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Regulation of output voltage and rotation speed of the turbine-generator assembly for a geothermal power plant

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ABSTRACT

The study presented in this article focuses on the modeling and regulation of the voltage and speed of the turboalternator in order to ensure power system stability and quality of service. The most important problem in the analysis of these systems is undoubtedly their stability. This model is based on the electrical and mechanical equations of the system, which gives us an idea of how the alternator behaves under load disturbances. This model was implemented on Matlab/Simulink, with the aim of establishing a controller-based control system for voltage and speed. The simulation results are satisfactory.

1. INTRODUCTION <HEADING 1 STYLE>

In large power systems, it's important to maintain frequency and voltage at their nominal values to ensure proper operation and balance between power generated and consumed.

Indeed, the biggest problem with electrical energy is its storage, so the quantities needed to cope with variations in demand and incidents must be produced instantaneously at the moment they are required Razemia A. (2007).

An increase in energy demand causes voltage dips and a reduction in rotational speed, and therefore in grid frequency. With the help of sensors, the speed value is measured and automatically corrected by speed regulators, by acting on the steam or gas intake at the turbine. The same applies to the output voltage, which is regulated by the exciter.

Geothermal power generation is based on the exploitation, mainly in regions of active volcanism, of deposits containing resources at temperatures of between 100°C and 350°C. At these sites, the steam produced at the top of the borehole feeds a turbine and an alternator to generate electricity. The condensed fluid is then reinjected into the reservoir to optimize its life Rajomalahy J. (2022).

2. SYSTEM DESCRIPTION

Geothermal energy is a renewable resource that can be used in two major energy sectors: - heat production and - electricity generation Rajomalahy J. (2017). The principle of the binary fluid power plant shown in figure 01 is as follows:

- The extracted geothermal fluid is fed into a heat exchanger where it transfers part of its energy to an organic fluid that vaporizes
- For the same pressure, this type of fluid has the particularity of vaporizing at lower temperatures.

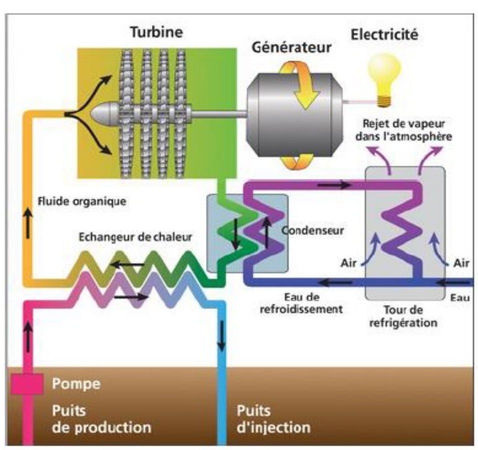


Figure 1: Operating principle of a steam power plant

- The vapors produced are then expanded in a turbine and condensed in contact with the condenser's cooling water circuit.
- The resulting liquid is then pumped back to the heat exchanger, where it undergoes a new cycle: vaporization, expansion, condensation and pressurization.
- The working fluid (organic fluid) operates in a totally closed circuit, while the geothermal fluid is reinjected into the reservoir. Plants of this type are of modest unit size (a few units or tens of MWe).

3. REGULATION MODELING AND SIMULATION

3.1 Control systems

Control systems consist of two essential devices, as shown in Figure 02.

- The first, a device used to regulate the alternator's output voltage through its exciter, the output voltage must be maintained at around 18.5 kV whatever the load disturbance.
- The second, a device used to regulate the speed of rotation and maintain it at a constant value by adapting the mechanical power. The generator operating speed depends on the mains frequency (f = 50 Hz, p = 1).

