Gas turbines: Modelling for stability Studies

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Abstract

In this paper, we look at the modeling of gas turbines with an intent to analyse their use on transient stability simulations, so that the behavior of a power network can be predicted in a reliable and cost efficient way, in case changes in its normal operating regime occur.

Keywords: Gas turbines, Rowen Model, Acceleration Control, Temperature Control, Simplified Synchronous Machine Model

1. Introduction

Power plants with gas turbines are characterized by having high operational agility and low implementation costs. These factors, coupled with the increase in the energy efficiency, achieved through the developments in the way that they are designed and the evolution of the materials used in their construction, as well as the evolution that natural gas brought by being used as fuel, have made them very popular in power systems. Since its composition is well defined, consisting of at least one compressor, a combustor, a turbine and an exhaust duct, the quality with which we simulate them depends on the model used.

2. Background

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2.1. Models Comparison

There are several models capable of characterizing the behavior of a turbine. These have different levels of complexity, so the choice of the best model to use has to be made taking into account the variables and components that are known and those that have to be calculated, as well as the type of study to be performed. The most commonly used models for the integration of Gas turbines with power grids are the Rowen, IEEE, CIGRE and GGOV1 models. The two last models are more focused on combined cycle power plants modulation.

2.2. Rowen Model

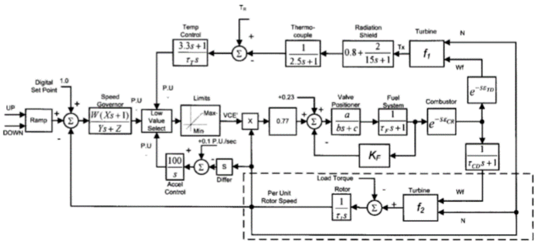

Figure 1: Rowen Model Block Diagram

In the Rowen model, the dynamics of the turbine are described by two blocks characterized by algebraic functions. Block f_1 is a function of the fuel flow and rotor speed and calculates the exhaust temperature of the turbine while block f_2, a function of the same variables, calculates the output torque of the turbine. Delays are added to these functions. These are associated with the gas transport, the combustion process and the compressor discharge time constants.

2.3. IEEE Model

The IEEE model is divided into two parts. One refers to the controls of the turbine (temperature, airflow and fuel flow) and another one referring to the thermodynamic equations from which the mechanical output power is extracted. Regarding the diagram associated with the turbine controls, the underlying equations are nonlinear equations so they have to be solved using methods such as New-

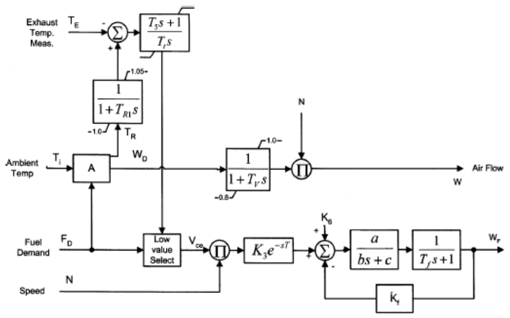

Figure 2: IEEE Model Turbine Control

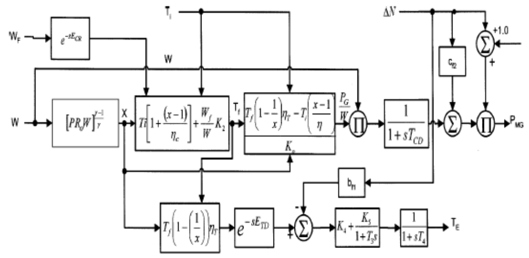

Figure 3: IEEE Model Thermodynamic Equations

ton Raphson's. The diagram construction of the thermodynamic equations is based upon the isentropic efficiencies in the compressor and turbine. There, the exhaust reference temperature, a parameter related to the cycle pressure ratio, the air flow, the ignition temperature, the compressor efficiency and the temperature variation in a compressor ideal cycle, are computed.

