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Speed and active power regulation systems in hydroelectric plants - a review

Sistemas de regulação de velocidade e potência ativa em usinas hidrelétricas – uma breve revisão

Sistemas de regulación de velocidad y potencia activa en plantas hidroeléctricas - breve revisión

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Marcos Shigueo Yamashita
ORCID: https://orcid.org/0000-0002-8932-7338
ENGIE Brasil, Brazil
E-mail: marcos.yamashita@engie.com
Luís Fernando Ferreira de Campos
ORCID: https://orcid.org/0000-0002-9496-4884
Universidade do Sul de Santa Catarina, Brazil
E-mail: luisf_ferreira@gmail.com
Oscar Mitsuo Yamashita
ORCID: https://orcid.org/0000-0001-6715-626X
Universidade do Estado de Mato Grosso, Brazil
E-mail: yama@unemat.br

Abstract

This work presents a study based on the speed and power control of a large hydroelectric power plant through the mathematical modeling of the real system and the use of computational simulations to validate the field data and evaluate the response of the control systems studied over different scenarios. A reference analysis was necessary to provide basic concepts about the system studied as well as topics related to theories of control, modeling and controller designing. Specific data from the presented case studied were applied to the mathematical modeling. In doing so, it was possible to validate the calculated models by using computational simulations. This validation was performed by comparing simulation results with field testing records obtained from the power plant studied. More computational simulations were executed using validated and adjusted mathematical models to evaluate operational performance of the speed governor system. Additionally, some proposals of adjustments were made by applying known controller tuning methods in order to improve the equipment performance.

Keywords: Speed governor; Control modeling; Simulation; Root locus analysis; Ziegler-Nichols.

Resumo

Este trabalho apresenta um estudo sobre a regulação de velocidade e potência ativa de uma usina hidrelétrica de grande porte através da modelagem matemática do sistema real e uso de simulações computacionais para validação dos dados de campo e avaliação da resposta das malhas de controle estudadas sob diferentes cenários. Uma análise bibliográfica foi realizada apresentando conceitos básicos sobre o sistema a ser estudado além de tópicos relacionados a teorias de controle, modelagem matemática e projeto de controladores. Dados específicos do estudo de caso apresentado foram levantados e aplicados na modelagem matemática permitindo executar simulações computacionais para validação dos modelos calculados. Esta validação foi realizada comparativamente tomando como referência registros oscilográficos de testes reais executados na usina em estudo. Com os modelos matemáticos ajustados e validados, as simulações computacionais foram utilizadas para avaliação das atuais condições de operação dos reguladores de velocidade e, aplicando técnicas conhecidas de sintonia de controladores, possibilitaram a proposição de como o sistema poderia melhorar seu desempenho com base nos resultados encontrados.

Palavras-chave: Regulador de velocidade; Modelagem; Simulação; Análise do lugar das raízes; Ziegler-Nichols.

Resumen

Este trabajo presenta un estudio sobre la regulación de la velocidad y potencia activa de una gran central hidroeléctrica a través de la modelación matemática del sistema real y el uso de simulaciones por computadora para la validación de datos de campo y evaluación de la respuesta de las redes de control estudiadas bajo diferentes escenarios. Se realizó un análisis bibliográfico presentando conceptos básicos sobre el sistema a estudiar así como temas relacionados con teorías de control, modelado matemático y diseño de controladores. Los datos específicos del caso de estudio presentado fueron recolectados y aplicados a la modelación matemática, permitiendo la ejecución de simulaciones por computadora para validar los modelos calculados. Esta validación se realizó comparativamente tomando como referencia registros oscilográficos de pruebas reales realizadas en la planta en estudio. Con los modelos matemáticos ajustados y validados, se utilizaron simulaciones computacionales para evaluar las condiciones de operación actuales de los reguladores de velocidad y, aplicando técnicas conocidas de ajuste de controladores, permitieron proponer cómo el sistema podría mejorar su desempeño en base a los resultados encontrados.

Palabras clave: Regulador de velocidade; Modelado; Simulación; Análisis del lugar de las raíces; Ziegler-Nichols.

1. Introduction

For a country to remain sovereign and at a growth rate, it is essential that there are resources that enable economic growth. As one of the fundamental resources in an economy, the production of electric energy stands out, which, in Brazil, has been developed to meet the growing demand caused by factors linked to industrialization and urbanization processes, population growth and technological development in the offers and use of electricity (Energy Research Company, 2007).

In this context, energy generation systems stand out for taking advantage of available natural resources and transforming them into electrical energy, meeting different performance and quality requirements demanded by regulatory and controlling institutions of the electrical system. In addition, there is a need for power generation plants to present good numbers in their quality indicators, with the guarantee of continuous and safe operation of their generating park, so that the projects become economically viable. The direct result of the needs of the electricity sector is reflected in the application of investments in various equipment throughout the concession period of the assets, the largest being those intended for equipment considered essential for the reliable and safe operation of the generation plants.

In a hydroelectric generation plant, one of these pieces of equipment that requires investments at regular intervals is the speed and active power regulation system, commonly known as speed regulator. This system allows controlling the rotation of the turbine of synchronous machines and mainly performing frequency control, also known as load/generation control, ensuring the reliable and economic operation of the electrical system in terms of frequency stability (Cenaqui, 2018).

A speed and active power regulation system has as its main element the equipment known as a speed regulator. Within the context of electric power generation, the speed regulator is an essential component for the operation of generating units through the primary control of speed and active power.

According to Santos (2012), the speed regulator is a control device that aims to ensure the dynamic balance of the machine. It compares the shaft's angular velocity signal to the value it was set to have. If there is any difference between these two values, an error signal is generated which will be processed by the electronic devices. These devices are set to give the proper command to the valves that control the oil flow to the servomotors that act at the angular positions of the distributor guide vanes and rotor blades, re-adjusting the angular velocity. Valves, in general, are of the proportional type, that is, the oil flow to the servomotors is proportional to the intensity of the regulator signal.

The concepts presented in this article allow us to understand the phenomena involved in the speed regulation of hydroelectric plants and their mathematical modeling. This article presents basic concepts about speed and active power regulation systems, describing its operation and application, in addition to identifying its main components. Still within the theme of speed regulation and active power, a topic about the modeling of this system is addressed in order to support concepts that are applied so that the objectives of this work are achieved.

In this way, this work aims to advance in the studies of speed regulators in the generation of hydroelectric energy, seeking to expose the theoretical basis of a real hydroelectric plant. Finally, by applying this development, results can be generated with conclusions about performance and alternatives to guarantee the desired response.

2. Methodology

This review article is a qualitative and descriptive research on speed and active power regulation systems in hydroelectric plants, following indications based on Alape (2012).