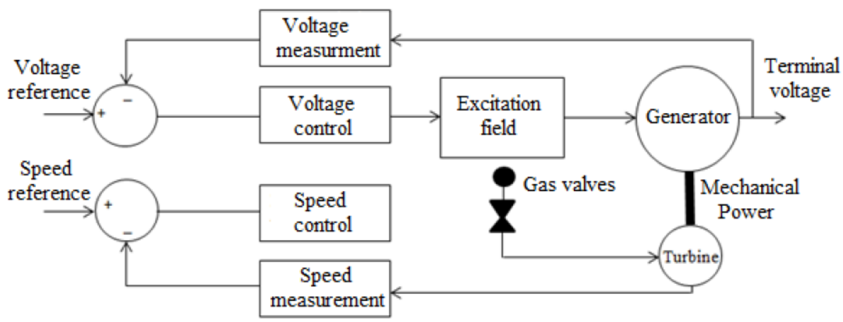


Figure 2: Control circuit, Juste T. (2013)

3.2 Alternator output voltage regulation

Voltage control is a fundamental concept that ensures continuity of service, provides good power quality to consumers and, above all, creates a balance between the power produced and that consumed. To ensure this regulation, it is necessary to introduce a controller called "automatic voltage regulator", whose main task is to maintain the voltage amplitude across the synchronous generator at a specified level. This ensures the balance of reactive power to be supplied or absorbed according to load requirements. This controller represents a very important means of ensuring the transient stability of the power system. The voltage regulator acts on the excitation current of the alternator and regulates the magnetic flux in the machine, thus adjusting the output voltage to a specified value Elshafei A. (2005). Figure 03 shows a simplified model of the regulator used.

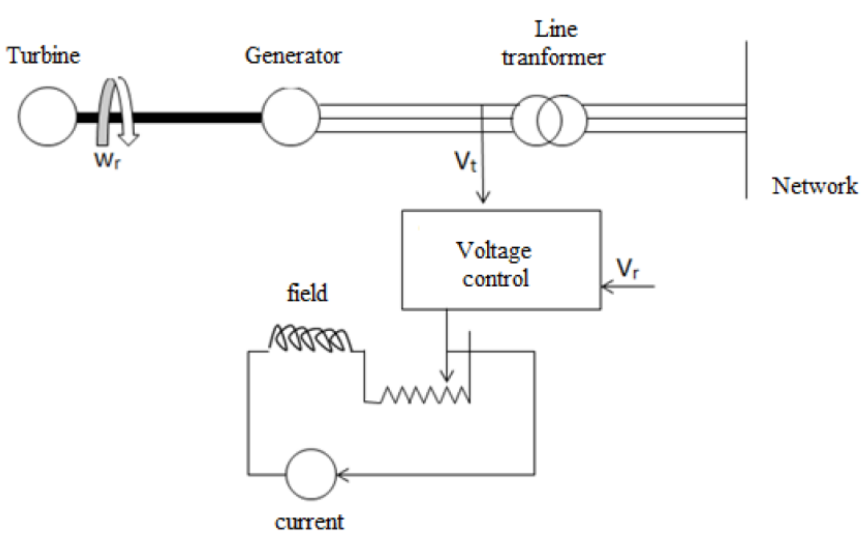


Figure 3: Control unit representation

The schematic model used in our study is shown in Figure 04, and consists essentially of a voltage sensor, a comparator (summator), an amplifier, a PID regulator and a voltage limiting system.

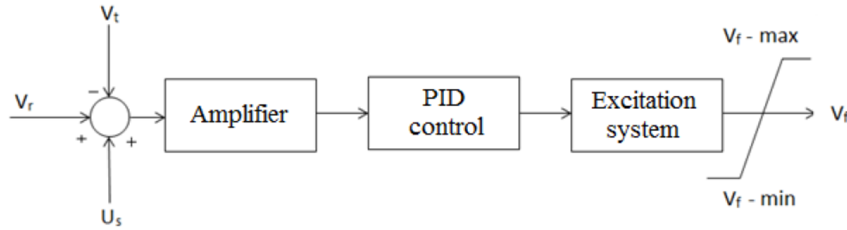


Figure 4: Schematic model of a controller

where:

The variable V_r represents the voltage setpoint used as a reference which satisfies the steady-state conditions. The voltage regulator initially compares the value of the alternator output voltage V_t with that of the setpoint V_r . The difference (error) is amplified to give the excitation voltage V_f required to maintain the desired equilibrium, which is limited between two values by a limiting system (V_{f-min}, V_{f-max}).

A complementary signal U_s can be added to the summation node. This is a control signal known as a power stabilizer. It adds a voltage signal proportional to rotational speed to the input of the generator's voltage regulator to produce a torque that is in phase with the variation in rotor speed. The power stabilizer corrects the decay of the damping torque and counteracts any weak oscillations by forcing the excitation system to vary rapidly and at the right moment Hassan M. (1991).