2.4. CIGRE Model

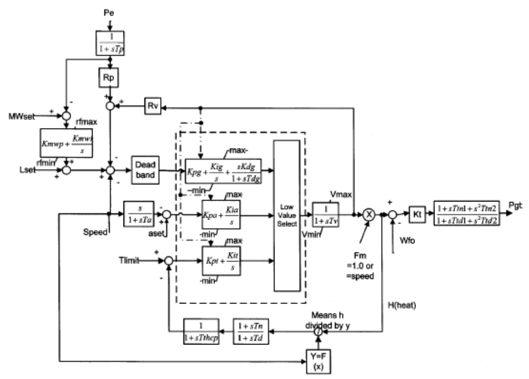

Figure 4: CIGRE Model Block Diagram

The CIGRE model features gas and steam turbines in a combined cycle plant. It has the control structure based on the choice of a signal between three control loops: load-speed, temperature and acceleration. Adding to that, there is a loop responsible for maintaining the power at a fixed value.

The dynamics of the turbine are modeled by second-order equations. The temperature is not explicitly calculated, being insted, associated with an equation that relates its value to other of the turbine variables, for instance, the speed of the rotor.

2.5. GGOV1 Model

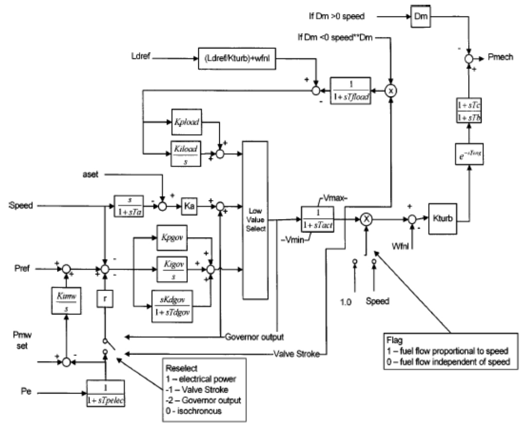

Figure 5: GGOV1 Model Block Diagram

The GGOV1 model uses the block diagram format to model the thermal generation units through three different elements: regulation, supervision and load management. The simulation of a gas turbine is dependent on the model parameters that are selected. The regulator element has a PID (proportional-integral- derivative) configuration. The supervisory element represents the load limit imposed by the operation of the plant. In the case of the gas turbine, this limitation is imposed by the exhaust temperature limit. The load management element is associated with the regulation of the turbine's power output and the dynamic behavior of the fuel flow.

3. Model Selection and implementation

After evaluating the models, the final choice is made between the Rowen and IEEE models, because they are the ones that best represent the turbine for the intended study. By direct comparison, changes in the parameters of the IEEE model are more difficult to understand, since changes made in one parameter influence the others, and vice versa. This makes the variations more accentuated and less easy to analyze. For Rowen's model, these changes are easier to understand so, for those reasons, it is the model chosen for the study to be performed.

3.1. Rowen model with alterations

The Rowen model is characterized by three control loops (load-speed, temperature and acceleration) that feed a block diagram that controls the fuel flow, using a signal selector that chooses the smallest of the input signals. The fuel flow signal is subsequently used, by the functions f_1 and f_2 in conjunction with the rotor speed signal, to calculate the exhaust temperature and the rotor torque, respectively.

$$f_1 = T_R - af_1 \times (1 - wf_1) - bf_1 \times (speed) \quad (1)$$

$$f_2 = af_2 - bf_2 \times (wf_1) - cf_2 \times (speed) \quad (2)$$

$$speed = 1 - N \quad (3)$$

TR represents the nominal exhaust temperature, $wf1$ is the fuel flow and *speed* represents the speed deviation to rated speed. $af1$,$af2$,$bf1$,$bf2$ and $cf2$ represent constants that characterize the turbine to be used.

Reg. de Velocidade				Sistema de combustível					Dinâmica da turbina		
W	X	Y	Z	a	b	c	τ_f	K_f	ε_{CR}	τ_{CD}	ε_{TD}
K_d	0	0.05	1	1	0.05	1	0.4	0	0.01	0.1	0.02

Parâmetros da turbina				
Modelo	rpm	P.Nominal[MW]	T.Nominal[ºC]	τ_1[S]
5001M	5100	18.2	513	16.2

Figure 6: Turbine and Rowen Model Parameters

For this test, the parameters used are those of the previous tables.

