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Historical Background of the Origin of the Speeddroop, Additional Control Signals and Analogic Retrofit of a Governor of a Francis Turbine, Using Operational Amplifier IC741

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Abstract: It is well known that governors of turbines, moving synchronous machines are responsible to maintain the rotation of the rotor of the generator constant and then the electric frequency constant, independently of the changes of electric loads connected to the power electric net. This paper treats about the origin and necessity of the permanent and transitory speedoops in the control mash of a governor. First, we develop the historical background origin of a governor. The basic controls actions are studied, and the analogic circuits related, using operational amplifiers. Then, as an easier way, the author uses an analogic generic PID governor to explain how the permanent speedroop is needed to set the power delivered by a hydraulic turbine (Francis) and then the transitory speedroop. Additional control signal as Power Joint Control and Automatic Generation Control-AGC are introduced. As a suggestion, a simple analogic Power Joint Control circuit example, using operational amplifier 741 is given, but not tested in a workbench. The using of the Automatic Control Generation-AGC, a supplementary control, is introduced because of the necessity to correct the frequency deviations. It is also given a simple circuit example of AGC, not tested in a workbench. This paper ends with an analogic retrofit of a governor of Francis turbine of decade of 1960 of 180 MW using analogic electronic. The author employs IC 741 operational amplifier. Prior simulations of the Laplace's model of the governor were made using Matlab-Simulink. Because of the little acquisition time of the available oscilloscope, the author made a transformation in the original Laplace model that reduced the step response time by a factor of 20 but the methodology and know-how to make an analogic retrofit was conquered. The governor was built and tested in a workbench. The hydraulic circuit was simulated with 741 amp ops. The electronic simulation corresponded to the mathematics simulations showing the success of the analogic retrofit. The physical space needed by the equipment was reduced from the size of a refrigerator to a size of a shoe box. Although an analogic retrofit is considered obsolete today, the analogic retrofit has robustness, and it is cheaper.

Keywords: Governor, Speedroop, Automatic Generation Control-AGC, Power Joint Control, Analogic Retrofit

1. Introduction

Governors of turbines of synchronous generators have the function to maintain the rotation of the rotor of the generator constant in order to maintain the electric frequency of the power electric net constant, independently of the changes of the electric loads connected to this net.

The author explains the real necessity of the signal called "speeddroop". In order to facilitate the comprehension of it, he uses a generic analogic PID Francis governor as example. We introduce the historical background of the development of governors. We study the basic PID actions and their analogic circuits using operational amplifiers. We also analyze the origins of the permanent and transitory speedroops signals, power joint control and their error correction by means of the Automatic Generation

Control-AGC, simple circuit examples are given, not tested in a workbench. Finally, we make the analogic retrofit of a governor of decade of 1960 of a Francis turbine of 180 MW of a synchronous generator using the IC741 operational amplifiers. The original electronic governor employed discrete components like transistors, resistors… What demanded a large physical space, the size of a refrigerator. The analogic retrofit demands a size of just a shoe box. Although a retrofit today uses digital electronic an analogic retrofit has the advantages of being more robust and cheaper. [1, 2, 3, 10, 15]

2. Historical Background

There is a legend that says that James Watt's father had a sawmill, moved by waterfall, figure 1.

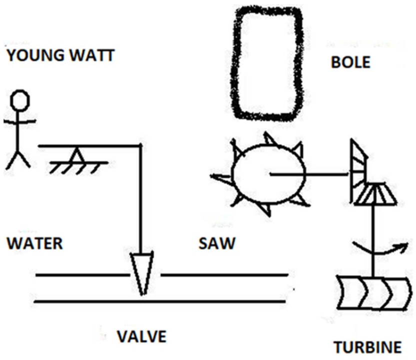

Figure 1. *James Watt's father sawmill.*

The function of the child Watt was to control the rotation of the saw. This way, when the bole should be cut the rotation of the saw lowered and the child Watt had to move the lever down to open the valve to admit more water in the turbine to cut the bole, as soon as the bole was cut the saw increased a lot the rotation and he had to lifted up the lever to close the valve in order to the saw rotated in the nominal rotation. We can imagine that this task was boring to a child. As an adult, James Watt created his pendulum to control the rotation of the Steam Machine, shown in figure 2.

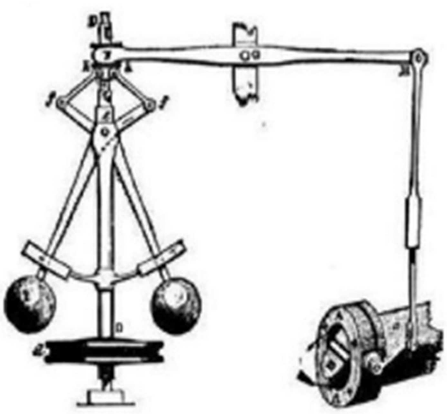

Figure 2. *James Watt's pendulum.*

The pendulum works in this way: as soon as the rotation increases the flying balls move away each other and them the levers close the valve of steam admission, in contrary as soon as the rotation diminish the flying balls approach each other and the levers open the steam admission valve. Later the theoreticians resumed it in the canonical form of a regulator which the governor is a special case, shown in figure 3.

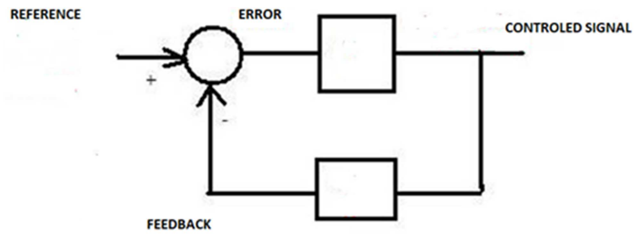

Figure 3. *Canonical form of a regulator.*

If we represent the velocity of rotation versus the opening of the valve (power generation) we would have the figure 4.

