Load Frequency Control of Distributed Generation using GA Optimized PID Controller

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Abstract–
The dynamic behaviour of the frequency in Electrical Power Systems (EPSs) s directly related to the balance between the mechanical power and the electrical power of each generator system. In the operation of EPSs, a nominal value is established as a reference for the balance of powers, the load changes (electrical power) are reflected in the level of the frequency, which makes it necessary to modify the mechanical power to restore the equilibrium. When faced with small changes in load, it is generally possible to modify the mechanical power without having appreciable deviations from the frequency; this is not possible in the case of significant generation losses, so frequency control is carried out through changes in electric power. This paper presents an approach of load frequency control of distributed generation system using a proportional-integral-derivative (PID) controller optimized by a stochastic optimization method known as Genetic Algorithm.

Key words : ACE, EPS, GA, IEGC, LFC, PID, etc.

1. INTRODUCTION

An Electric Power System (EPS) allows energy to be efficiently transported from the various possible sources to homes, industries and businesses. By having several points of consumption and generation operating simultaneously and interconnected, EPSs are among the most complex systems ever made by mankind [1]. Therefore, they require an adequate study and design of their components, transmission, generation and distribution systems.

An EPS must fulfill some fundamental requirements [2]:

- Maintain continuity of operation even with variations in the demand for active or reactive power;
- Operate with minimal cost and with minimal ecological impact;
- Maintain power quality with minimum standards of:
  - Voltage
  - Frequency
  - Reliability

In short, it can be considered that the system is expected to supply its consumers with quality and reliability.

Quality is related to the compliance of the system parameters, that is, they must present voltage and frequency values within certain limits. This is important for consumers, as machines are designed to work with fixed electrical values and variations in these, even if small, can cause premature failure or malfunction. Therefore, maintaining the parameters at the established values or with few variations is an obligation of the electric power system. In this sense, Indian Electricity Grid Code (IEGC) establishes minimum and maximum values for voltage and frequency: the voltage is in percentage according to the nominal voltage and type of customer; and the frequency must be between 49.5 Hz to 50.2 Hz in permanent operation [4].

Reliability is related to the continuity and stability of the electrical power system. Mainly so that there is no interruption in service due to causes unrelated to productive capacity, and the ability to recover from transmission failures. For stability, a system must have the ability to return to a state of equilibrium after a disturbance. In the area of stability, there are three categories of stability: tension, frequency and angular [5]. Although there is a division of instabilities, instabilities rarely occur in a pure way,

as one can lead to another and the distinction may not be so clear [5]. Despite this, voltage and frequency have a specific control system for each one.

Although the subjects, quality and reliability, are different, they are related to the minimum variation of the voltage and frequency values in relation to their nominal values, that is, the stability. The Control of the Electric Power System can be divided into two parts: a) Voltage and Reactive Power Control; and b) Frequency and Active Power or Load and Frequency Control. Both act in the generation of electric energy. As each control is a very broad topic, this work deals only with the control of load and frequency. The control of this parameter can be done in isolation, as there is a decoupling between voltage and the system frequency in conditions close to the nominal ones [7].

The security level of a system can be identified according to the operating states of the system. In the operation of an EPS, five operating states are recognized [8] [9] [10] [11], as shown in Figure 1.
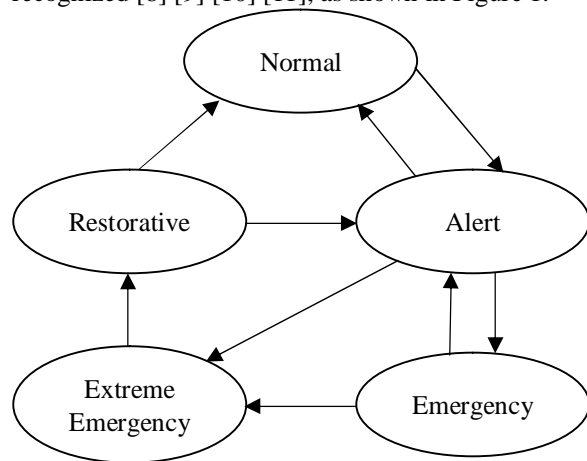
Figure 1: States of operation of an electrical power system [8]

In the normal operating state the generation is adequate to satisfy the demand and there is no overloaded equipment, in this state the generation and transmission reserve margins are sufficient to maintain an adequate level of security to withstand possible disturbances in the system.

If the probability of a disturbance increases and / or there is an operating condition with reduced reserve margins, the level of safety will be reduced, which will lead to a state of alert. In this state the demand is satisfied, but for some contingencies there will be elements overloaded in the system and / or violation of operational limits. It is an insecure state.