For the development of the literature review, the Prisma Statement method was used, with a composition of 9 items (some of which were subdivided) and steps previously defined, aiming at eligibility criteria, description of review sources, search strategies, material selection, results and data synthesis in the form of a flow diagram (Moher et al., 2009).

In this way, the methodology was based on the following operational axis: organization of bibliographic research based on published books, banks of theses and dissertations from several universities and colleges (public and private), scientific articles, regular newspapers, scientific magazines, documents, websites of companies and professionals related to the theme, also covering texts posted on the internet, and other wide-ranging virtual communication media. Data available on electronic platforms, mainly Google Scholar, Scielo, Periodicos CAPES, Web of Science and Scopus were used. For the present search, complete articles in English and Portuguese were included.

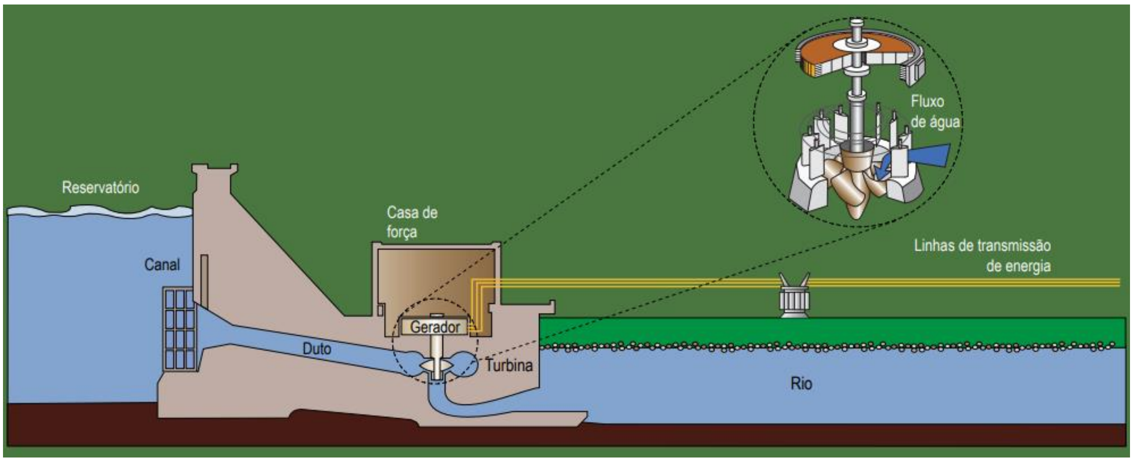
3. Typical Composition of a Hydroelectric Plant

According to ANEEL (2008), the structure of a hydroelectric plant is basically composed of a dam, a water intake and adduction system, a power house and a spillway, which work together and in an integrated manner. The main objective of the dam is to interrupt the normal course of the river and allow the formation of the reservoir that, in addition to “storing” the water, has other important functions such as allowing the formation of the gap necessary for the configuration of hydraulic energy, capturing water in adequate volume and the regularization of the flow of the rivers in the face of the seasonality of the climate (rain or drought).

The intake and adduction systems are formed by tunnels, channels or conduits that have the function of taking the water to the power house where the turbines are, which are formed by a series of blades connected to an axis connected to the generator. The rotating movement of the turbines converts the kinetic energy, resulting from the passage of water through the blades, into electrical energy through the generators. After passing through the turbine, the water is returned to the natural bed of the river through a structure called tailrace (ANEEL, 2008).

Also according to ANEEL (2008), there is a structure called spillway that has the main function of allowing water to exit whenever the reservoir levels exceed the recommended limits due to excess flow or rain or the existence of water in quantity. greater than that needed for energy storage or generation. Figure 1 briefly shows the components mentioned above through the typical schematic profile of a hydroelectric plant.

Figure 1 – Schematic profile of a hydroelectric plant.



Source: ANEEL (2008, p.50).

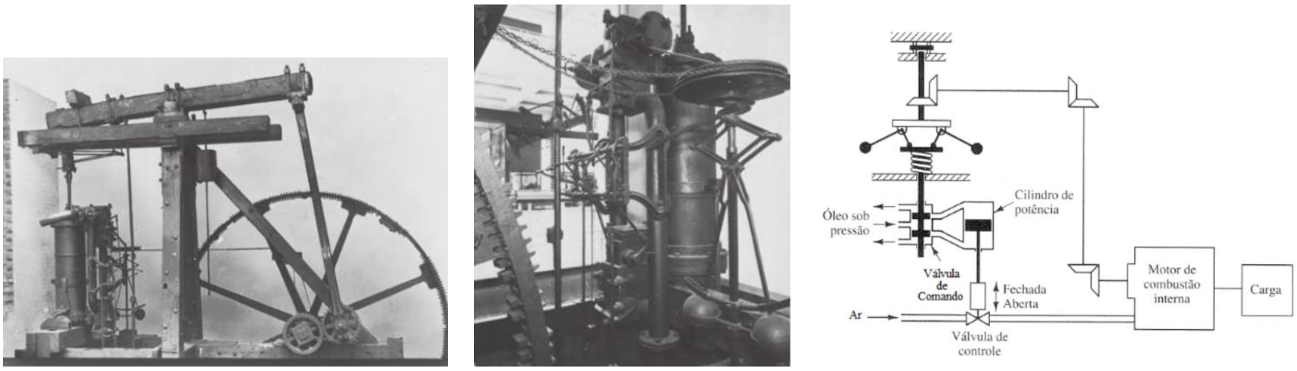
Each of the subsystems mentioned has its own dynamics and somehow influences the treatment of speed regulation and active power of a hydroelectric plant. In this way, it becomes necessary to contextualize the speed regulator within a plant, seeking to understand the dynamics that interrelate each subsystem.

4. History of Speed Governors

Speed regulation systems start from the basic principles of feedback of dynamic systems, or also known as closed loop systems. According to Franklin, Powell, & Emami-Naeini (2013), the central idea is that the output of a system can be measured and relayed to a main control unit used to perform the control itself. It has been proven that a feedback signal like the one written above can be used to control a wide variety of dynamic systems, including, for example, aircraft and hard drives for data storage.

One of the most well-known problems in the control of more complex systems is the search for a way to control the rotation of an axis in order to keep the speed within expected standards, being applicable in the past, mainly, for windmills. The classic solution found is the well-known feedback system using devices called flying balls adapted by James Watt for use in steam engines in the 1788s (Franklin, Powell, & Emami-Naeini, 2013). Figure 2(a) shows a photo of a James Watt engine and details of the flying balls in Figure 2(b).

Figure 2 – Feedback with flying balls – (a) James Watt steam engine; (b) detail of feedback using flying balls. (c) Schematic of a feedback system using flying balls.



(a) (b) (c)

Source Figures 2(a) and 2(b): Franklin et al., (2013, p.9 and p.10). Figure 2(c): Santos (2012, p. 11).