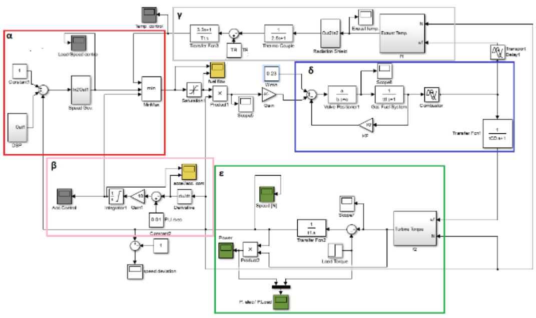

Figure 7: Rowen Model Block Diagram in Simulink

For the load-velocity regulator (α), considering a 4% *droop*, it is obtained, for K_d, which is given by the inverse *droop*, a value of 25. For the fuel flow control (δ), ttf (τ_f) represents the time constant of the fuel system, K_f, which applies feedback to the fuel system, is considered null and ε_{CR} and τ_{CD} represent the delay in the combustion reaction and the compressor discharge time constant, respectively. For f_1 (γ), the coefficients associated with the calculation of the exhaust temperature are obtained by relating it with the following formula, for temperatures in degrees Celsius:

$$T_R = 390(1 - W_F) + 306(1 - N) \quad (4)$$

For f_2 (ϵ), associated with the calculation of the rotor torque, the association is made with the equation:

$$f2 = 1.3(W_F - 0.23) + 0.5(1 - N) \quad (5)$$

The block that models the rotor dynamics is split into two independent and equivalent blocks to make possible the insertion of an initial value for the rotor speed, in the Integrator block:

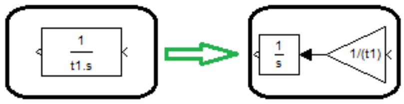

Figure 8: Modifications to Rotor Dynamics Block

For the acceleration control (β), some changes to the initial configuration have to be considered. One was the limitation of the signal through an anti-windup control, so that it does not increase linearly when the loop is not active. That steady increase causes delays in the response of the loop. The maximum limit chosen for the acceleration control signal, which has a negative initial slope when activated, is zero. This alteration also leads to switching the position between the integrator and gain, so that the limitation is not violated. Another alteration consists in changing the entry of the gain of the control to a smaller value since, for the original value, the signals present an undesired oscillatory transient.

With the signal of acceleration control limited, the selection policy of the loop controls of the model has to be changed. Thus, the following solution is chosen:

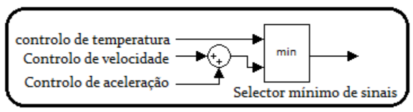

Figure 9: Control loop Selection

This way, the acceleration controlling indirectly influences the fuel flow control. Being the acceleration control, when actuated, a negative signal, when it is added to the speed control signal, it causes, at the input of the loop selector, a lower signal than that of the speed control. This ensures the correct operation of the model.

The main differences with these changes are as follows:

Original Model	Observation	Altered Model
The turbine is stationary which causes an initial transient to the rated speed with a duration of approximately 100 Seconds	*Initial Transient*	The speed is initialized with the nominal value which makes the initial transient non-existent. There is only one adjustment oscillation of the model to this condition
Acceleration control is not limited. When it is not active it has an increasing linear evolution resulting from its integral characteristic	*Acceleration Control*	Acceleration control limited by an anti-windup function with upper limit set to zero. For this reason it is possible to be added to the speed control signal without changing the model's behavior
When called upon to intervene, there is a time gap between the need for action and the effective takeover	*Acceleration controls activation time delay*	The control action is immediate

Figure 10: Main differences after Model Moficication

3.2. Model Simulation

Once the changes in the model are applyed, its behavior is evaluated for variations in the load torque value, so that the behavior of the acceleration and load controllers can be analyzed.

