generator obtained by the voltage and current product.

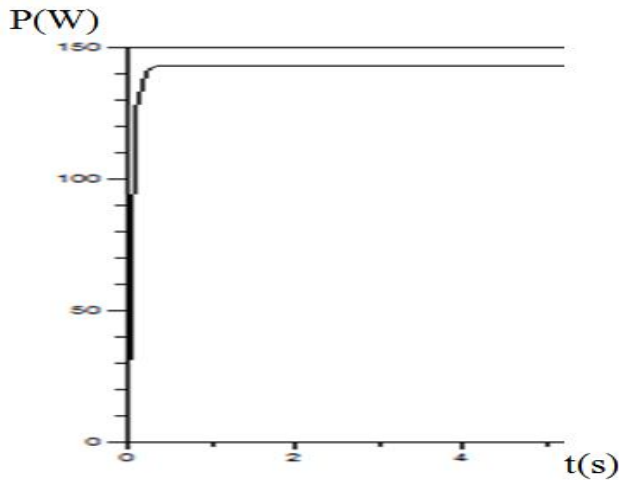


Figure 11: Active power available at the terminals of the 150W photovoltaic generator

In practice, the power curve of the photovoltaic module does not reach the maximum value because it does not reach the short-circuit current or voltage equal to zero. In this theoretical context, the only loss represented is the voltage drop caused by resistors in series (R_S) of 1Ω and parallel (R_P) of 21Ω .

Note that the graph became more accentuated, typical of purely resistive circuits.

Figure 12 shows the power with the hydroelectric and photovoltaic generators in parallel. The total power supplied is the sum of the powers of each equipment.

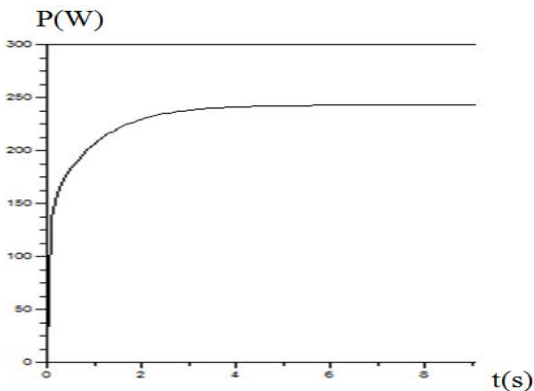


Figure 12: Sum of the powers of the water and photovoltaic generators

The graphs shown in Figures 14 can be considered as ideal, where the responses of the generators are only influenced by the properties of the equipment such as resistors and reactances. In practice a major problem of the facilities are the influences by the external environment such as dry period and shading.

To simulate the external variations, a reduction of 10% in the efficiency of the photovoltaic panel and 20% in the hydroelectric generator was inserted. This variation was performed by inserting the loss directly into the step function, simulating a reduction in the flow and solar radiation. It is noted in Figure 13 that the decrease is reflected directly in the power supplied.

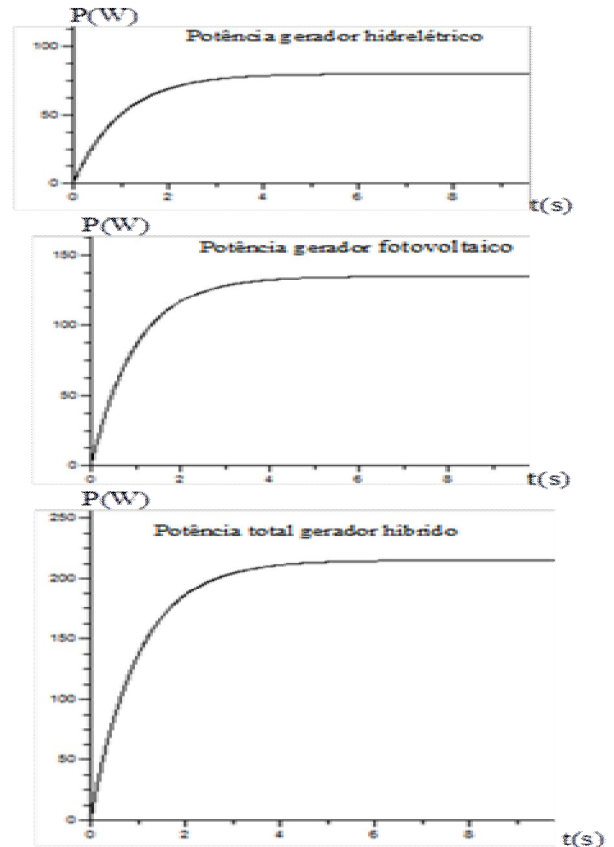


Figure 13. Hydroelectric power generation, photovoltaic and total powers

3.7.2 First scenario

Hybrid system with hydroelectric and photovoltaic generation and fuel cell connected to the DC bus in closed loop.

This simulation was performed considering the same reductions of 10% and 20% of the first scenario in the efficiencies of the generating equipments, but at the moment connected by a control system in closed loop.

It is observed that in Figure 14 the presence of the fuel cell component contributes to the final result. The output power even with the reduction of the efficiency of the generation system remains stable in steady state.

Closed loop operation, while meeting the goal, while maintaining power supplied at constant load under variations from primary sources, does not meet power quality requirements. The variation in high transient regime can lead to the burning of electrical-electronic equipment connected to this bus.

A solution for overshoot reduction consists in inserting the PID component in the closed loop, assuming the energy variation in the maximum limit of 10%.