In the state of emergency some elements of the system are overloaded; In most emergency situations, the instantaneous disintegration of the system is not directly reached, but there is some time to carry out

control actions, which allows directing the system to a normal or at least alert state; These actions depend on the magnitude of the disturbance and the time available.

If the emergency controls are ineffective or take a long time to be carried out, the system may fall into a state of extreme emergency, where the disarticulation of the same begins, causing the formation of electric islands; in this case the supply of the service is not fulfilled and the uncontrolled separation of elements begins.

The last state is the restorative, where the restoration of the disintegrated system is carried out, trying to comply with all the operating restrictions to bring the system to the normal state, or at least, to the alert state.

EPSs generally arrive at states of emergency as a result of a combination of events, sometimes due to more severe contingencies than those considered as design criteria, and others as a result of a "normal" contingency where the protection and / or control devices they did not operate correctly, initiating a series of events in cascade, which is known as system collapse. The objective of emergency controls is to avoid total or partial collapse through automatic actions.

Avoiding a collapse affects economic and social aspects. The time required to start a plant and operate at its nominal capacity can be several hours depending on the type of generation. At the same time, with the interruption of the energy supply, the production processes are stopped with the corresponding economic losses. The social impact can also be of serious consequences, since the paralysis of some services creates panic situations and conditions conducive to acts of vandalism.

2. IMPORTANCE OF THE LOAD FREQUENCY CONTROL

Load frequency control (LFC) plays a fundamental role in the generation and distribution of energy in an interconnected power supply system. On the other hand, it is also crucial when it comes to ensuring the stability of a system and its proper functioning in real time.

As is known, electricity must be consumed simultaneously with its generation. The lack of knowledge and the lack of control we have over excessive demand complicates the control of this balance under optimal conditions. Throughout the years a high development in the techniques of prediction of the demand has been achieved. Based on climatological and social factors among others, it is possible to estimate with not too much error the active power that will be consumed in a system over the next few hours.
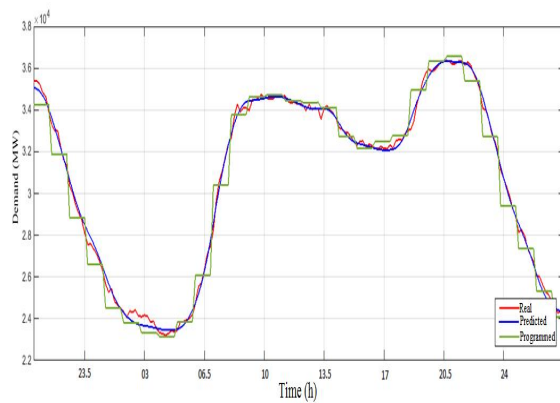
Figure 2: Demand in the Indian subcontinent system [12]
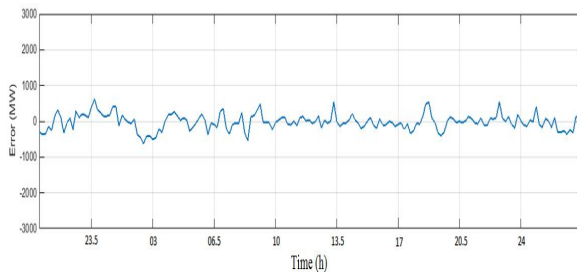
Figure 3: Difference between real and predicted demand in the Indian subcontinent system [12]

Figure 2 represents the demand in the Indian subcontinent system over a day, the prediction that was made and the generation program established. Despite the fact that the predicted power is quite adjusted to the one actually consumed, it is inevitable to make a certain error (Figure 3) that must be corrected in real time by the generators participating in the frequency regulation of the system.

The changes in active power mainly affect the frequency of the system, while the reactive power changes are directly related to the voltage. The low coupling between both controls explains their traditional study separately. This document will therefore focus on the study of frequency control and active power, commonly known as load frequency control.

The LFC control is gaining importance with the growth of the network and its global interconnection. The trend towards liberalized electricity markets and the unstoppable development of renewable energies are making the system move towards more robust connections between networks that eliminate the technical restrictions for a free international energy market. Today more than ever, the control of active power plays a fundamental role in the operation of the systems to guarantee a stable frequency in the event of contingencies or unforeseen changes.

At the level of local implementation in the generators, two control loops are mainly differentiated:

The primary control is the fastest and the first that goes into action when there is an error in the frequency. The generators are equipped with regulators that respond to changes in the load acting proportionally on the motive power. The response time of the control depends mainly on the characteristic delay of the turbine on which we are acting, normally found in the range of 3 to 30 seconds.