Increase in load torque

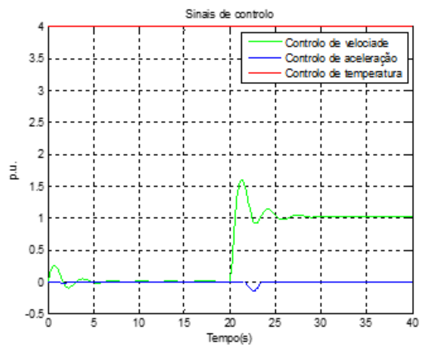

Figure 11: Load torque increase: control signals

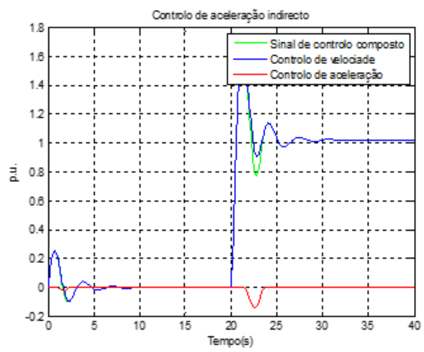

Figure 12: Load torque increase: Signal selector input signals

By increasing the load torque from zero to the unit value, it is observed that the speed load control increases in the same ratio to respond to the request. The acceleration control momentarily goes into action to limit the oscillations caused by the overshoot. The temperature control is not activated. It is limited to 4, to allow the observation of the remaining signals. The speed changes from the nominal value to 0.96 p.u., which is compatible with speed slip when it goes from no load to plain load with a droop of 4%.

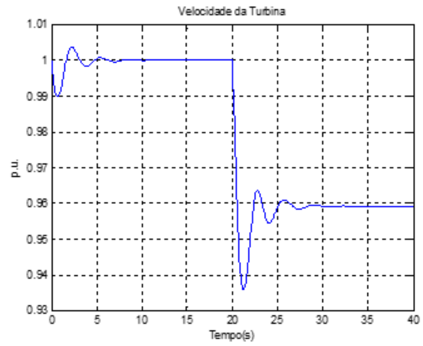

Figure 13: Turbine Speed

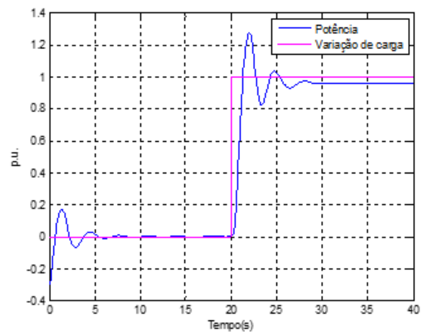

Figure 14: Mechanical And Electrical Power Comparison

Observing the evolution of the mechanical power it is verified that it evolves in order to satisfy the necessity created by the load torque. Thus, after a transient period, the mechanical power tends to equal the requested load torque, the differences are due to losses in the conversion process and approximation errors.

Temperature control activation

When the load torque is such that it forces the turbine to run above its exhaust temperature limit, the temperature control loop tends to act to bring the turbine back into a safe operating mode.

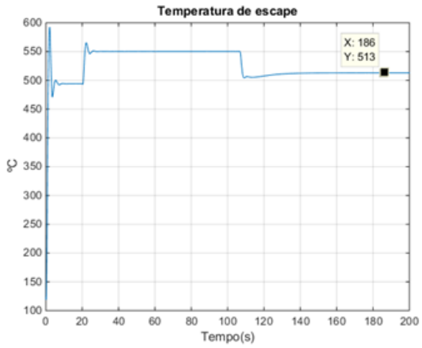

Figure 15: Exhaust Temperature

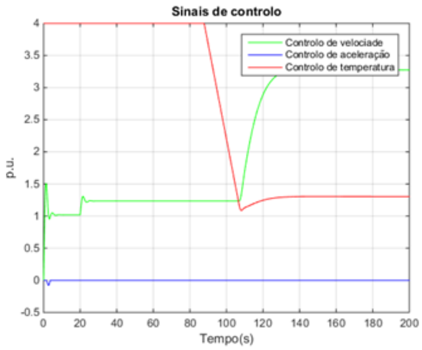

Figure 16: Temperature control activation

As can be seen, the load torque causes the turbine to operate at an exhaust temperature of 449C, and that causes the acceleration control to activate and bring the machine to operating mode limited to 513 C, which is the value of the exhaust temperature limit. Figure 16 shows the moment when the temperature control takes over the turbine control, close to 100 seconds. The mechanical power and speed are forced to new values by this new performance regime as shown next in figure 17 and figure 18.