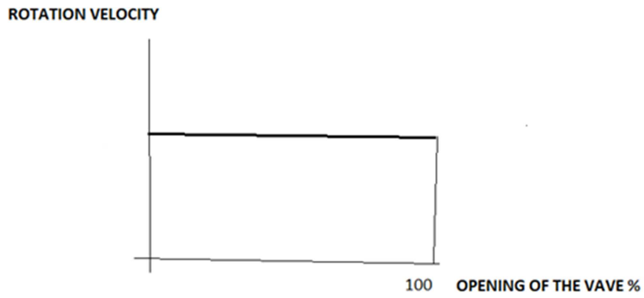

Figure 4. *Rotation velocity versus valve opening of the Watt's pendulum.*

This kind of governor is called isochronous. It appears to be the ideal governor but it has a terrible problem we cannot adjust the power delivered by the turbine, so we cannot perfectly control it. The way to solve this problem will be shown in the next paragraphs. [1, 2, 4, 5, 6, 12, 13, 14, 15]

3. Basic Control Actions

There are three basic controls actions: proportional-P, integral-I and derivative-D. We will see everyone.

3.1. Proportional-P

Figure 5 shows the basic proportional action.

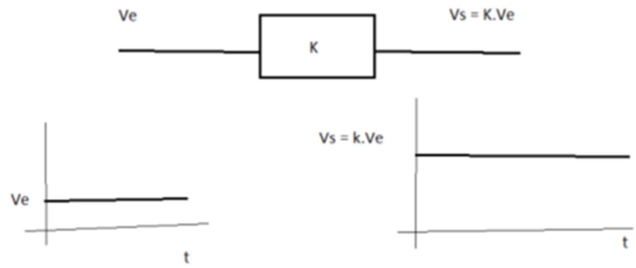

Figure 5. *Proportional action.*

Figure 6 shows the analogical circuit, using operational amplifier, of an inverter amplifier including the gain.

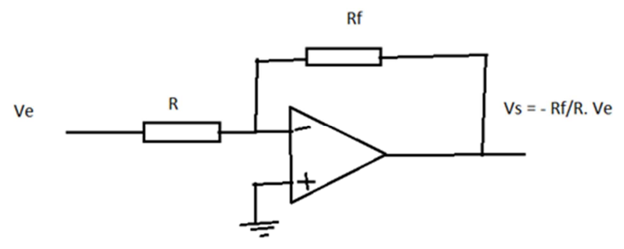

Figure 6. *Inverter amplifier.*

Figure 7 shows the circuit of a non-inverter amplifier including the gain.

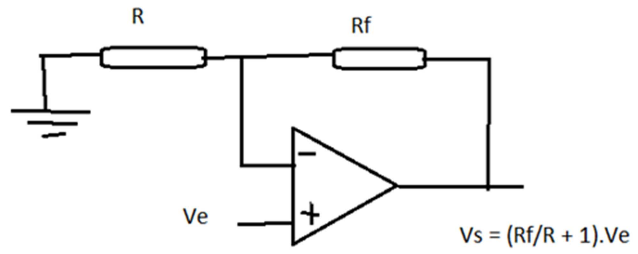

Figure 7. *Non-inverter amplifier.*

Figure 8 shows an adder with gain -1.

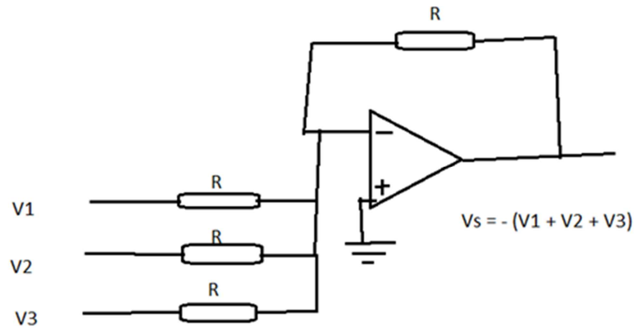

Figure 8. *Adder with gain -1.*

3.2. Integral-I

Figure 9 shows the integral action;

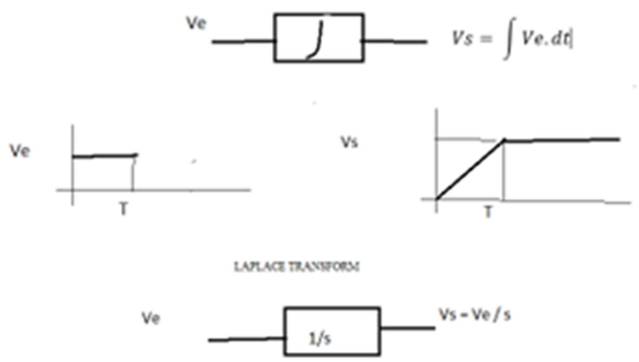

Figure 9. *Integral action.*

Figure 10 shows the equivalent circuit of the integrator.

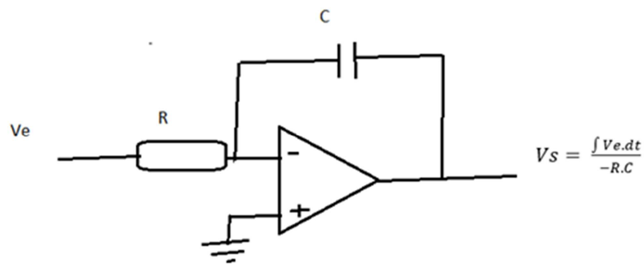

Figure 10. *Integrator equivalent circuit.*

3.3. Derivative-D

Figure 11 shows the derivative action.

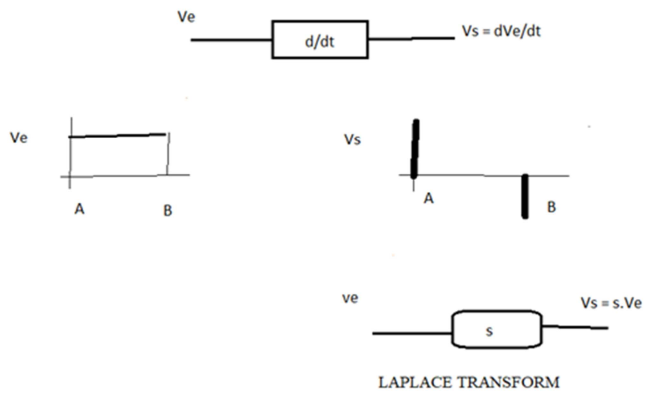

Figure 11. *Derivative action.*

Figure 12 shows the equivalent circuit of the derivate action. [1, 7]