The operation of the feedback proposed by James Watt is relatively simple: if the mechanical load coupled to the motor varies by altering the set value of the angular velocity, the rotational velocity of the spheres is altered. Then the spheres change the height of their center of mass following the laws of Classical Mechanics. By changing their height, they trigger the control valve that controls the oil flow to the servomotor. The cylinder, when moving, acts on the valve that controls the air flow to the engine, changing its power and, consequently, its rotation. The balance will only be reestablished when the angular speed of the machine returns to its nominal value, but when this occurs, the servomotor cylinder and the fuel flow control valve may have their positions changed (Santos, 2012). Figure 3(c) shows a simplified schematic of the main components of this system.

In 1824, with the evolution of steam engines equipped with speed feedback, more than a thousand machines of this type had already been produced in the world. At the end of the 19th century onwards, there was a technological leap forward with the invention of important components that are still used today, such as electromechanical relays, valves, transistors and integrated circuits (Reginatto, 2013). These inventions took the control systems to another level, since the mechanical reconduction of speed and other process variables would no longer need to be performed mechanically, and to the control of the system, complex calculations and functions could be applied before being difficult to execute or quite high cost.

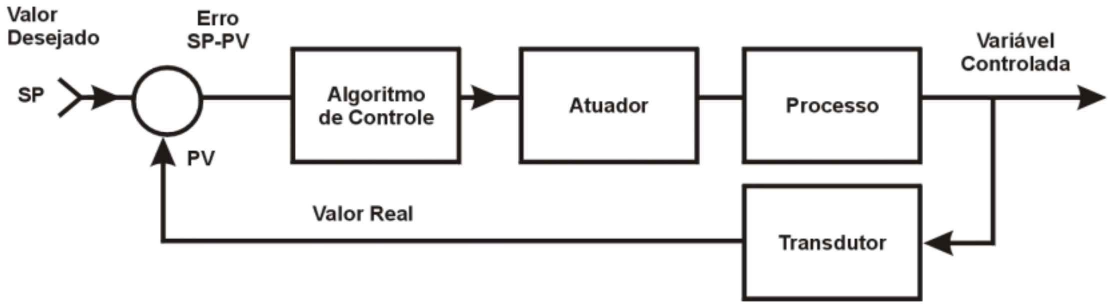
5. Operation of a Speed and Active Power Regulation System

A speed and active power regulation system operates based on the structure of a feedback control system, but in this case, as its name suggests, it is specifically developed for the rotation control of the rotating assembly of a synchronous machine and also for act directly on the stability of the electrical system, seeking the balance between load and frequency when the machine is associated with any electrical system.

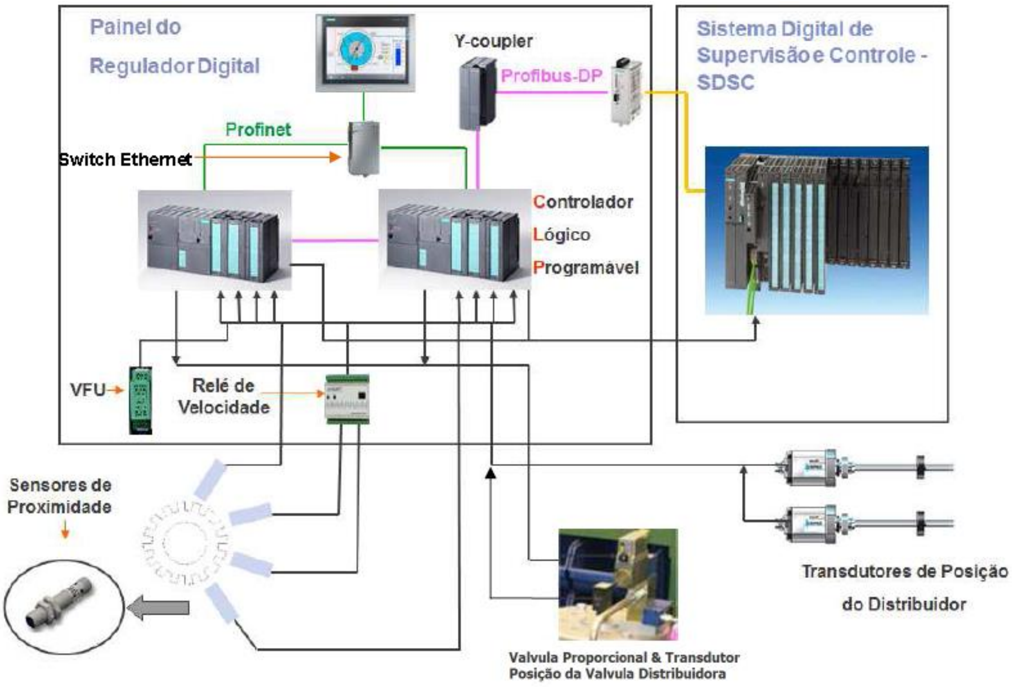
The control itself is only possible when operating a closed loop system. In Figure 3(a) there is a representation of this type of system in which the process variable called Process Value (PV) must be kept at the desired value called Setpoint (SP). The PV variable is measured by a transducer and compared with the SP value, generating an error signal. This error signal is passed to a control algorithm that calculates the output signal to the actuator in order to correct the process variable. The control algorithm will attempt to adjust the actuator until the error signal is eliminated. There are several control algorithms available, but the most used is the Proportional Integral Derivative, also known as PID. Since the control function runs continuously, the PV can then follow the SP value (Alvares, 2002).

In the case of speed regulators and active power of hydroelectric plants, the desired value is the SP informed by the plant operator or by the electrical system operator. The control algorithms of current systems are commonly implemented using programmable logic controllers that send a command signal to the hydraulic actuator basically composed of control valves, distributor valves and servomotors. The latter act on a regulation ring, which in turn position several guide vanes, which allow increasing or reducing the flow of water that flows through the turbine with the objective of imprinting a greater or lesser torque on the rotating assembly. A set of sensors installed on the machine perform the closing of the control loop, feeding back the system with real information about the process. Figure 5 shows an overview of the architecture of an active power speed regulator with its interface with the plant's Digital Supervision and Control System (SDSC), sensors and actuator.

Figure 3 – (a) Block diagram representation of a control loop; (b) Overview of a speed regulation system and active power of a large hydroelectric plant.



(a)



(b)

Source: Figure 3(a): Alvares (2002, p.4); Figure 3(b):Voith (2016).

6. Main Components of Speed and Active Power Regulation Systems

The main elements and mechanisms directly related to the speed regulator and active power that integrate the control loop and the energy generation process in a hydroelectric plant are described below.

6.1 Hydraulic turbine

The turbine is one of the main components of an electrical power generation unit that converts the hydraulic potential into the mechanical torque necessary for the operation of its associated generator. Basically there are two types of turbines for application in hydroelectric power plants: action and reaction turbines.