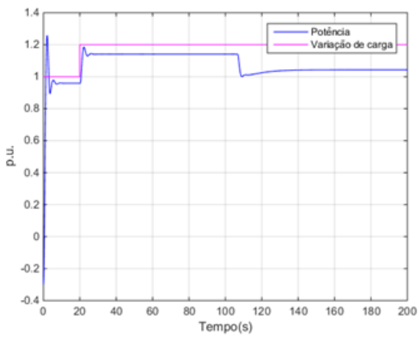

Figure 17: Mechanical And Electrical Power Comparison

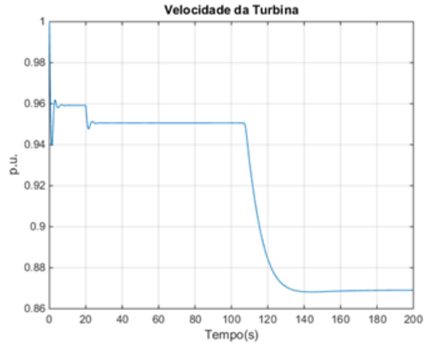

Figure 18: Turbine Speed

In the next point it is verified that for this final speed, forced by the temperature control, the turbine goes into instability. It cannot be seen here, because the observation window is too narrow Then the data of the simulations are compiled:

	Load Torque Reduction	Load torque Increase	
Load torque Variation (p.u.) (inicial-final)	1-0.5	0-1	1-1.2
Initial Speed (p.u.)	0.959	1	0.959
Final Speed (#Forced) (p.u.)	0.980	0.959	0.950 (#0.869)
Acceleration Control Activation	Sim	Sim*	Não
Initial Exhaust temperature (ºC)	494	212	494
Final Initial Exhaust temperature (#Forced) (ºC)	353	490	550 (#513)
Temperature Control Activation	Não	Não	Sim
Initial Mechanical Power (p.u.)	0.959	0	0.959
Final Initial Mechanical Power (#forced) (p.u.)	0.490	0.959	1.140 (#1.043)

Figure 19: Simulation Data Results

4. Turbine-Generator Group Simulation

Once the turbine is tested, it is interconnected to the model of a synchronous generator so that the behavior of the group can be observed. We use the simplified model of a synchronous machine that has as inputs, the mechanical power, the emf (electromotive force) and the stator terminals where it is connected to the network, and outputs a vector with information relevant to the simulation like, for instance , the machine voltages and currents, electrical power and speed deviation from the normal operating point. The generator's variables are calculated according to the parameters of the turbine and the turbine is initialized.

S_n [MVA]	V_n [KV]	Z_n [Ω]	H [s]	n_{pp}	E [p.u.]	P_{max} [p.u.]	ζ	$K_d M$
22.75	13.8	8.37	6.5	1	1.02852	5.1426	0.3	85.58

Figure 20: Generator Parameters

A fictitious grid is connected to the machine terminals in order to create the desired load variations in the study to be performed.

4.1. Short Circuit

Simulating a power cut between the turbine-generator group, in which the power nulled, the behavior of the model is analysed:

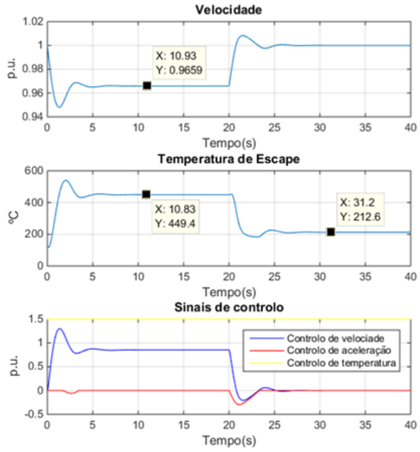

Figure 21: Signal Controls

It is observed that the speed increases, since the resistive torque created by the load is lost, stabilizing at the nominal speed, due to the fact that it is running at no load. It can also be seen that the acceleration control acts to limit this increase in speed. As for the temperature, it suffers a reduction, because the turbine undergoes a reduction in the fuel flow.

Consequently, the mechanical power created by the turbine also tends to zero.

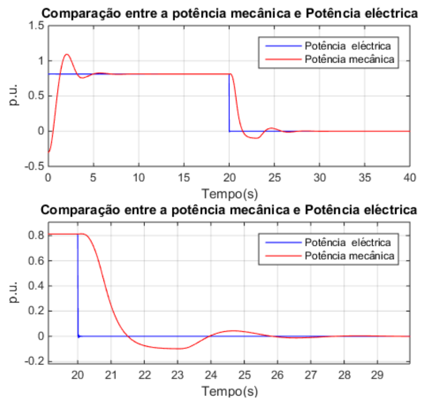

Figure 22: Mechanial and Electrical Power Comparison

However, it is noted that, before stabilizing at zero, the mechanical power assumes negative values. Such behavior is due to the fact that the transient has an overshooting oscillatory transient. To resolve this situation, it is necessary to act on the controllers' gains so that the transient becomes over-damped, thus avoiding overshooting.