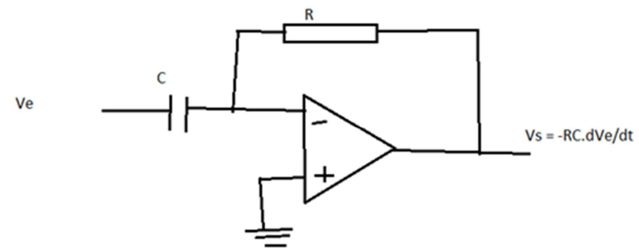

Figure 12. *Equivalent circuit of derivative action.*

4. Origin of Permanent Speedroop, Primary Control and Generic PID Governor Example

Figure 13 shows a generic PID analogical governor with the reference frequency of 60 Hz and the permanent speedrop of 5 %, the gain of the amplifier is (0.05). This governor uses a center null electrohydraulic valve, if we employed a proportional electrohydraulic valve, the layout would be different, we should use an integrator before the proportional electrohydraulic valve. The 100% opening distributor analogical values of the governor are 10 V.

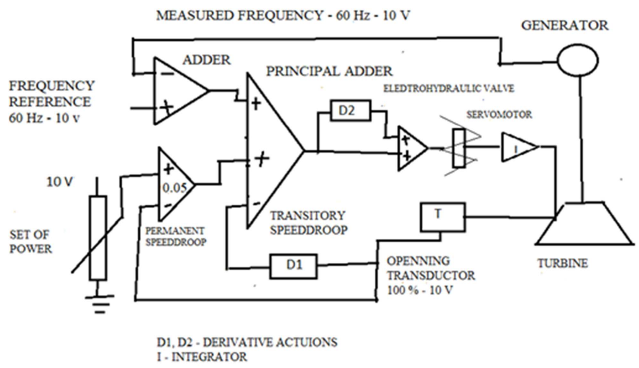

Figure 13. *Generic analogical PID governor.*

Now we will suppose two cases:

4.1. Case I

Generator connected to an isolated electric net, the potentiometer power set is adjusted to almost 0 V, the opening gate of distributor is almost totally closed, the minimal opening of the distributor just to maintain the nominal frequency of the generator in 60 Hz. Suddenly the full power of the turbine is demanded, initially the rotation of the turbine diminished because the generator tries to convert the mechanic rotation energy in electric energy to supply the electric load, the governor correct the gate of the distributor, the transitory speedroop acted and after some seconds we have a steady state. It is the game of complete zero sum. Looking to figure 13, we recognize that to the servomotor stop moving we should have the entry of the electrohydraulic valve with 0 V, in the same way the output of the principal adder. Figure 14 shows the new configuration of the analogic signals.

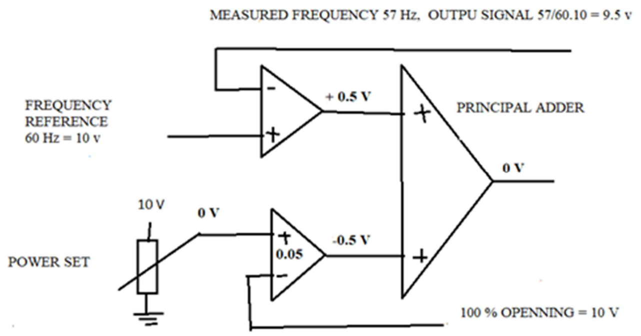

Figure 14. *Case I.*

Figure 15 shows the resultant permanent speedroop curve.

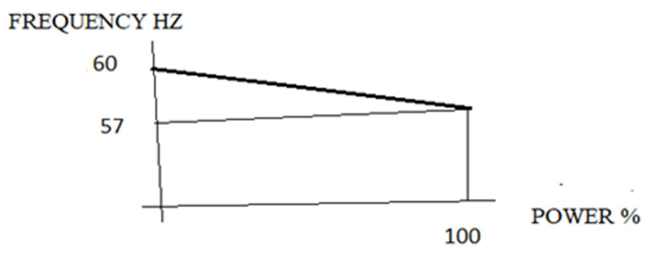

Figure 15. *Permanent speedroop curve, case I.*

We can also define speedrop by (1)

$$(60 - 57)/60.100 = 5 \% \tag{1}$$

But this expression alone, does not explain the origin of the speedroop, as many textbooks do.

4.2. Case II

Imagine a generator full loaded with the distributor gate opening at 100%, the power set potentiometer is adjusted to 10 V. The operator makes the mistake of open the principal circuit braker isolating the generator of the electric net. Initially the loss of the electric load will make the turbine increases the rotation to try to convert the loss of electric energy in cinematic energy. The governor will feel the increase of frequency of the generator and will command to close the distributor gate, the transitory speedroop will operate and after some seconds the governor will have a steady state, again we will have the game of complete zero sum in the principal adder shown in figure 16.

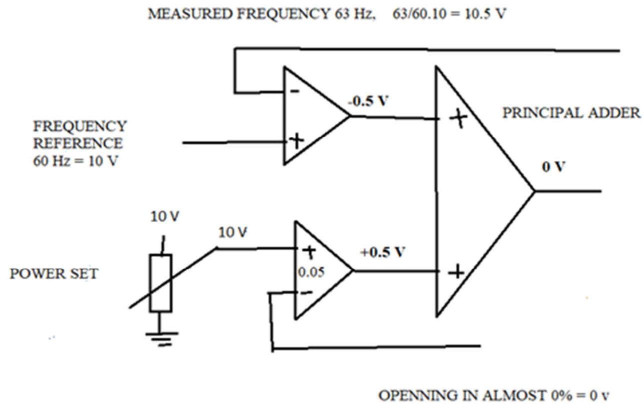

Figure 16. *Case II.*

Figure 17 shows the resultant permanent speedroop curve.