On the primary control the secondary control acts in a delayed manner. The objective of this control is to eliminate the permanent error in frequency. For this, it is responsible for varying the reference power of the generator through the action of an integral control loop. It is known as automatic generation control, or AGC (Automatic Generation Control), and is characterized by a response time somewhat slower than that of the primary control, of the order of 1 minute.

Both the primary and secondary control are controls that are implemented locally in the exchanges and respond automatically to changes. Hierarchically superior to both we could define a "tertiary" control or economic generation dispatch. This is intended to operate the system at the lowest possible cost based on the generation offers registered.

This paper aims to achieve an in-depth understanding of the bases of load-frequency control in electrical systems. For this purpose, the behavior of conventional generation plants will be studied in detail in response to disturbances in demand and / or generation, and a genetic algorithm based PID model is developed to allow simulations of various systems. The MATLAB-Simulink tool is be used for the implementation and simulation of the models. Section three presents a literature review related to the load frequency control with various approaches. Section four presents the proposed GA optimized PID controller. Simulation and results are elaborated in section five and finally the conclusive remarks are provided in section six.

3. LITERATURE REVIEW

The control of load and frequency regulates the frequency acting on the driving force of the plant, this being the most important function in the system in the automatic control system of a plant [6]. In addition, Kundur [2] states that an electrical system with a frequency outside the nominal directly influences the operation and performance of the system. This control is important for the balance between generation and consumption, because if it is affected there will be a variation in the frequency that can lead to instability [7].

The design method for load and frequency controllers differs greatly depending on the type of generation used, as each machine has its characteristics that vary according to the driving force used to move it. Therefore, the study for a hydroelectric is different from a thermoelectric. In India, hydroelectric power generation corresponds to 60% of the energy matrix [13], in addition, the country's water potential represents 20% of the earth's surface water reserves and is considered the largest on the planet. This makes studying this type of generation quite interesting on the national scene.

The difficulties encountered in this type of control are quite varied. The synchronous machine, for example, has non-linear characteristics and the system has several points of operation. This makes it difficult for the controller to get a good rejection of disturbances and performance in the transient and permanent regimes. In addition, the system is interconnected with several plants, each with its own controller and load, thus increasing the complexity of the control system as a whole.

The literature describes several types of controllers in order to solve the described problems. There are differences between the power systems studied, according to their configuration of plants, loads and transmission lines. Therefore, the studies carried out can be divided between the types of systems and types of controllers.

In real systems, it is difficult for a plant to operate in isolation, where only it and its load exist. Typically, the system consists of several generating units and different loads interconnected by transmission lines. Due to the difficulty of simulating very large systems, generally smaller systems from one to four areas are used, each area formed by a plant and a load interconnected by transmission lines [14].

The first load and frequency control studies were in systems with one area. An example is the work of Foord [15] who studied the transient response to an isolated plant close to the maximum load. Kusic et al. [16] presented the automatic control of an isolated hydroelectric plant.

Systems with more areas can be composed of plants of only one type or of different types, i.e. hydroelectric and thermoelectric, etc. In the work of [17], a system with two hydroelectric plants connected by a transmission line is studied and a Proportional-Integral-Derivative (PID) controller based on the maximum resonance peak is designed. Plants of different types are analyzed by [18], there are four plants, two of which are thermoelectric and two hydroelectric.

To control a system with several plants, two control strategies can then be adopted: decentralized or centralized. In the centralized system, all plants in the system are controlled by only one controller. Applied in the study by Quazza [19], a centralized control system is proposed in which the plants are interconnected by a control system that controls them at the same time. Despite being the best from the control point of view, it is more expensive due to all the necessary intercommunication between the plants. In the decentralized, each plant has its own controller. As an advantage, this is the cheapest, but it presents greater difficulties from the control point of view, since the controllers must work in a coordinated way even without having information from each other. This is the most frequent control strategy, as it is simpler and reduces computational effort [20]. All of the controllers mentioned below will be of this type.

For the controller project, there are several techniques, among them: the classic methods [19] [21]. PID optimization via genetic algorithms [22]; [23]; [24], synthesis of robust controllers [25], [26], [27], among others.

Some methods are considered classic because they use traditional or not so modern control techniques [20], following this logic, as an example, we can mention the works of [19] and [21].

Shirai [21] used Lyapunov's second approximation method together with the accommodation time theory. Quazza [19] proposed an approximation without interaction between frequency and the power flow of the transmission line so that each area is responsible for the variations in their loads.

Optimization by means of genetic algorithms aims to adjust parameters in order to minimize performance parameters. These can be of several types: Quadratic Error Integral times Time, Quadratic Error Integral, Absolute Error Integral, among others. Usually the controller has a fixed structure in which its values will be adjusted through the search performed by these algorithms. Some examples of this line of controller design were applied by: [22], [23] and [24].