Action turbines are represented by the Pelton-type turbines, patented in 1880 by engineer Lester Allen Pelton. This turbine has good results when operating at large drops (above 100 meters) and small flows (up to approximately 60m3/s). The mechanical structure of the Pelton rotor resembles a massive disk containing several double-concave shells tightly secured at its end. The adductor system is usually long and its structure is designed to withstand large pressure values (Santos, 2012). 4(a) shows the basic components of a Pelton rotor turbine.

Reaction turbines are used in plants with drops between 30 and 700 meters. In this type of turbine, water completely occupies the cavity occupied by the rotor and, when flowing through it, transfers both pressure energy and kinetic energy to the rotor blades (Cenaqui, 2018). Among the reaction turbines, two deserve to be highlighted because they are predominant in Brazilian hydroelectric plants: Francis turbines and Kaplan and Bulbo turbines.

In Francis rotor turbines, water under pressure enters a spiral conductor, the auger, which surrounds the moving blades and flows through fixed blades in the radial direction into the turbine. The water then flows downwards through the impeller, exerting pressure against the moving blades, driving the impeller. Speed control is exercised through the movement of the distributor, through which the water flows before reaching the turbine rotor (Cenaqui, 2018).

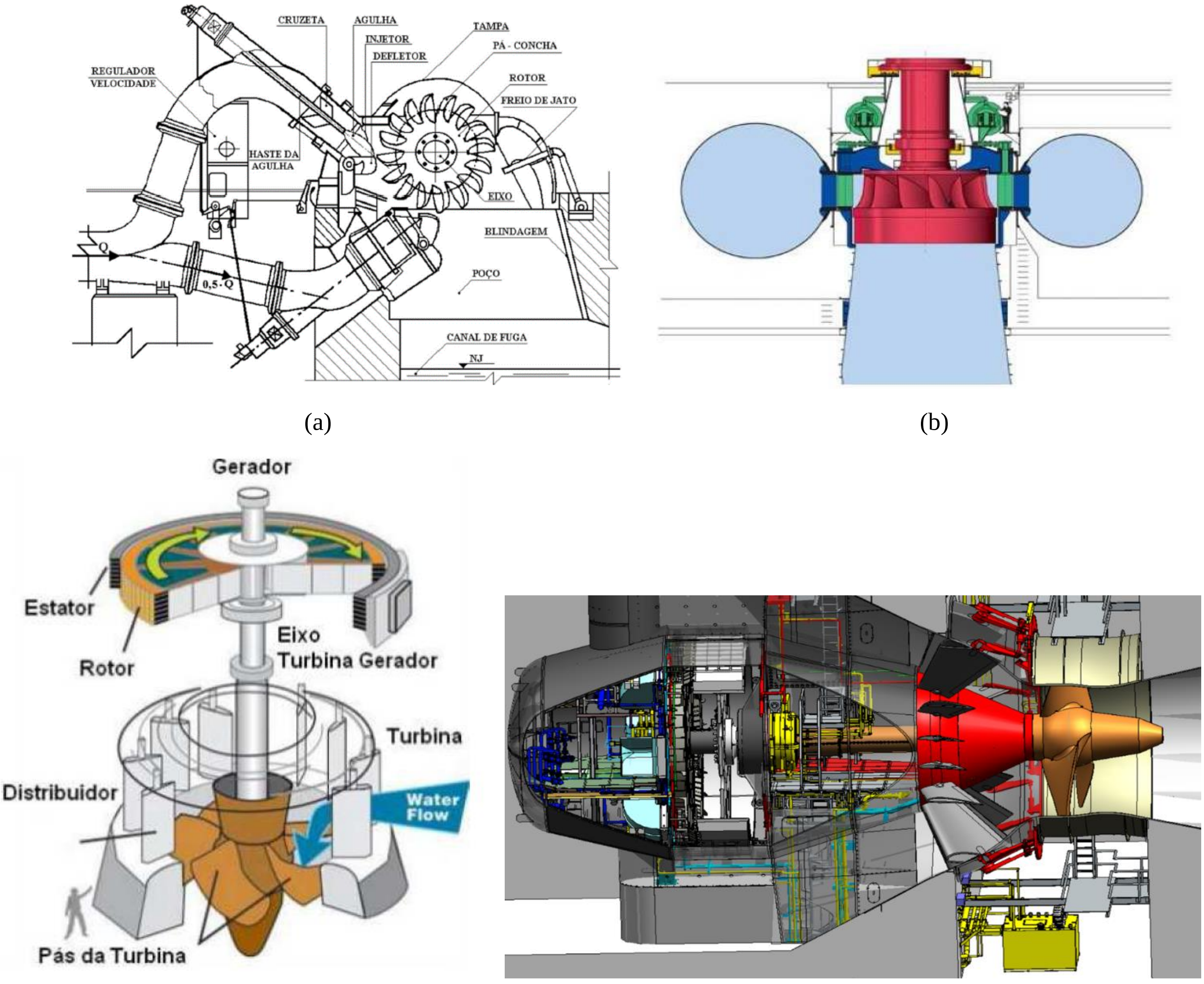
Due to its constructive versatility, since it can take different forms, Francis turbines have a wide operating range, with excellent performance, especially in medium-head use, and can even work in some small and large waterfalls. (Santos, 2012).

Figure 4(b) presents a scheme of turbines of this type.

In Kaplan or Bulbo turbines, despite being considered reaction turbines, the shaft drive is caused by the action of pressure (potential energy) and water velocity (kinetic energy) and has application in plants typically with drops between 2 and 150 meters. Speed control is exercised through the combined and coordinated movement of the distributor and blades, ensuring maximum efficiency at all operating points (Cenaqui, 2018). Figure 8 presents a schematic and main components of a Kaplan-type turbine machine.

The Bulb turbine is nothing more than a variation of the Kaplan turbine where the turbine-generator set is surrounded by a hermetic capsule and is immersed in the water flow (Cenaqui, 2018). Figure 4(d) shows a cutting scheme of a Bulb turbine.

Figure 4 – (a) Schematic of a Pelton turbine and associated elements; (b) Schematic of a Francis turbine (rotor and shaft highlighted in red); (c) Schematic of a Kaplan turbine; (d) Sectional view of a Bulb turbine.