Various studies have been carried out by an IEEE group in the field of power system element modeling concerning excitation systems. There are three types of excitation systems that are frequently used Rajomalahy J. (2017):

- ″The Potential-Source Static Excitation System″, in which the excitation voltage response time is very short,
- ″The Separately Excited Static Diode-Rectifier Excitation System″, which exists in two forms, the first called Nominal Response Excitation System and the second called High Initial Response (HIR). Excitation voltage response time for the former is between 0.2 and 0.5s which is much slower than that of the HIR.
- ″The Brushless Excitation System″ which has a similar response to the second model. However, mathematical models of these three types of excitation systems are available as follows: Type IEEE ST1 for the first model, type IEEE AC1 is chosen for the Brushless Excitation System model and type IEEE AC2 for the HIR model.

In our study, we have chosen to use the IEEE ST1 system model, as it is the most widely used. This system is mainly characterized by its rapid response and sensitivity.

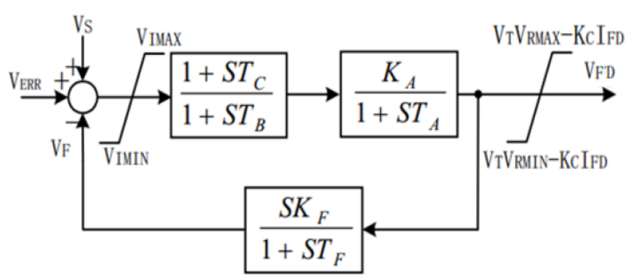


Figure 5: Model of IEEE-type ST1 excitation system

In order to control the excitation voltage, a simplified model, in which we have neglected the time constants (T_c , T_B , T_F), is represented as follows:

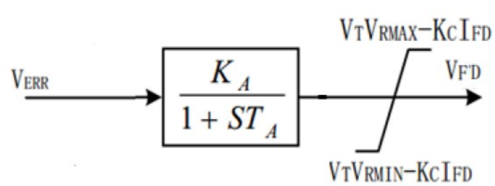


Figure 5: Simplified model of the IEEE-type ST1 excitation system, IEEE (1915)

Substituting the simplified model of the excitation system into the model of an automatic voltage regulator gives the following model:

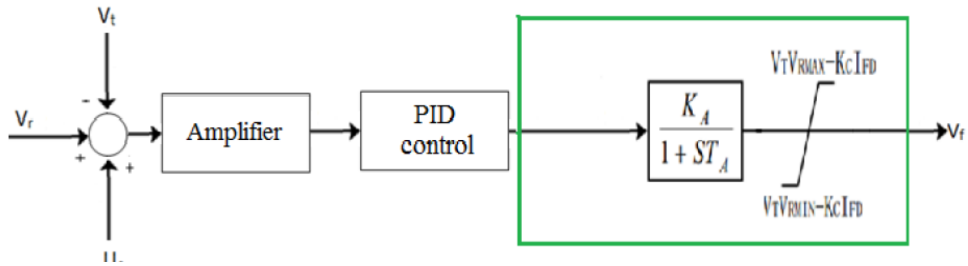


Figure 6: Schematic model of a controller

3.3 Speed control of the turbine-generator assembly

Controlling the speed of rotation of the turbo-alternator assembly is necessary to ensure the stability of the 50 Hz mains frequency and to protect the alternator from stalling. To achieve this, it is necessary to introduce a PID controller whose main task is to maintain the speed of rotation at around 3000 rpm. The control loop consists mainly of a PID controller, a servomotor and a turbine. Figure 08 shows the speed control principle.

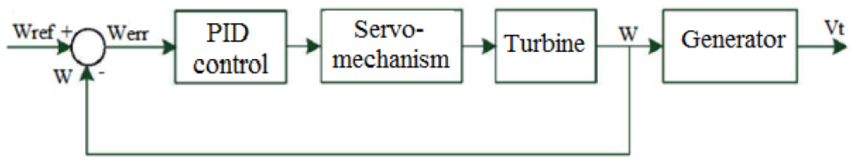


Figure 08: Speed control principle

The PID controller acts on the turbine's gate position as a function of the speed variation with respect to its nominal value. It also ensures correct turbine operation, IEEE (1915).