Abdel et al. [22] used genetic algorithms to adjust parameters of a PI controller in order to minimize the Quadratic Error Integral and the Quadratic Error Integral times Time and a two-area system model. Shankar et al. [23] proposed, also for a two-area system with hydroelectric and thermoelectric plants, a PID controller and parameters adjusted by genetic algorithms in order to minimize the quadratic error. Saxena et al. [24] used a multiobjective function based on the Integral Quadratic Error criteria and the Integral Quadratic Error times Time, minimizing it using genetic algorithms. The procedure is applied in a two-area system and the controller of the two areas is obtained at the same time. The controller structure was an integrator.

Another group of possible control solutions is through a robust controller. The advantage of the robust controller over other techniques is to maintain stability and performance even with variations in the

system parameters [28]. This characteristic is interesting given the non-linearity of the electrical power system. Traditionally, they result in a linear controller with variable structure and some examples of this technique were made by [25], [26], [27].

Shibata et al. [25] proposed a method that uses a robust μ-synthesis controller for the case of a three-area system. The uncertainty is associated with the damping coefficient of each of the machines in the system. Finally, it is shown that it performs better than a traditional PID. Lu et al. [26] used an infinite Hcontroller for a system containing 8 machines and 36 buses. The result showed that this controller is superior to the conventional controller. Tan and Xu [27] used a model with an uncertainty in the turbine model in order to demonstrate that by extrapolating this uncertainty to an unmodulated dynamics, the system can be unstable if the controller is not robust.

In the Dynamic Systems and Control Group of the Federal University of Paraná, some works in the area have already been developed. Aurelien [29] presented, a comparative analysis based on frequency control in hydroelectric plants using PID and infinite H controllers [29].Donaisky et al.[30] presented a proposal for a hybrid model of the type PWA (Piece-wise Affine) for the hydraulic network of UHEs. In addition, the author proposed to combine this model with a Load and Frequency controller forming a hybrid MPC (Model Predictive Controller). Results were applied in a case study based on a Brazilian hydroelectric power plant, where the MPC controller must perform better than the traditional PID [30].

The genetic algorithm allows a wide search for values of the parameters of the controller, this in general obtains controllers with good performance. Robust control techniques, on the other hand, describe requirements that the controller must meet in order to be robust to variations in system parameters. A technique that uses both, can be a controller with good and performance and robust.

4. PROPOSED METHODOLOGY

A. System Model

Normally, when the generators are relatively close to one another, they tend to rotate in unison and the turbines usually have similar transient responses. When we have a group of these generators closely related to each other we can say that they form an area of control. In an electrical power system we can have a multitude of control areas connected between them. Each of these areas can be connected to any other, which implies that all connected areas must reach the same electrical frequency. The connection between areas is made through a line with a determined reactance X_l. For the study of the load frequency control we will consider that the line is

without losses, that is, the resistance will be zero and, therefore, the line will not dissipate power.
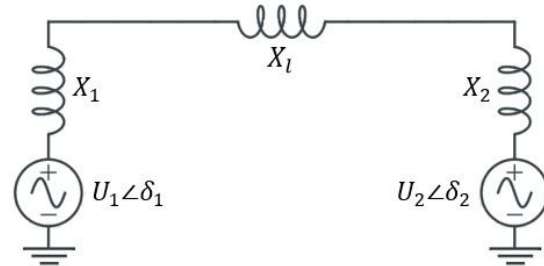
Figure 4: Basic diagram for a power system of two areas [31]

Under normal operating conditions, the power transmitted through the line is given by the following equation:

$$P_{12} = \frac{|U_1||U_2|}{X_s} \sin \delta_{12}$$

(1)

Where, X_s is the sum of all the inductances between areas $(X_s = X_1 + X_1 + X_2)$ and δ_{12} is the phase difference between areas $(\delta_{12} = \delta_1 - \delta_2)$

For small deviations in the power flow through the line it can be assumed:

$$\Delta P_{12} = \left(\frac{dP_{12}}{d\delta_{12}}\right)_{\delta_{12_0}} , \Delta\delta_{12} = \frac{|U_1||U_2|}{X_s} \cos \Delta\delta_{12_0} \Delta\delta_{12}$$

(2)

A new term P_s known as synchronizing power is defined:

$$P_s = \left(\frac{dP_{12}}{d\delta_{12}}\right)_{\delta_{12_0}} = \frac{|U_1||U_2|}{X_s} \cos \Delta\delta_{12_0}$$

(3)

Therefore, the power exchanged through the line remains as:

$$\Delta P_{12} = P_s\Delta\delta_{12}$$

(4)

The term P_{12} takes positive values when the power flows from area 1 to area 2 and negative if the power goes in the opposite direction. It should be remembered that the direction of the power flow is determined by the phase difference $(\Delta\delta_{12} = \Delta\delta_1 - \Delta\delta_2)$.