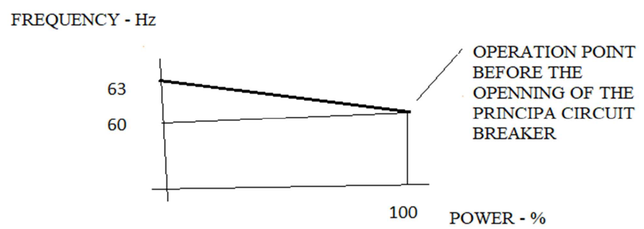

Figure 17. *Permanent speedroop curve, case II.*

Again, we can define permanent speedroop as (2)

$$(63 - 60)/60.100 = 0.05 \% \tag{2}$$

We can observe that the speedroop is an introduced feedback signal just to control the power produced by the turbine. But it introduces a little error in the control net, this is known as Primary Control. Someone can ask how to correct this error? This is the matter of the paragraph 6. [1, 2, 15]

5. Transitory Speedroop

Looking to figure 13, suppose we command a step of power set, adjusting the power set potentiometer, initially it will have a step in the output of the principal adder, it will make a transitory output in the derivative block (located in the output of the principal adder). The distributor begins to move and the feedback transitory speedroop block, of derivative action, will send a transitory signal to initially amortize the step command in the principal adder, avoiding strokes in the hydraulic and mechanic part of the governor, this is the origin of the transitory speeddroop signal. The adjust of the transitory speeddroop is between 20 to 80%. To synchronize the generator, the transitory speedroop is normally of lower value, permitting a quick response of the governor. After the synchronization, it assumes a higher value, the automatism selects this. [1, 2, 15]

6. Supplementary Control – Automatic Generation Control-AGC Action

The way to correct the error introduced by the permanent speedroop is to introduce the action of the supplementary control, named AGC – automatic generation control. It acts in the reference of the governor.

6.1. Case I

In reference to case I, paragraph 4.1, figure 18 shows the action of the AGC that brings the power set potentiometer to 100% opening of the distributor gate and correcting 60 Hz frequency, correcting thus the error of frequency.

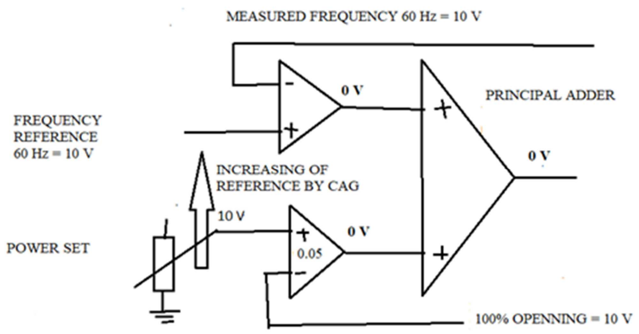

Figure 18. *Case I AGC action.*

Figure 19 shows the resultant permanent speedroop curve.

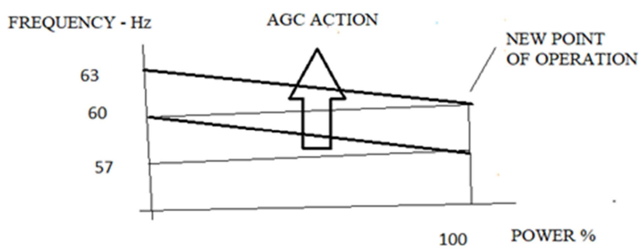

Figure 19. *Case I permanent speedroop curve.*

6.2. Case II

In reference to case II, paragraph 4.2, the AGC action brings he power set potentiometer to almost 0 V and 60 Hz frequency, correcting the frequency error. Figure 20 shows the action of the AGC.

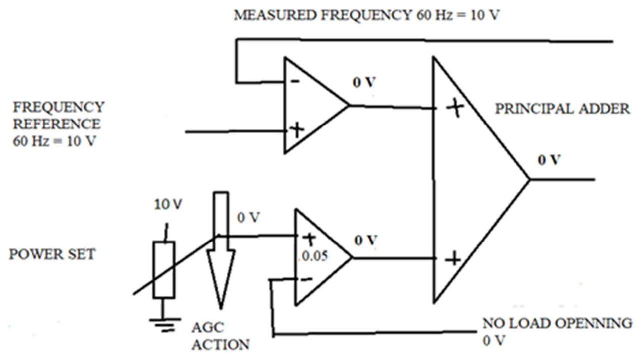

Figure 20. *Case II AGC action.*

Figure 21 shows the resultant speedroop curve of case II.

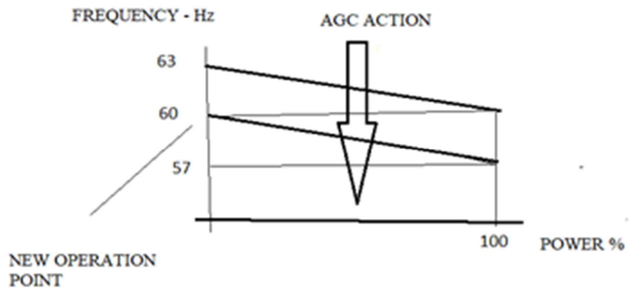

Figure 21. *Case II resultant permanent speedroop curve.*

The next paragraph we will see an example of AGC circuit. [1, 2]

7. Power Joint Control and Automatic Control Generation-AGC

7.1. Power Joint Control

It is common for a power station with more than two generators that we have a power joint control that allows to control equally the power of each generator. Figure 22 shows a suggestion of a simple analogical power joint control of three units using op amps IC 741 whose feeding is of +/- 15 VDC. The nominal power of the power-station is represented by 15 VDC, and of each unit to 10 VDC. This circuit was not tested in a workbench.

The power joint control works like this: consider just two units in power joint control, unit 1 and unit 2 so switches S1s and S2s are closed and S3s are opened. Suddenly we moved the wiper of the power station set potentiometer power, up; a command to increase the power of the power station. OA1 output is the sum of powers of units 1 and 2. The output of OA2 is the difference between the command to increase the power of the power station and the real sum of the two units i.e., OA2 compares the command of total power of the power station with the sum of each unit in joint control. As just switches S1s and S2s are closed the gain of OA3 is 1/2 and then charging C1, moving M1 and M2, the motors of the power units set potentiometers, 1/2, until the output of AO2 becomes zero again and then the new power of the power joint control and each unit, in power joint control, is adjusted. The constant time introduced by R1 and C1 should be more than the primary control of the governor.