(a) (b)

(c) (d)

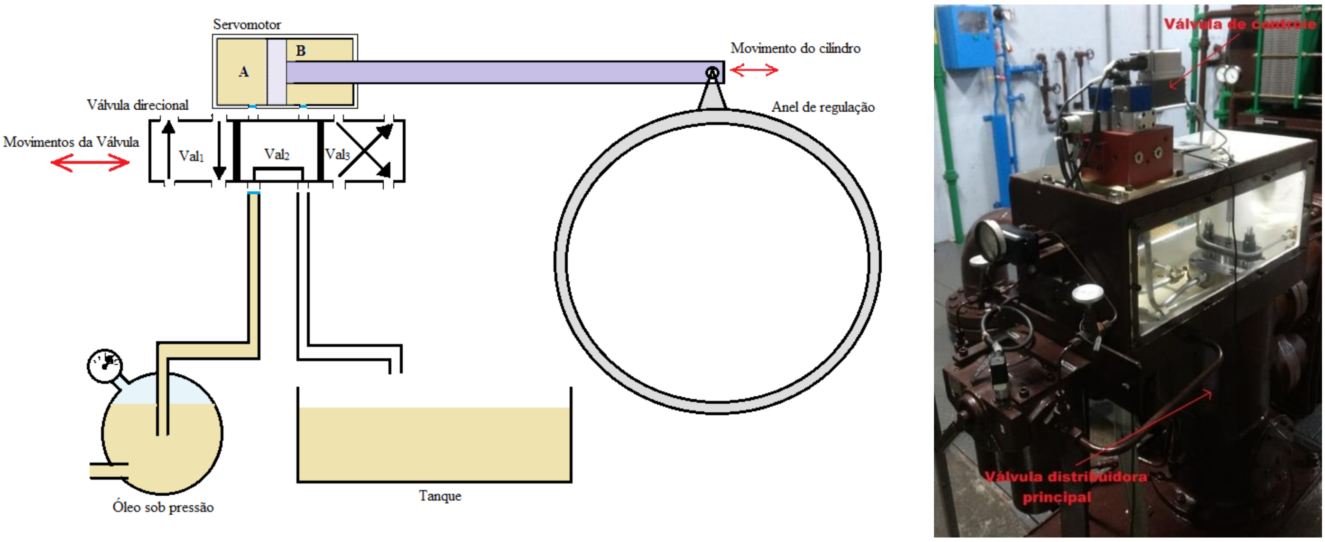
Source Figure 4(a); 4(b); 4(c): Cenaqui (2018, p. 28, 29 and 30); Figure 4(d): Andreas (2016).

6.2 hydraulic actuator

So that the speed regulator can control the speed of the generating unit through an electrical signal sent to the process, a step of amplification and transformation of the control signal is necessary. In the case of hydroelectric plants, the electrical control signal from the speed regulator is sent to a set of directional valves that distribute oil pressure between the servomotor chambers. Figure 5(a) illustrates in a simplified way the movements that the directional valve performs under commands from the speed regulator. These movements become displacement of the servomotor cylinder.

Directional valves can be composed of two-stage systems in which there is a pilot control valve that performs the movement of a main distributor valve with a large flow, sufficient to meet the requests necessary for the movement of the servomotors. In systems in which the oil operates under a higher pressure, the tendency is that the control valve itself can pilot the servomotors, since a higher pressure makes it possible to reduce the size of the equipment used, allowing the main distributor valve to be removed from the project. Figure 5(b) shows a system consisting of a proportional control valve coupled to a main distributor valve in a system that operates at a nominal pressure of approximately 60 bar.

Figure 5 – (a) Schematic of oil flow to servomotor chambers using a directional valve. (b) Hydraulic actuator assembly of a hydroelectric plant.



(a) (b)

Source: Figure 5(a): Santos (2012, p. 56); Figure 5(b): Authors.

6.3 Distributor

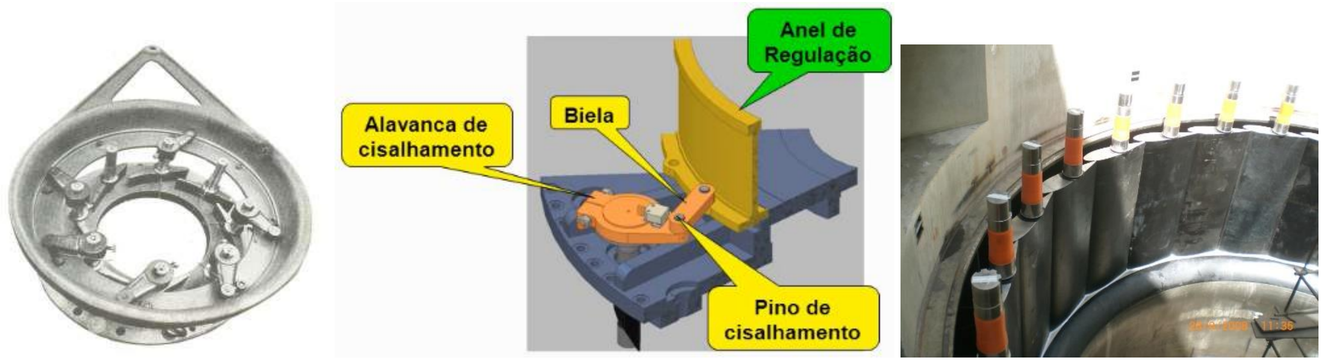
The distributor aims to accelerate and direct the water flow in a convenient way to be used by the turbine rotor. It generates the appropriate angular momentum to turn the rotor and also regulates the water flow or flow that passes through it, and consequently controls the mechanical power (Santos, 2012).

The adjustment ring is one of the components that make up the distributor. This component transfers the linear movement of the servomotors to a synchronized angular movement of the guide vanes. The adjustment ring, as its name suggests, has a circular shape and is installed in such a way as to allow its rotation around the machine axis and, through connecting rods, transmit its rotational movement to the blades. Figure 6(a) shows a real image of a regulation ring in which it is possible to see at the top the “V” shaped structure that is connected to the servomotor, in the tangential direction, which will move the regulation ring.

Figure 6(b) shows a detail of how the adjustment ring connects to the axis of the guide vanes through connecting rods and a shear lever. The shear lever connects directly to the corresponding guide vane shaft. A shear, or break, pin is used on the connecting rods ensuring that the distributor closes in an emergency even when one or more vanes are locked or obstructed.

In addition to the regulation ring, the guide vanes are also part of the distributor and are the elements that are in contact with the water and, therefore, allow the direction of its flow to the rotor. Figure 6(c) shows, still in an assembly stage of the generating unit, how the blades are arranged, in this case being fully closed.

Figure 6 – (a) Distributor with adjustment ring; (b) Connection of the adjustment ring with the guide vanes; (c) Distributor system guide vanes.



(a) (b) (c)

Source Figure 6(a): Santos (2012, p. 29); Figure 6(b): Adapted from GE ENERGY HYDRO (2017); Figure 6(c): Author's elaboration (2008).