To calculate the frequency in permanent regime we can start from the reasoning for a single area and include the power term exchanged by the line (ΔP_{ij}):

$$-\Delta w_1 \left(\frac{1}{R_1} + D_1\right) = \Delta P_{12} + \Delta P_{L1}$$

(5)

$$-\Delta w_2 \left(\frac{1}{R_2} + D_2\right) = \Delta P_{21} + \Delta P_{L2}$$

(6)

Taking into account that the areas that are connected have the same frequency in steady state $(\Delta w_1 = \Delta w_2 = \Delta w)$ and that the power exchanged $1 - 2$ is the opposite to the $2 - 1(\Delta P_{12} = -\Delta P_{21})$ the equations (5) and (6) changes to:

$$-\Delta w = \frac{\Delta P_{L1} + \Delta P_{L2}}{\left(\frac{1}{R_1} + D_1\right) + \left(\frac{1}{R_2} + D_2\right)}$$

(7)

To calculate ΔP_{12}, equation (7) is substituted in any of equations (5 or 6):

$$\Delta P_{12} = \frac{\Delta P_{L2}\left(\frac{1}{R_1} + D_1\right) - \Delta P_{L1}\left(\frac{1}{R_2} + D_2\right)}{\left(\frac{1}{R_1} + D_1\right) + \left(\frac{1}{R_2} + D_2\right)}$$

(8)

B. Control of Exchanges in Lines of Link

When the system is operating under normal conditions, it is not only intended to maintain the frequency at its nominal value, but also to follow as far as possible the generated generation plan, maintaining the power exchanges along the lines in the values desired. For this, each area must assume the demand differences by modifying the generation of the generators of the area itself.

This control is called ACE (Area Control Error) and is formulated as a linear combination of frequency error and power exchanges along the lines:

$$ACE_i = \sum_{j=1}^{n} \Delta P_{ij} + B_i \Delta w$$

(9)

Where ΔP_{ij} are the deviations of power by the lines with respect to the predicted values. In a system that has an ACE system in operation, these deviations end up being canceled. By the action of integral control, the error in frequency is also eliminated, which implies that the ACE signal will be equal to 0 with the stabilized system.

The constant B_i determines the intensity of the response when imbalances occur in the neighboring areas. An optimal response of the ACE system is reached when the constant B_i takes the value β_i. Where β_i is the response characteristic characteristic of the system.

$$\beta_i^{opt} = \beta_i = \frac{1}{R_i} + D_i$$

(10)

To demonstrate the optimal response of the ACE when $B_i = \beta_i$, we will assume a two-area system in which a certain load variation occurs in area 1 (ΔP_{L1}). The desirable thing for this case would be that only the ACE of the area in which the disturbance occurs would act.

$$ACE_1 = \Delta P_{12} + B_1 \Delta w$$

(11)

$$ACE_2 = \Delta P_{21} + B_2 \Delta w$$

(12)

Substituting the equations (7) and (8) in above equations, we have:

$$ACE_1 = \frac{-\Delta P_{L1}\beta_2}{\beta_1 + \beta_2} + B_1\left(\frac{-\Delta P_{L1}}{\beta_1 + \beta_2}\right) = \frac{-\Delta P_{L1}(\beta_2 + B_1)}{\beta_1 + \beta_2}$$

(13)

$$ACE_2 = \frac{\Delta P_{L1}\beta_2}{\beta_1 + \beta_2} + B_2\left(\frac{-\Delta P_{L1}}{\beta_1 + \beta_2}\right) = \frac{\Delta P_{L1}(\beta_2 - B_1)}{\beta_1 + \beta_2}$$

(14)

Following the previous reasoning, it must be fulfilled that $ACE_2 = 0$:

$$ACE_2 = \frac{\Delta P_{L1}\left(\beta_2 - B_2^{opt}\right)}{\beta_1 + \beta_2} = 0$$

(15)

This condition is met for $B_2^{opt} = \beta_2$. Analogously, $B_1^{opt} = \beta_1$ is also shown.

C. Load Frequency Control Using PID Controller

The PID controller [32] is the so-called three-term controller. The first term K_p will have the effect of reducing the rise time. An integral control K_i that will have the effect of eliminating steady state error, but may worsen the transient response. And a derivative control K_d that will have the effect of increasing system stability, reducing overshoot, and improving the transient response. The effects of each of the K_p, K_i, and K_d controllers in a closed-loop system.