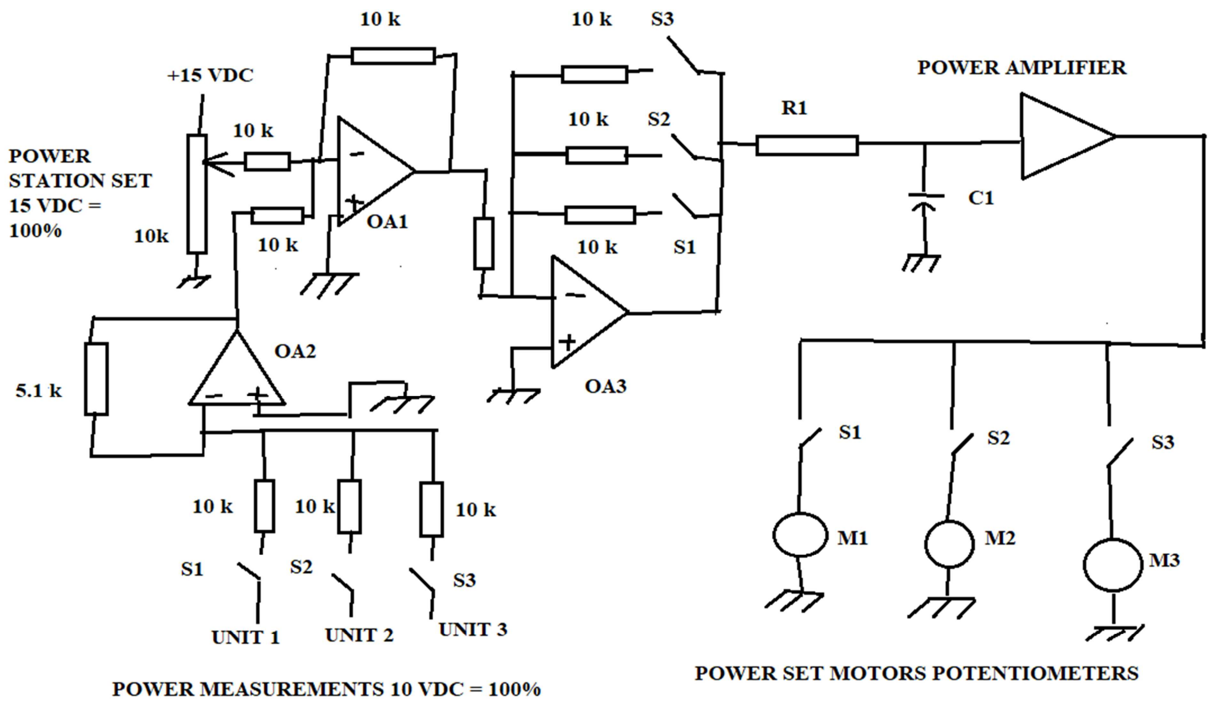

Figure 22. *Simple power joint control.*

7.2. Automatic Generation Control-AGC Circuit

Figure 23 shows a suggestion of circuit of the AGC, not tested in a workbench.

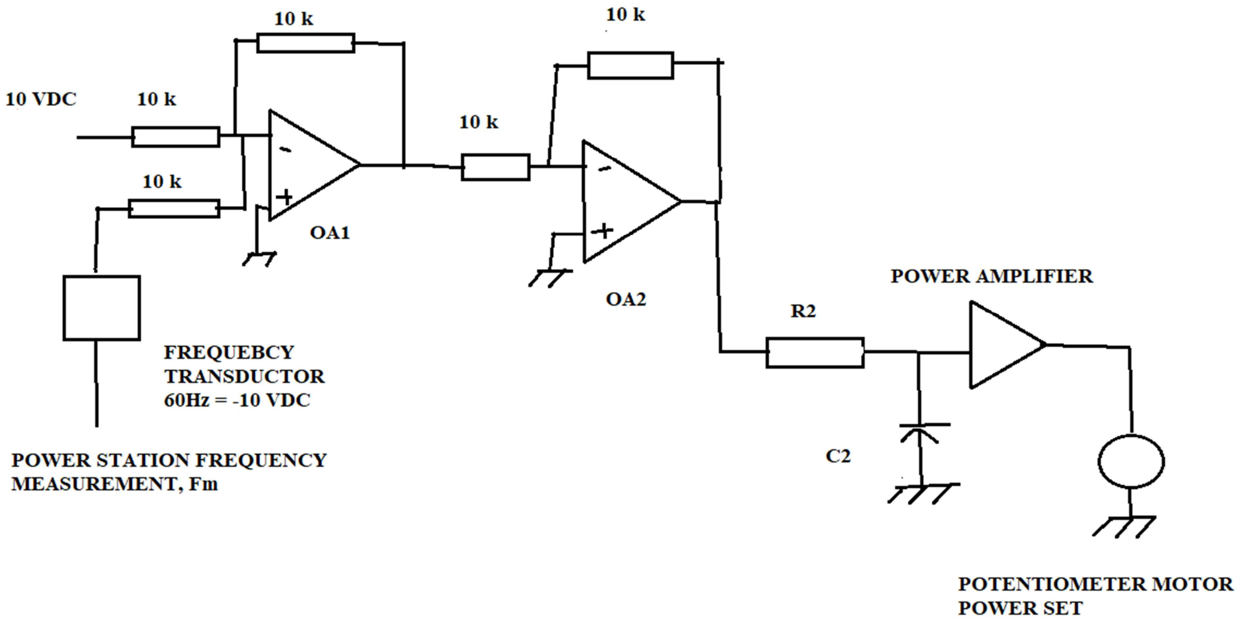

Figure 23. *Automatic Generation Control-AGC.*

This circuit works like this: the frequency of the power station, Fm, is compared with the 60 Hz reference = 10 VDC in OA1, an IC741, then the result signal is corrected the polarity by OA2, an IC741 too, then C2 is charged, introducing a constant of time that must be bigger than R1C1 (Power Joint Control, figure 22), so the motor of the potentiometer of the power set of the Power Joint Control will move, in case all the units are in Power Joint Control or each unit, in case of individual control, the automatism, selected, decide that. The entire order of action to correct the frequency error must be: first, the primary control; second, the power joint control, third the supplementary control i.e., the AGC. [2, 7, 8]

8. Analogic Retrofit

8.1. Original Model

Figure 24 shows the mathematical original model of a governor of a Francis turbine of 180 MW of decade of 1960 that we want to make an analogic retrofit.