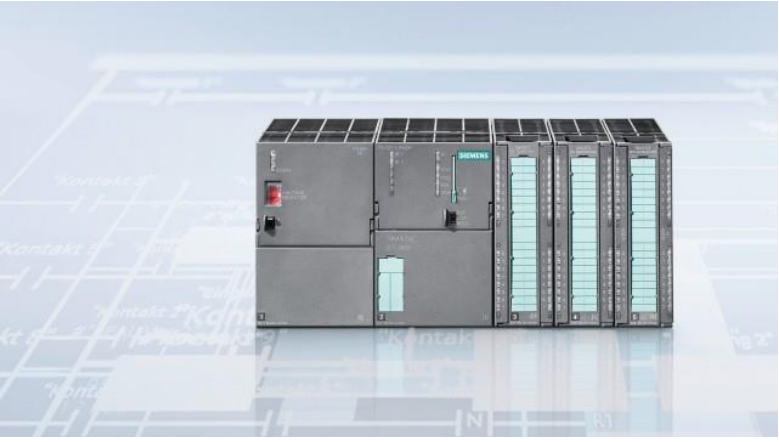
6.4 Main Control Unit

The main control units currently used are programmable logic controllers, commonly called PLC. These are nothing more than digital electronic devices, which use a programmable memory to internally store instructions and implement specific functions, such as logic, sequencing, timing, counting and arithmetic, controlling, through input and output modules, various types of machines or processes (definition of the National Association of Electrical Equipment Manufacturers of the United States of America – NEMA) (Zancan, 2011).

In hydroelectric power plants speed regulators are typically equipped with one or more PLCs in which all the automation and control logics are programmed, the latter being commonly performed through PID-type structures.

Currently, there is a wide range of programmable logic controllers available on the market from well-known manufacturers in the national market such as Siemens and General Electric (GE), but regulators developing companies have also invested in creating their own specific programmable control platforms, such as Andritz Hydro and Reivax (Yamashita, 2018). Figure 7 exemplifies a controller model widely used in large hydroelectric plants.

Figure 7 – Siemens programmable logic controller model SIMATIC S7-300.



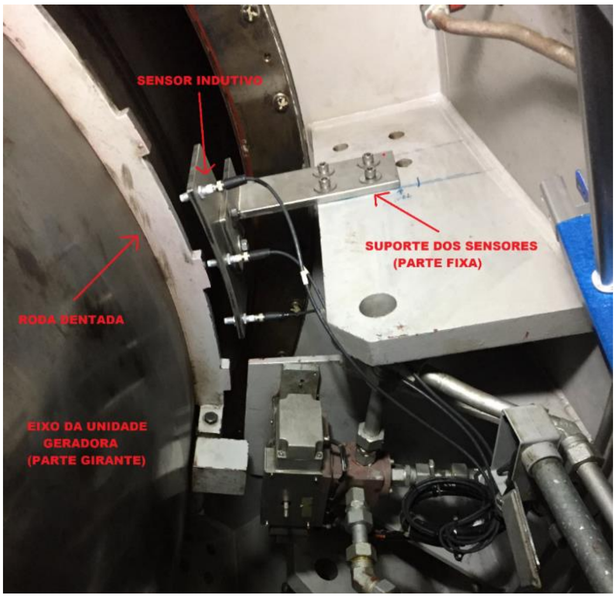
Source: Siemens (2019).

6.5 Signal transduction

In order for a speed and active power regulation system to fulfill its functions, some essential information is obtained through a set of transducers. The main signals obtained by the transducers are: rotation of the generating unit, opening of the guide vanes and active power.

The rotation of the generating unit can be obtained in different ways. The most used nowadays in large hydroelectric plants is a system composed of a sprocket and inductive sensors. The sprocket is installed on the machine shaft and the inductive sensors remain fixed, reading the "teeth" that pass through their faces when the shaft rotates. The presence or absence of the "teeth" is captured by the sensors and later converted into the output as a pulsed signal that will be sent to the PLC, the latter performing the calculations based on time, converting into revolutions per minute (rpm), frequency (Hz) or even in percentage, according to the convenience and need of the logic programmed in it. Figure 8 shows a speed measurement system with the main elements identified.

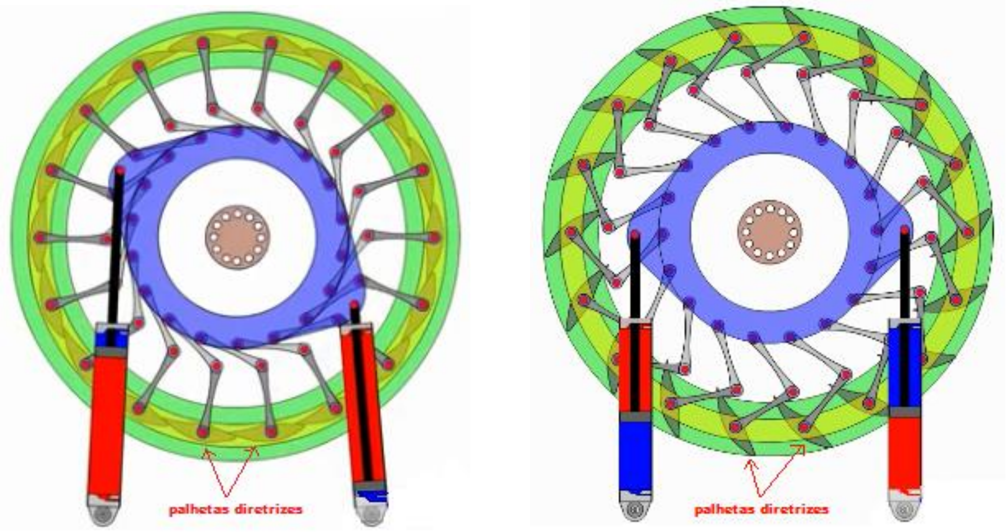
Figure 8 – Sprocket and inductive sensors for speed measurement.



Source: Author's elaboration (2018).

Linear transducers installed in servomotors are commonly used to measure the opening of guide vanes. Typically, the servomotors are active components of the hydraulic actuator set responsible for moving the adjustment ring, and this finally moves the guide vanes that, when opening or closing, allow a greater or lesser flow of water that flows through the turbines. Figure 9(a) shows how the opposing linear motion of the servomotors is converted into the opening or closing of the guide vanes by turning the adjustment ring.

Figure 9 – Servomotor performance in opening and closing guide vanes – (a) closed guide vanes; (b) open guide vanes.



(a) (b)

Source Figures 9(a) and 9(b): Adapted from Ersoy (2013).

The transducers installed in the servomotors convert their movement into information, generally in a current of 4 to 20mA proportional to the opening. However, in some cases this opening can also be measured directly on the adjustment ring, informing the PLC of the angular position of the guide vanes. The option for one or the other solution depends on the project that each manufacturer develops and both aim to feed back one of the speed regulator control loops with the desired signal. Figure 10 (a) illustrates a real application in which linear transducers are used in a redundant configuration coupled directly to the servomotor.

Figure 10 – (a) Linear transducers installed in a hydroelectric power plant servomotor. (b) Active power transducer manufactured by Siemens SICAM T series.