This controller is defined by the transfer function shown in equation (16).

$$G - K_p + \frac{K_i}{s} + K_d s$$

(16)

The representation of the equation (16) in the time domain is given by equation (17):

$$U(t) = K\left\{e(t) + \frac{1}{T_i}\int_0^t e(t)dt + T_d\frac{\partial e(t)}{\partial t}\right\}$$

(17)

The development of adaptive controllers using Genetic Algorithms in a method not widely used, due to the lack of knowledge of the use of characteristics of GA in this type of applications. Some of the works carried out in this regard and which were taken as the basis for the realization of this project are referenced [33] [34] [35] [36].
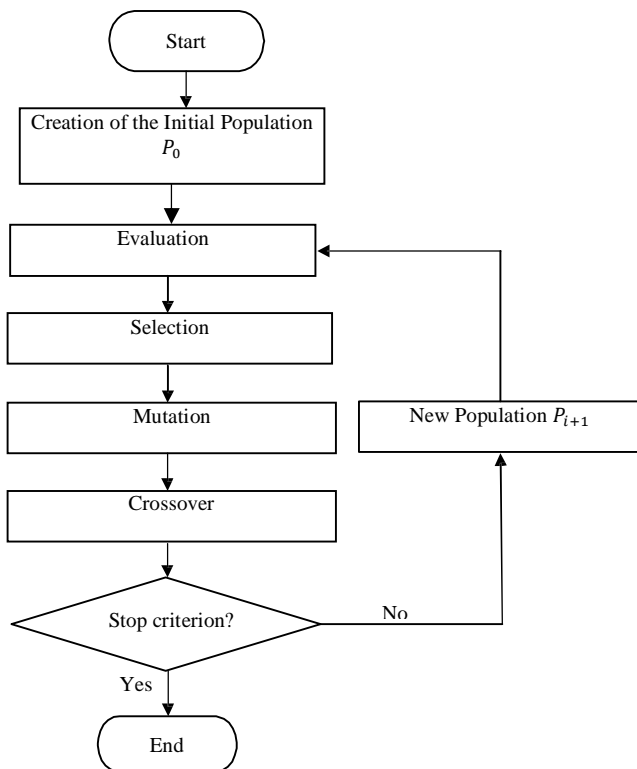
D. Genetic Algorithm

Along with the advent of computational technologies during the 20th century, algorithm developments emerged with the purpose of performing numerical or combinatorial optimizations, one of the first investigations was carried out by John Holland, professor at the University of Michigan, who proposed one of the first evolutionary algorithms: The Genetic Algorithm (GA) [37]. Holland was based on the works of Charles Darwin's Theory of Natural Selection of species, where it is stipulated that members of a population will tend to spread according to their ability to adapt to their environments.

The other theoretical reference of genetic algorithms are Gregory Mendel's Laws of Inheritance, which stipulate the hereditary character of the dominant and recessive characteristics of individuals who

reproduce sexually. These precepts imply that the best individuals in a given population have a better chance of survival and reproduction; the possibilities decrease or are null for the weak [37]. The GA, created by John Holland is characterized by the steps described in the following pseudocode [38] [39]:

1. Define a fitness function or objective function,
2. Generate a series of possible solutions (chromosomes) in a random way forming a set called population,
3. Coding the population,
4. Evaluate the objective function with the population, thus starting the ith generation,
5. Select solutions to be reproduced,
6. Apply a crossover operation,
7. Mutate some elements resulting from crossing,
8. Replace elements of the population of the ith generation with the best elements of step 6 and step 7,
9. Stop, if the stop criterion is met, and if not go to step 4.

The steps described can be shown graphically in Figure 5.

Figure 5: Flow chart of Genetic Algorithm

General Structure of GA

It begins with an initial population of random solutions (population). Each individual in the population is called a chromosome, which represents a solution to the problem. Chromosomes evolve through successive iterations, also called generation. During each generation the new chromosomes are evaluated, using the aptitude measure. Then, by means of the crossover and mutation operators, the chromosomes with the highest probability of survival are selected in order to carry out the exploration and exploitation of the objective function. Finally, they are reintegrated into the current population, after finishing the number of generations, the individual with the highest performance is selected, which represents the most optimal solution.
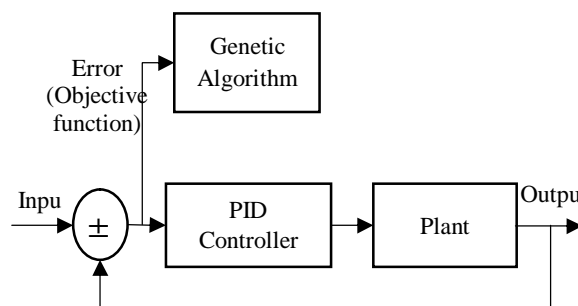
Figure 6: Genetic algorithms applied to PID controllers