We will respect the original projected constants of time in the retrofit, to avoid overcharges of forces and hydraulic strokes, using then, the concept of reverse engineering.

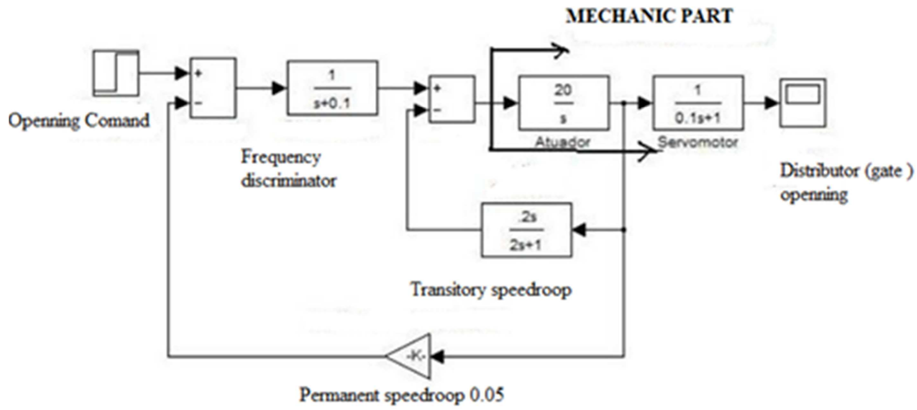

Figure 24. *Mathematical original model of a governor.*

Figure 25 shows the 20% step response, simulated by Matlab-Simulink in the model of figure 23.

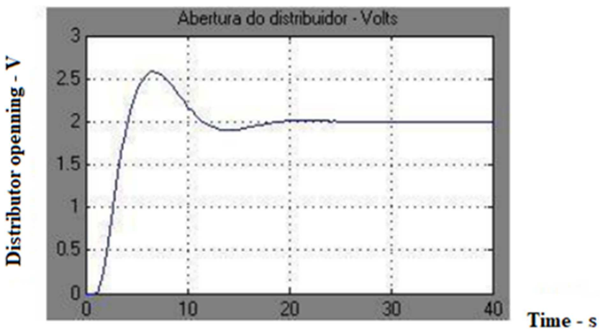

Figure 25. *20% step response of the originalgovernor.*

8.2. Scaled Model

We see in figure 25 that the time response is almost 40 s. We did not have an oscilloscope with this acquisition time, so we decide to create an equivalent governor, reducing the time by a factor of 20, so in the original model of figure 24 we substituted s by s/20. The scalled model is shown in figure 26.

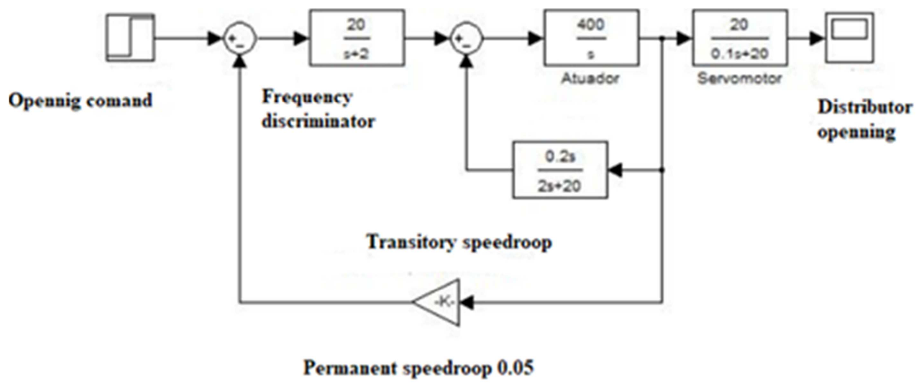

Figure 26. *Scaled model.*

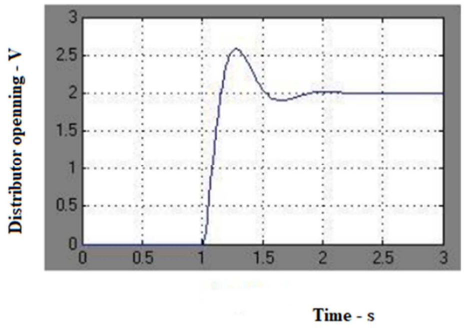

*Figure **27**. 20% step response of the scaled model.*

Figure 27 shows the new 20% step response time of the scalled model.

8.3. Reduced Model

Figure 28 shows the scaled model of figure 26, reduced just to amplifiers, adders and integrators according to paragraph 3. [1, 11]

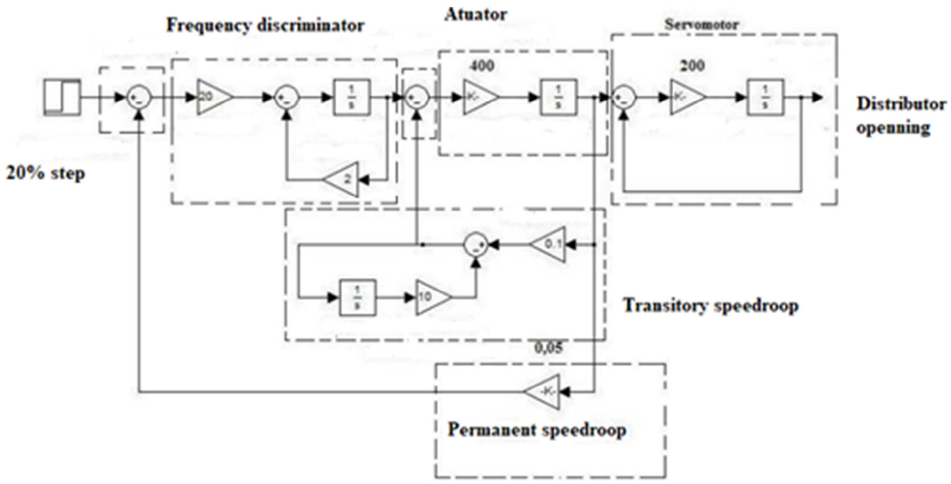

***Figure 28.** Reduced mathematical model.*

9. Analogic Electronic Circuits and Workbench Tests

In this paragraph we will detail the analogic electronic circuits, 10 VDC will be equivalent to 100% of distributor opening. The mechanic part of the governor (actuator and servomotor) will be emulated to an electronic circuit.