(a) (b)

Source Figure 10(a): Author's elaboration (2018); Figure 10(b): Siemens (2018).

Active power is the quantity measured through the terminal voltage and current signal of the generator to which the regulator is connected. This information comes from the so-called potential transformers (PT) and current transformers (CT) respectively. In current speed regulators, there are two ways of measuring active power: using an independent active power transducer or through the PLC itself, which has voltage and current measurement boards. The two solutions have the common objective of feeding back one of the speed regulator control loops to allow control of the active power delivered to the electrical system to which the machine is connected. Figure 19 shows one of the possible transducer models used in hydroelectric plants.

7. Automatisms and Interface with the Plant's Control System

In order for the speed regulator to operate correctly, it must be integrated into the plant through an interface with the plant's control system. This interface is commonly performed using cabling or an industrial communication network. It is common that this integration is also done by the two means so that there is redundancy, increasing operational availability in case of failure of the communication network.

The signals transmitted and received by the speed regulator can basically be divided into two types: digital signals and analog signals. Digital signals are binary commands with diversified functions, ranging from alarm signals and information on the regulator's operating conditions to even commands or protection signals for emergency shutdown of the system in case of serious failures. Analog signals are information sent from the regulator to the plant's control system that allows the operator and the control system to supervise and obtain data on important variables such as speed, active power and distributor opening.

With data from digital and analog signals, speed regulators can be operated remotely from the plant's control room through supervisory systems, in which the regulator's commands and information are displayed on screens developed in operating stations, which are than dedicated computers with specific software for this application. In older plants, remote operation is performed through conventional commands using switches, pushbuttons and analog indicators. Figures 11(a) and 11(b) show the two existing technologies in hydropower plants.

Figure 11 – Control room of hydroelectric plants – (a) with conventional interface; (b) with digital interface via supervisory.

(a) (b)

Source Figures 11(a) and 11(b): Author's elaboration (2018).

8. Control Loops

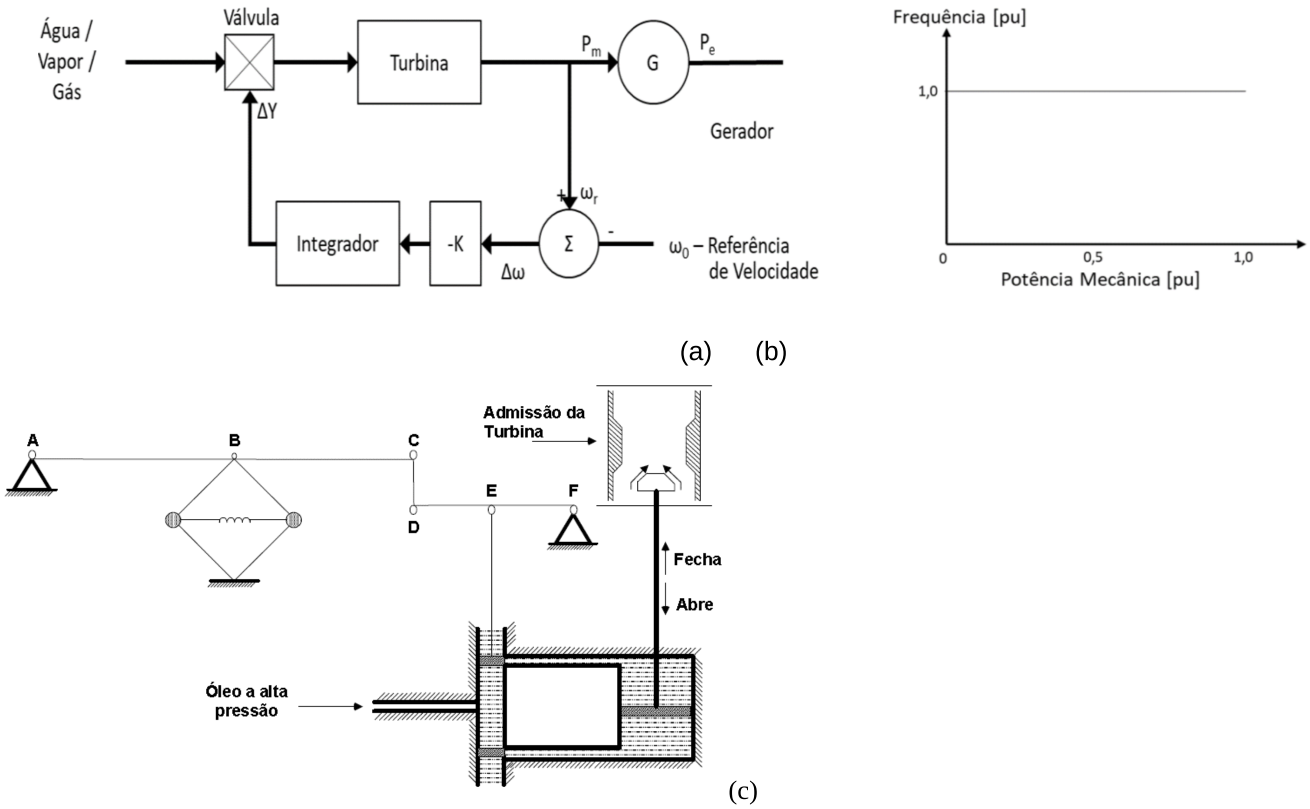
Modern speed governors have more than one control loop unlike early systems that had only one speed control loop. It is possible to find at least two different control loops with the generating unit interconnected to the electrical system (droop) and one more speed control loop for the condition of a machine isolated from the electrical system, that is, only rotation control (isochronous).

8.1 Isochronous Regulator

The isochronous regulator employs a proportional-integral (PI) controller to regulate the frequency to its reference value. It works properly when the generator operates isolated from the electrical system (Cenaqui, 2018). Its block diagram and characteristic curve are shown in Figure 12(a) and 12(b).

When an isochronous regulator starts to operate with more than one generating unit, a state of frequency equilibrium can be reached in several forms of variations and, therefore, the distribution of loads between the machines would be indeterminate since each generating unit would do all the work. effort as possible to reach your reference speed. In addition, there would be more serious stability problems with this type of control system. In this way, it can be seen that a control system is needed that is capable of carrying out an adequate load sharing between the generating units, within their nominal capacities (Gatta, 2012). Figure 12(c) illustrates what the mechanical diagram of an isochronous regulator using a flying ball system would look like.

Figure 12 – Isochronous speed control – (a) Block diagram; (b) Characteristic curve of the variation of power as a function of frequency; (c) Mechanical diagram of the isochronous regulator.



(a) (b)

(c)

Source: Figures 12 (a) and 12(b): Cenaqui (2018, p. 16); Figure 12 (c): Gatta (2012, p. 11).