For the algorithm defined above, the objective function is given by:

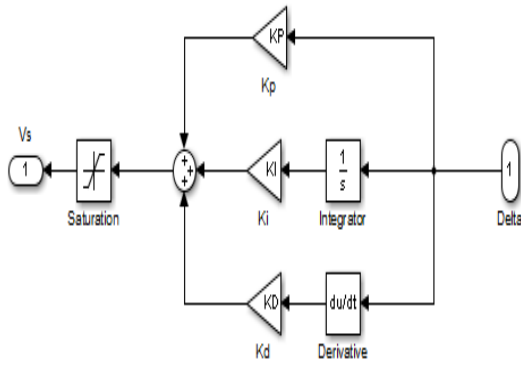$$\text{Objective Function} = \int \text{error}(t)\,dt \tag{18}$$

5. SIMULATION AND RESULTS
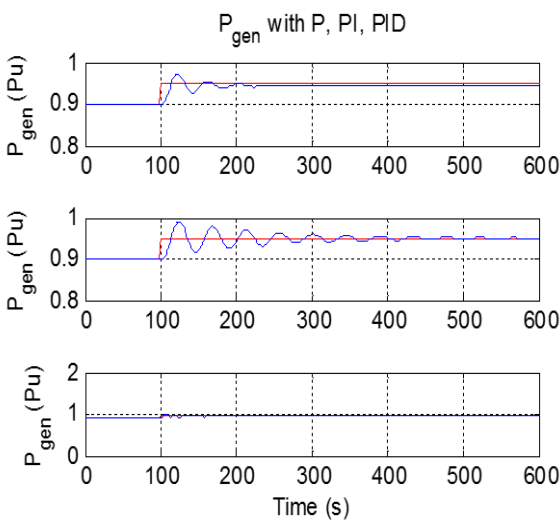
A. Simulation Parameters

Table 1: Simulation parameters

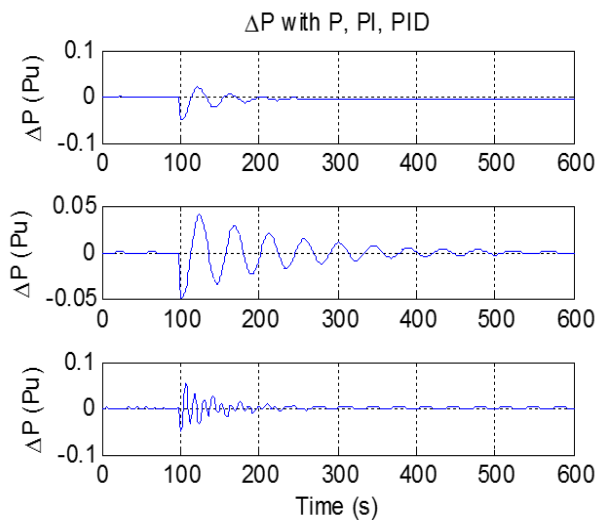|	K_P	K_I	K_D
P- Controller	0.0655	--	--
PI Controller	0.0590	0.0027	--
PID Controller	0.0786	0.0749	3.3366

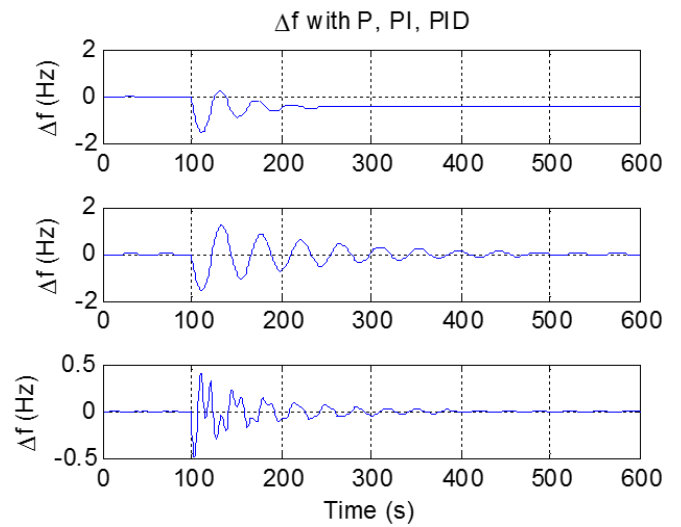## B.   Simulation Results

Figure 7: Simulink diagram for proposed PID controller
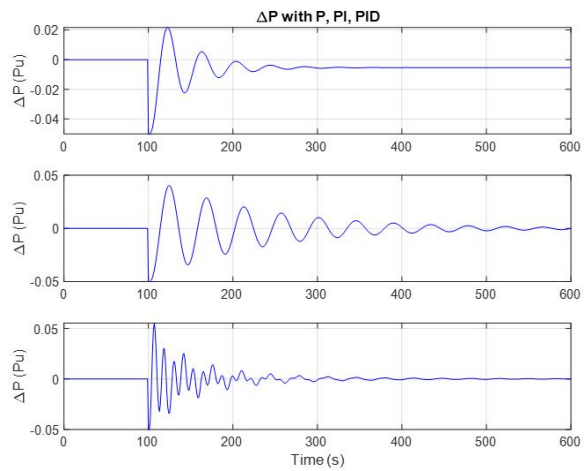