9.1. DC Sources

Figure 29 shows the electronic diagram of the +/- 15VDC regulated, symmetric sources needed to feed the 741 op. amp.

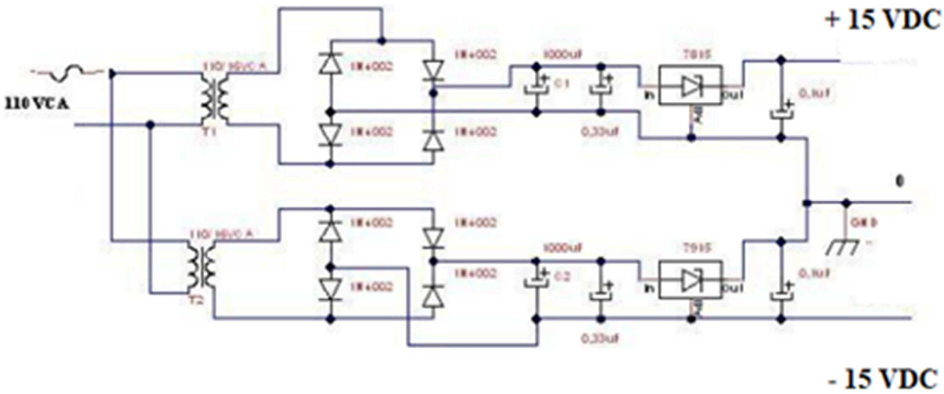

***Figure 29.** +/- 15 VDC regulated symmetric Sources.*

The transformers are both of 110/16 VAC, 16 VA, the fusible of 1 A and the IC 7915 and 7817 need radiators.

9.2. Electronic Part of the Governor

Figure 30 shows part I of the electronic governor, it was divided in part 1 and part 2 because the size of the figure.

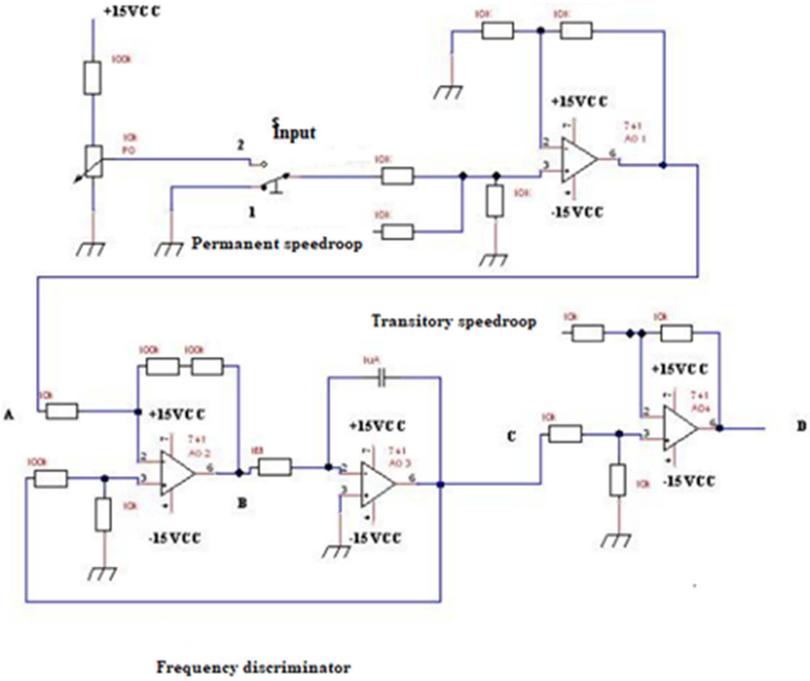

Figure 30. *Part I of the electronic part of the governor.*

Figure 31 shows part II of the electronic part of the governor.

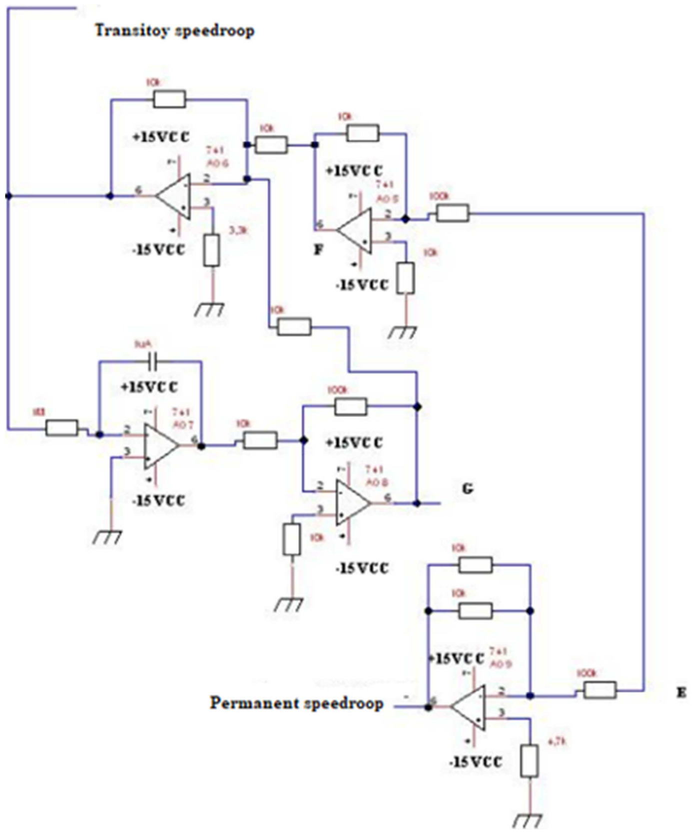

Figure 31. *Part II of electronic part of the governor.*

9.3. Mechanic Part of the Governor

Figure 32 shows the electronic circuit to emulate the mechanic part of the governor. [1, 7, 8, 9]