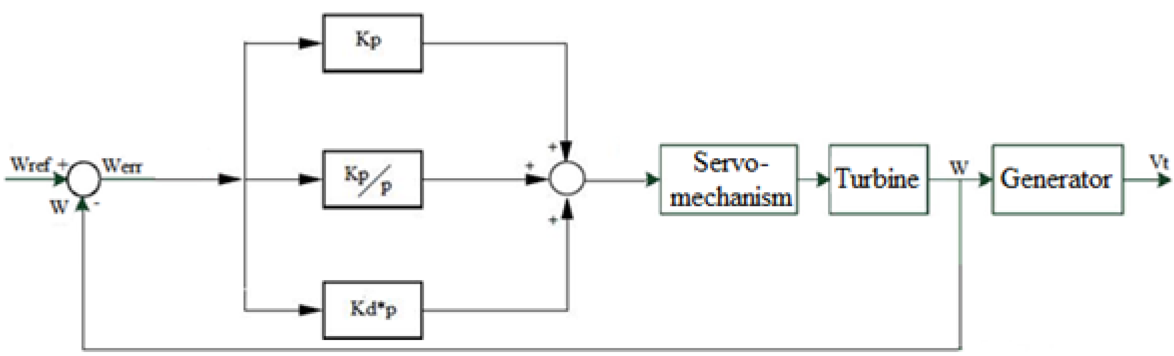


Figure 09: PID controller and servomotor

3.4 Speed control of the turbine-generator assembly

Setting up a PID involves determining the values of the coefficients, T_i and , which enable the desired process response to be obtained with the following characteristics: robustness, speed and precision.

$$F(p) = \frac{Y(p)}{\varepsilon\,(p)} = K_p + \frac{K_i}{p} + K_d p = K_p\left(1 + \frac{1}{T_i p} + T_d p\right)$$

Each coefficient affects the system response as follows:

$\boldsymbol{K_p}$ **:** Influences rise time. Decreasing the rise time results in greater overshoot with improved static error.

$\boldsymbol{T_i}$ **:** Sets the speed at which the error is integrated. The smaller Ti is, the faster the correction signal grows.

$\boldsymbol{T_d}$: It sets the application time for each "jump" of the error signal.

3.4.1 *Parameter determination using the successive approach method*

This involves modifying the controller's actions and observing the effects on the recorded measurement until the optimum response is obtained. We start by adjusting the proportional action, then the derivative action and then the integral.

This technique has the advantage of being simple and can be used on any type of system, except that its iterative nature makes it difficult to use on processes with high inertia.

3.4.2 *Procedure*

We start with a very small $\boldsymbol{K_p}$ and cancel the D and I actions. A setpoint step is applied. If the gain is low enough, the response should be well damped, then increase the gain $\boldsymbol{K_p}$ and apply another setpoint step, repeating until overshoots appear on the output. Set $\boldsymbol{K_p}$ to half the value obtained when the overshoot occurs.

Apply the same procedure for T_i and return to 2 times the value causing overshoot. The same applies to T_d, and we return to a third of the value causing the overruns Rajomalahy J. (2014).

After applying the successive approach method, the optimal parameters that meet the stability and speed criteria are as follows:

The PID controller parameters for regulating the resulting output voltage are:

$\boldsymbol{K_p}$ = 200 ; $\boldsymbol{T_i}$ = 0.014 s et $\boldsymbol{T_d}$= 0.025 s

The PID controller parameters for regulating the speed of the turbine-generator assembly are:

$\boldsymbol{K_p}$ = 20 ; $\boldsymbol{T_i}$ = 0.01 s et $\boldsymbol{T_d}$= 0.013 s

These results are satisfactory, as the overrun in terms of results obtained has been significantly improved (30%).

3.5 Simulation block diagrams

The simulation procedure consists of associating the alternator with the voltage control block diagram**,** Figure 10, and the speed control block diagram, Figure 12, and putting them together as shown in Figure 11.

This system gives an idea of the behavior of machine quantities such as output voltages (V_a , V_b , V_c), currents (I_a , I_b , I_c), speed (ω_r) and internal angle (δ).