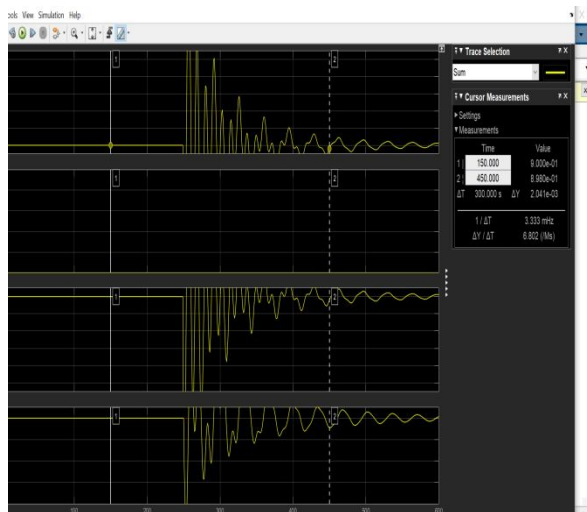**Figure 8:** Power generation in system with P, PI and PID

Figure 9: Power deviation in system with P, PI and PID

Figure 10: Frequency deviation in system with P, PI and PID
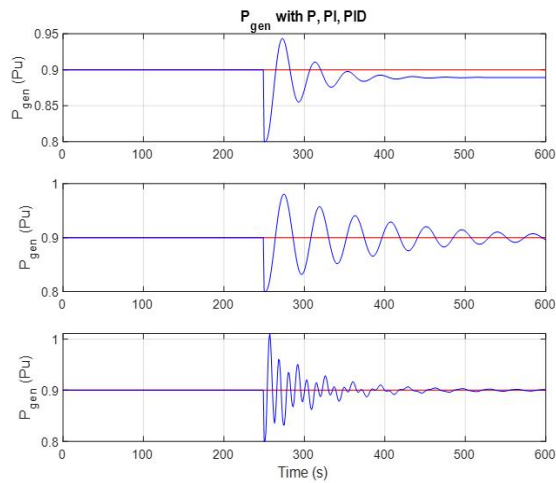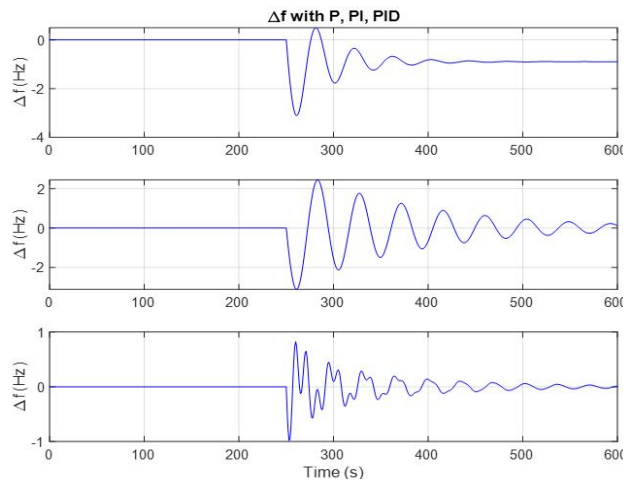

Figure 11: Comparison of PID and GA-Optimized PID

Figure 12: Power generation in system with P, PI and PID optimized by Genetic algorithm

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Figure 13: Power deviation in system with P, PI and PID optimized by Genetic algorithm

Figure 14: Frequency deviation in system with P, PI and PID optimized by Genetic algorithm

6.   CONCLUSION

Recently, Genetic Algorithm have been widely applied in the area of automatic control and power electronics to control the efficiency of electrical energy conversion. In order to obtain an optimal operation of the genetic algorithm, a greater number is recommended in the number of generations, since the more generations are evaluated, the better the performance of the individuals will be.

Initially, the objective function was taken to minimize the error value of the system, but, when carrying out tests with oscillatory systems or plants, the algorithm assigned a good performance to individuals who brought the control system to instability. This is why we opted to take the integral of the error as the objective function value of the individuals as an objective function, thus obtaining a well-performing PID controller.

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