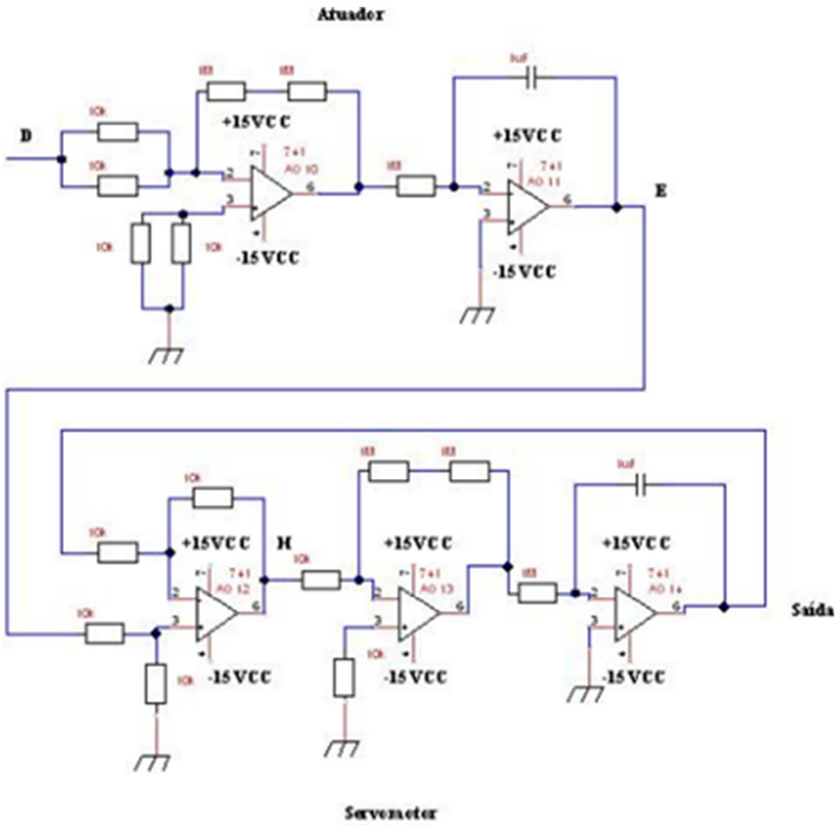

Figure 32. *Electronic emulation of mechanic part of the governor.*

NOTE: ALL IC 741s IN THOSE CIRCUITS USES NULL POTENTIOMETERS, NOT SHOWN IN THE CIRCUITS, TO DO NOT OVERCHARGE THE DIAGREAMS.

9.4. Workbench Tests

Figure 33 shows the photo of the complete analogic retrofit circuit, mounted in the workbench.

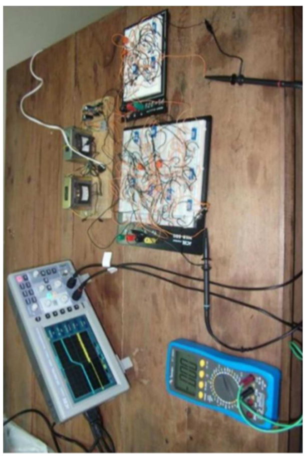

Figure 33. *The complete circuit of the retrofit mounted.*

The bigger card in figure 33 is the electronic part of the analogic retrofit of the governor. The smaller card is the emulated electronic circuit of the mechanic part of the governor.

9.5. Linearity

Figure 34 shows the linearity between the input (opening command) and the output (distributor opening).

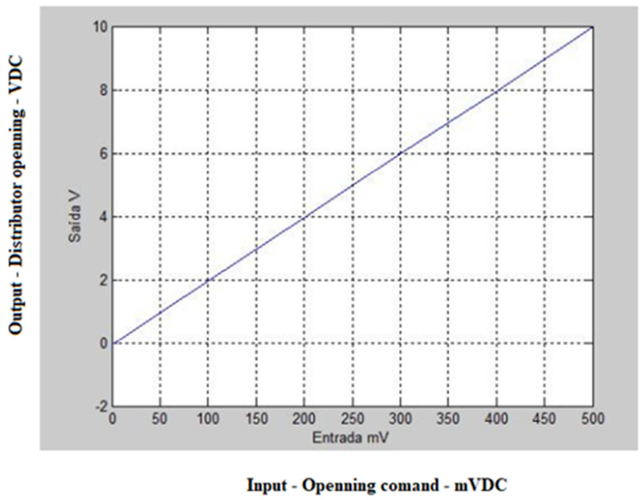

Figure 34. *Distributor opening (output) versus opening command (input).*

9.6. 20% Step Response

Figure 35 shows the screen of the oscilloscope for the 20% step response. The blue signal is the output (distributor opening). The yellow signal is the input (opening command). [1]

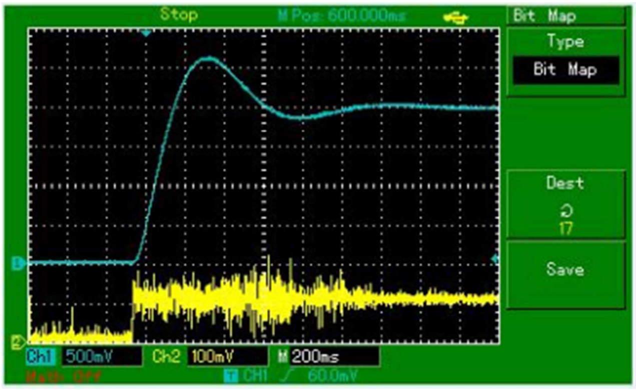

Figure 35. *Screen of the oscilloscope for the 20% step response.*

10. Conclusion

Comparing figure 27 to figure 35, we observe that they are quite similar, they show that our analogic retrofit obtained success, although, in fact, we did the analogic retrofit of the scaled model (reduced time response). That result showed us the viability of the methodology of the entire process of the analogic retrofit using op. amp. 741. Certainly, a power amplifier stage is needed at the last output of the 741 of the retrofit, to feed the electrohydraulic valve.

Although an analogic retrofit is considered in our days obsolete, compared to a digital retrofit, the analogic has the advantage of being more robust against electromagnetic noises and cheaper. The major disadvantage, compared to the digital ones, is that, when we desire to change any of the functions of the analogic, like the transitory speedroop, we must change the hardware, while in the digital, just the software. [1, 10]

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