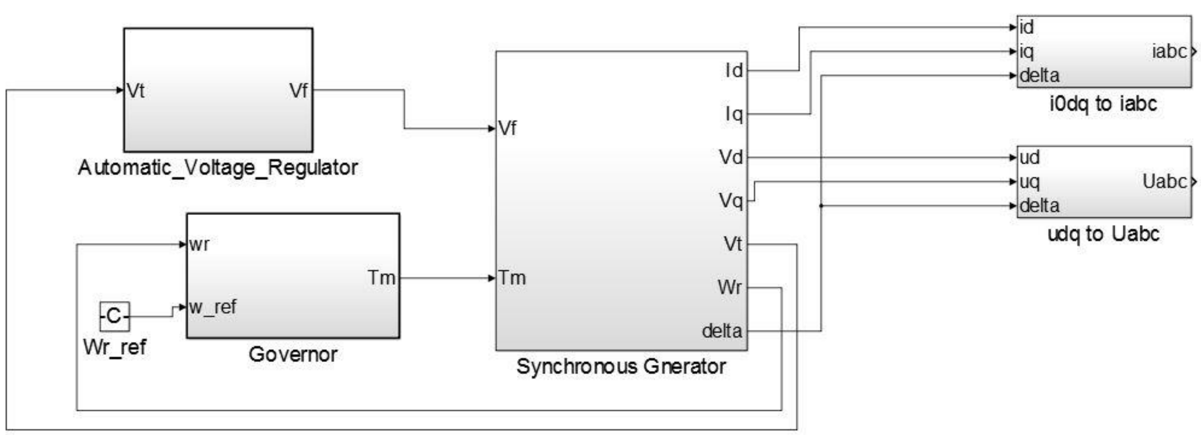


Figure 10: Combined generator structure and control blocks in Simulink

The output voltage regulation block diagram in Matlab/Simulink is:

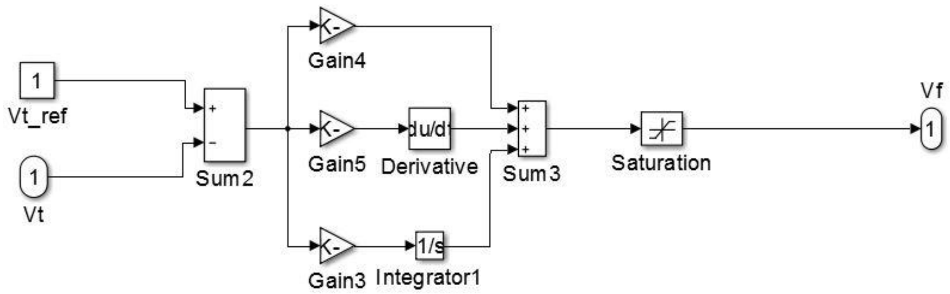


Figure 11: Structure of the output voltage regulator in Simulink

The speed control block diagram in Matlab/Simulink is:

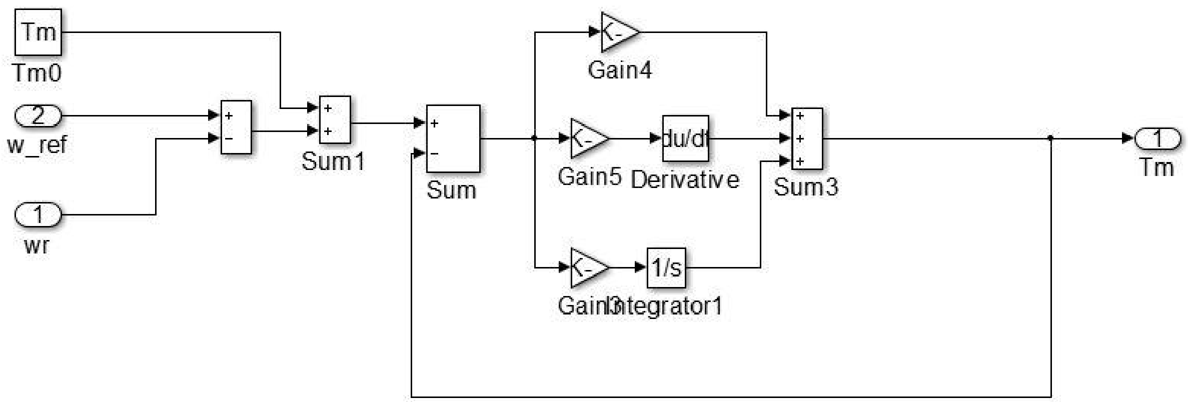
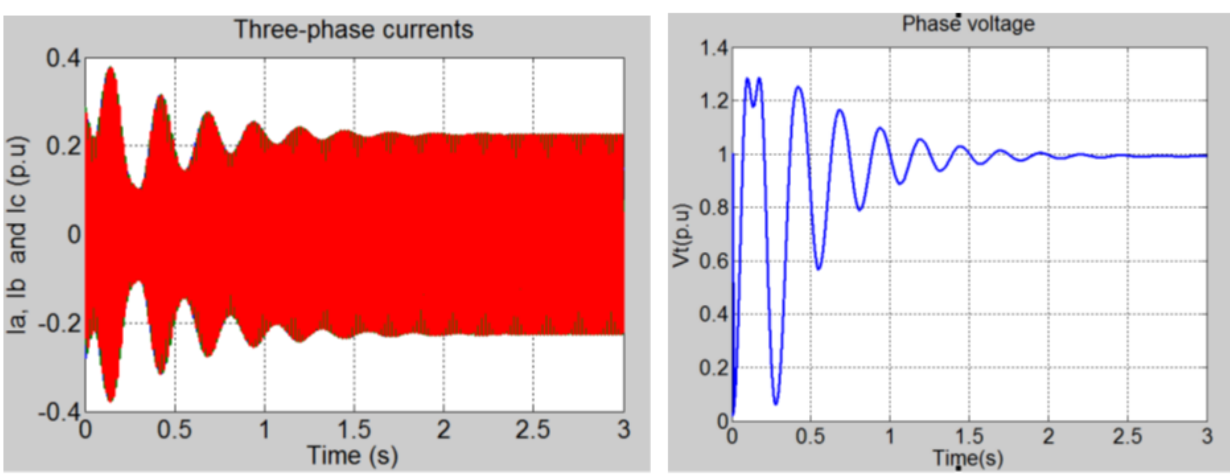


Figure 12: Structure of the speed controller (ω_r) in Simulink

4. RESULTS AND INTERPRETATION

4.1 Simulation block diagrams

Switching on a load at time t = 0s



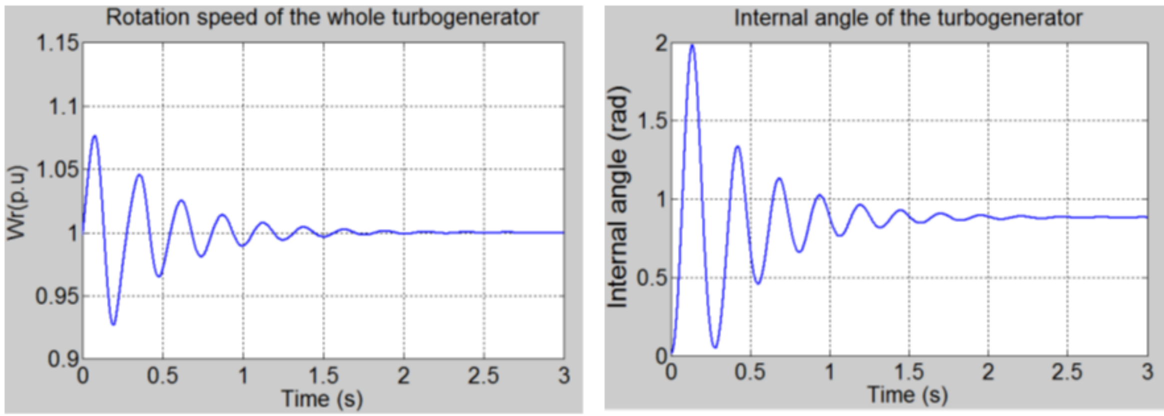
(a) (b)

Figure 13: (a) Currents of the three phases at t = 0s, (b) Voltage of one phase at t = 0s

The currents and voltages of the three phases are shown in Figure 13. When the alternator is at no load, no active power is required from the load, so all currents are zero. When the alternator switches on a load at time t = 0 s, this causes an increase in currents (I_a , I_b , I_c). The transient period lasts about 1.5s, after which these currents reach a new steady state. Loading causes a disturbance in the output voltage, which varies rapidly and peaks at 1.3 (p.u) (Figure 13 b). The recovery time is around 1.5s, after which the voltage oscillates slightly around the nominal value before stabilizing.