Regulator with speed drop

Also known as a droop speed governor, it features a characteristic of reducing rotor speed as load increases, suitable for parallel generator operation and load sharing. The statism, or simply droop, expresses the relationship between the change in speed ($\Delta\omega$) and the change in power (ΔP), according to the equation below:

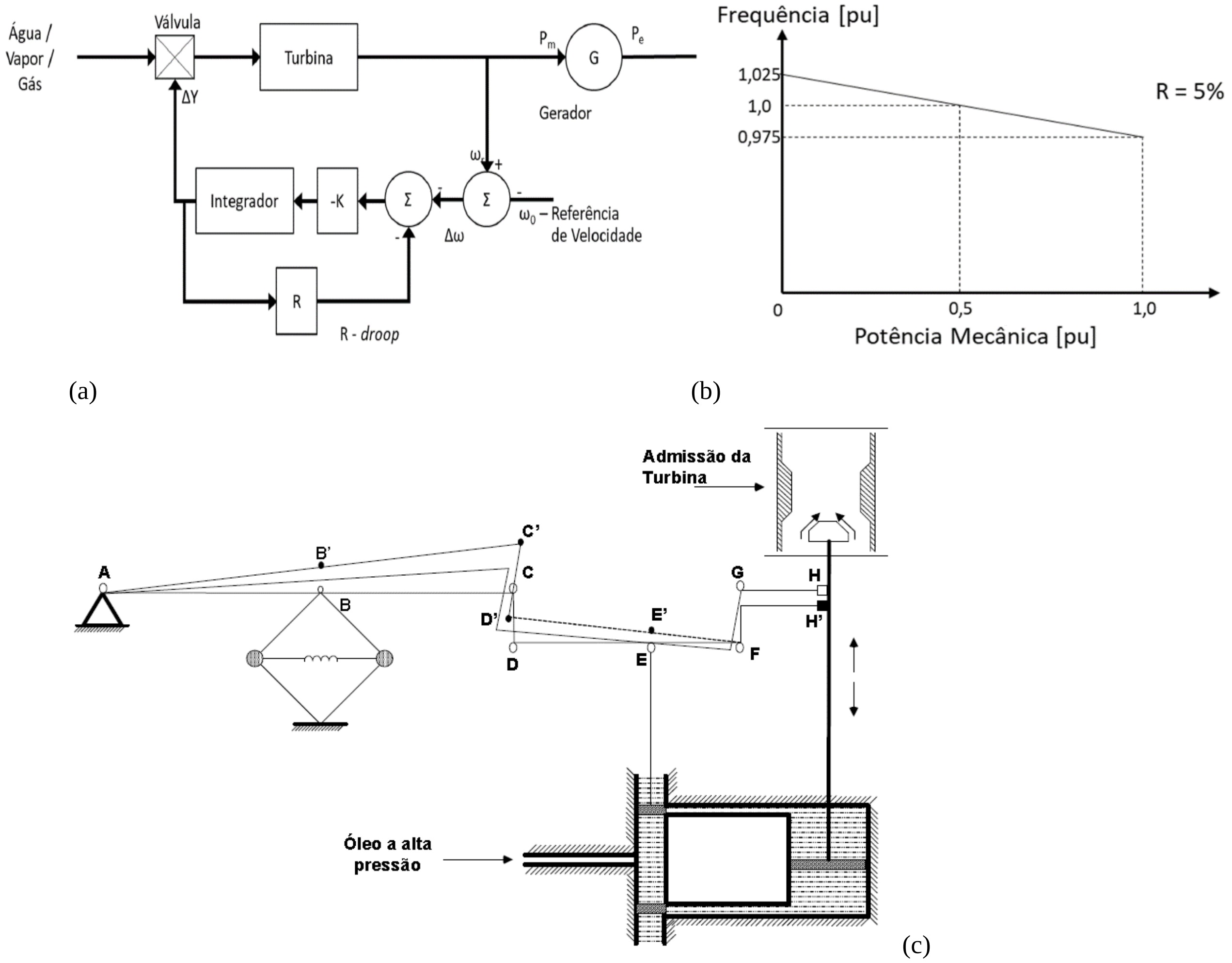
$$R=-\Delta\omega/\Delta P \quad (1)$$

Figures 13(a) and 13(b) show the block diagram and the characteristic curve of the droop regulator.

Figure 13(c) shows the mechanical diagram of the droop speed governor in which, to make a faster and more stable governor, a feedback is established, indicated by the points “E”, “F”, “G” and “ H". It can be seen that the movement of point “H”, in this case, also promotes the movement of point “E”, in the same direction. In this case, only point “A” is fixed (Gatta, 2012).

In this specific case, the system reaches a new faster equilibrium state that is not characterized by the nominal speed of rotation, or by the nominal frequency (Gatta, 2012), that is, the point of accommodation of the afterload speed will no longer be the preload configured reference, but any point that will depend on the applied load considering equation (1).

Figure 13 – Droop speed control – (a) Block diagram; (b) Characteristic curve of the variation of power as a function of frequency; (c) Mechanical diagram of the governor with droop.



(a) (b)

(c)

Source: Figures 13(a) and 13(b): Cenaqui (2018, p. 17); Figure 13(c): Gatta (2012, p. 13).

9. Modeling of Speed and Active Power Regulation Systems

In order to be able to solve the problem associated with the modeling, simulation and validation of speed and power regulation adjustments of a hydroelectric plant, it is necessary to analyze the dynamics of the various components of the regulation network, where the main components are: reservoir, adduction systems, turbine-generator group and the electric power system. Each of these components has its own dynamics (Souza, 2004).

Also according to Souza (2004), other aspects also affect regulation, such as load characteristics, turbine characteristics, configuration of electrical systems, etc. As if the number of components and the conditions that affect the dynamics of the speed and active power regulation loop were not enough, there is also the influence of one generating unit on the other and vice versa, as in the case of plants with several generating units and with several penstocks sharing the water adduction structure of the reservoir.

Dynamic models are based on differential equations, sometimes nonlinear, that describe a physical system. With the help of the Laplace Transform, it is possible to create a block corresponding to this physical system (which is often conveniently linearized). When this physical system is related to another system, you can connect them through their common state variables and create the block diagram. The computational solution of these diagrams is not analytical but numerical (Santos, 2012).

10. Final Considerations

In this work, only the adduction systems, turbine-generator groups, speed and power regulators and the load were treated, seeking through a simplified approach to obtain sufficient data to allow an analysis of the control loop associated with the regulation of speed and active power of plants. hydroelectric plants.

In this way, from the dynamic models discussed here and in-depth in the form of a bibliographic review, we seek to encourage and propose analyzes by engineers and technicians who work directly with speed regulation systems and active power in hydroelectric plants. This can make adjustments to the system possible, aiming to improve its performance. These adjustments, meeting the pre-established requirements of performance and use of tuning techniques and tools from control theories, could generate savings and efficiency in this sector that is so important for energy generation.

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