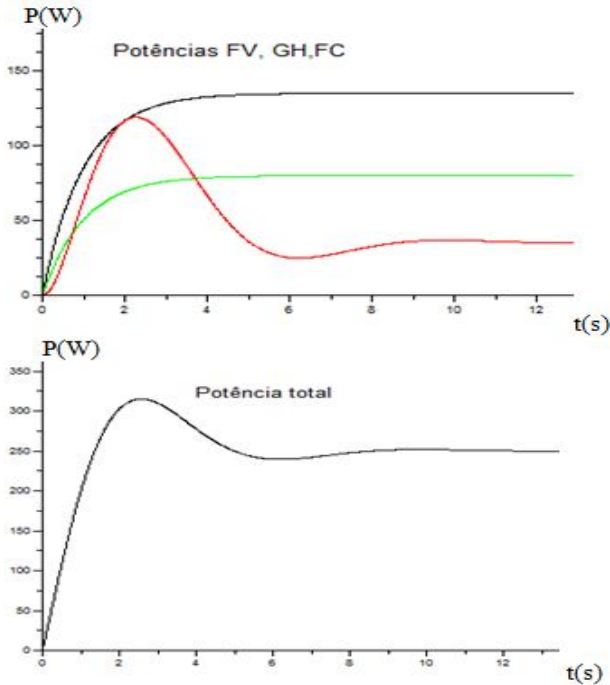


Figure 14: Hydroelectric generating power, photovoltaic power and total power in closed loop

In order to reduce the disturbance caused by the insertion of the fuel cell, the PID controller is adjusted so as to reduce the peak in the transient regime, ensuring the delivered power quality. The simulation is recalculated with the same reductions and the result is presented in graph form. Figure 15 shows the potencies of hydroelectric, photovoltaic and fuel cell sources and the power output with reduced ridge value, taking into account the maximum limit.

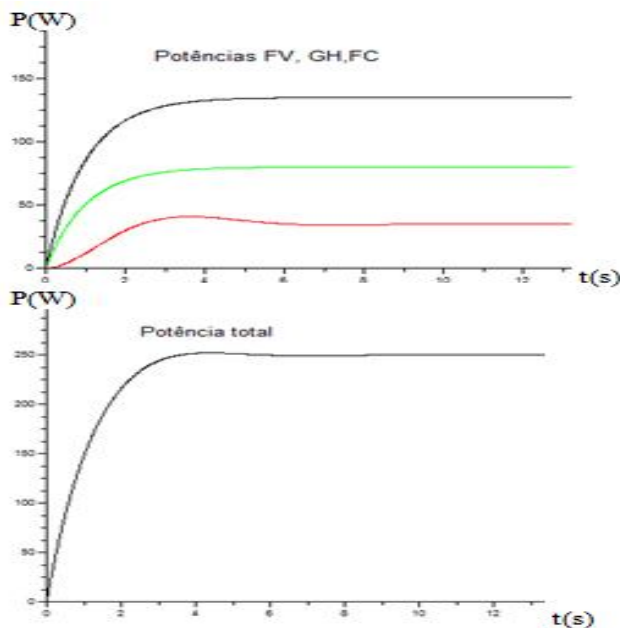


Figure 15: Hydroelectric, photovoltaic, fuel cell and full power output in closed loop and PID control.

The electrolyzer connected to the DC bus is considered to be a constant load, its consumption will remain until the storage cylinder is complete, indicating high level.

Whenever the system requests the fuel cell component, the control valve opens, releasing the fuel and the electrolyzer re-consumes. The graph of Figure 16 shows the consumption of a 10W electrolyzer, reducing the availability of power generation.

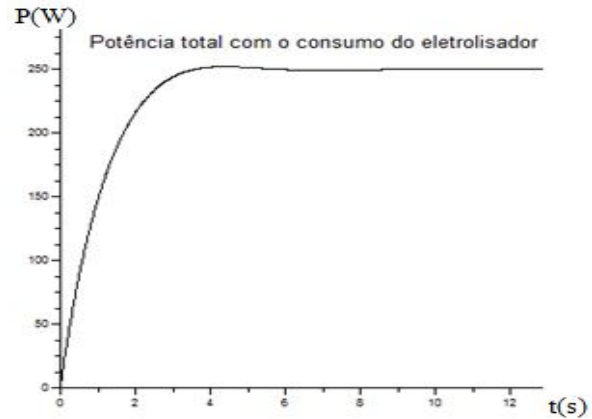


Figure 16: Total power available with the electrolyzer in operation

In the first scenario, the tests clearly show that the metrological variables directly affect the set behavior. The solutions found to this problem are mostly to consider the worst case and to size the project to meet this demand, where it is not always possible, due to lack of space in the installations of new photovoltaic panels or due to the difficulty of dam constructions. The damming of water. In the second scenario, the simulation test behaved as expected, even under conditions of reduction of photovoltaic and water sources the output power remained in expected acceptable levels. The PID controller allowed the control of the available energy limit, allowing the connection without risk to electrical and electronic equipment.

4. CONCLUSION

The objectives established for this work were achieved, mainly with respect to the presentation of the development of a dynamic model based on PID control theories and optimization to evaluate the integrated performance of the energy generation and storage system.

The use of hybrid generation systems based on renewable sources, photovoltaic, hydroelectric and fuel cell controlled by a closed loop system, aim to minimize the variations in the energy supply caused by the meteorological conditions and load variations.

The energy delivered to consumers must have characteristics of reliability and quality suitable for the application. With the implementation of the PID control in the mesh, it was possible to leave the electrical characteristics within the appropriate parameters for the supply.

The satisfactory results observed in the simulations were performed with SCILAB / SCICOS software. The stability of output power under adverse conditions shows that the system is doable for the intended application.

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