4.2 Rotational speed (ω_r) and internal angle (δ)

Adding a load causes a disturbance in speed. The PID controller intervenes on the drive torque to bring it back to its initial value after a transient period lasting 1.5 s. The same applies to the internal angle, which takes on a new value due to the inrush of current. This value is reached after a disturbance caused by the speed control system lasting 1.5 s (Figure 14).



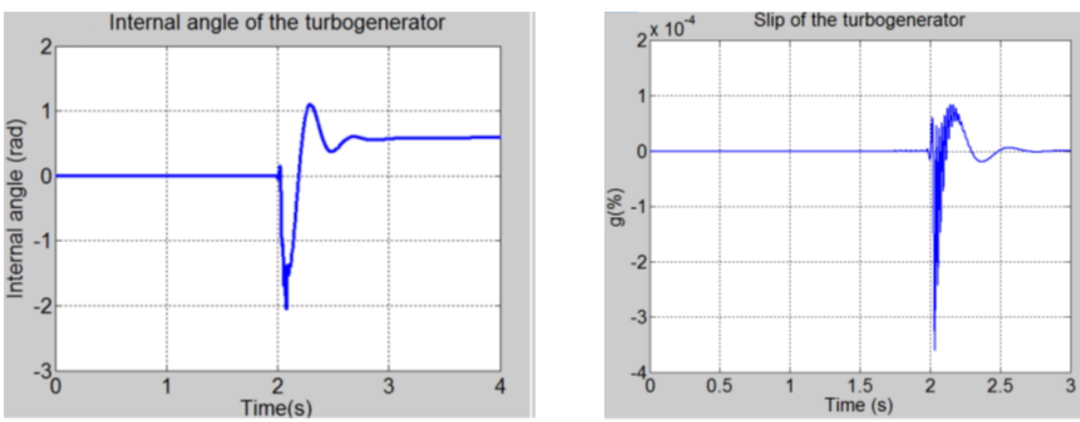
(a) (b)

Figure 14: (a) Alternator rotation speed at t = 0s, (b) alternator internal angle δ at t = 0s

Load disturbance causes voltage variation. This variation is quickly eliminated by the control system. The same applies to speed. Recovery time to nominal values is of the order of 0.2s for voltage and 0.5s for speed (Figure 14).

4.3 Internal angle (δ) and alternator slip

Figure 15 shows the internal angle and the alternator slip after a disturbance at time t = 2 s. The internal angle takes on a new value, which is reached after a disturbance caused by the speed control system lasting 0.8 s. Slip is disturbed during the control period (transient) and returns to its zero value.



(a) (b)

Figure 15: (a) Alternator internal angle (δ) at t=2s; (b) Alternator slip at t=2s

5. DISCUSSION

We have illustrated the essential results obtained from the expected operation of the global model, which was used to study robust regulation and control systems for synchronous generators to improve output voltage and rotational speed.

We have developed a model of the IEEE ST1 excitation system with all its components. We applied voltage regulation using an automatic regulator called AVR to the excitation system. A PID control system to regulate the alternator speed has also been implemented.

Finally, we have developed a global model for dynamic performance simulation that assembles the three main essential block diagrams of the turbine-generator set in the form of Matlab/Simulink block diagrams.

6. CONLCUSION

To conclude, we were particularly interested in high-power alternators. We also had access to the data needed to run our Model. This data covers the parameters with which we were able to develop a mathematical model of the alternator.

This model is based on the turboalternator equations. This enabled us to develop a synthesis for the regulators to control the output voltage and speed of the turbine-generator assembly. Finally, this model was implemented in Matlab/Simulink.

Our study was based on nominal values. The results obtained from the global model we have established are satisfactory. Overall, our final year project enabled us to:

- Develop an exciter state model based on the IEEE reference model.
- Speed control based on an ideal turbine model.
- Perform voltage regulation on the IEEE static excitation system.

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