4.2. Temperature control actuation

Temperature control is influenced by the severity of the effort required by the turbine to operate. Thus, the higher the temperature rise over the limit value allowed by the model, the faster the temperature control will take over. To minimize response time and preserve the physical integrity of the turbine, an anti-windup control is applied to the integral component of the temperature control, thus ensuring that the response is as fast as possible.

By applying to the generator terminals an increase in power demand that activates the temperature control, we obtain the following results.

The simulation is separated into two parts, one in which one can guarantee a new stable operating point and another where the variation is so pronounced that the group loses its synchronism;

No loss of synchronism

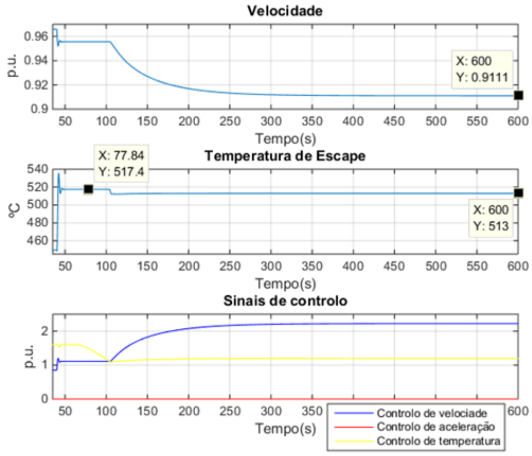

Figure 23: Signal Controls

It can be seen in this case that the temperature control reacts immediately from a value closer to the remaining control signals. As soon as it assumes control of the turbine, it forces the operation to be within the exhaust temperature limit and the speed and power signals to adapt to that new regime.

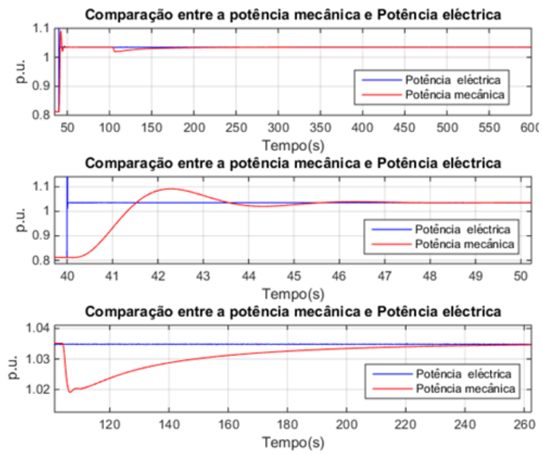

Figure 24: Mechanial and Electrical Power Comparison

In the figure it can be seen that, since the temperature control has an integral component, by imposing a new operating regime, it forces the mechanical power to match the electric power again. This imposition is compensated by the reduction of speed.

With loss of synchronism

When the load request forces the turbine to pass the stability limit, the signals take the evolution shown below.

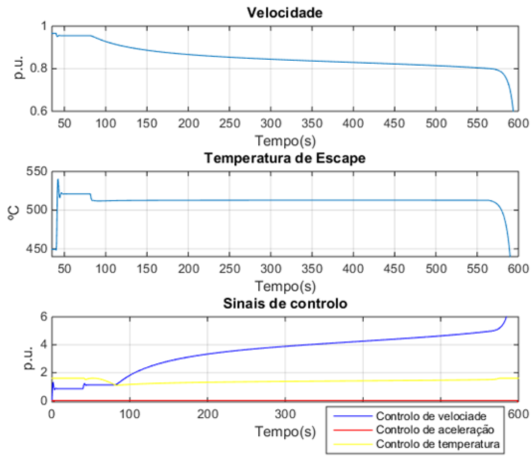

Figure 25: Signal Controls

It is verified that the speed is reduced to the point that it loses the stability, near the 550 seconds.

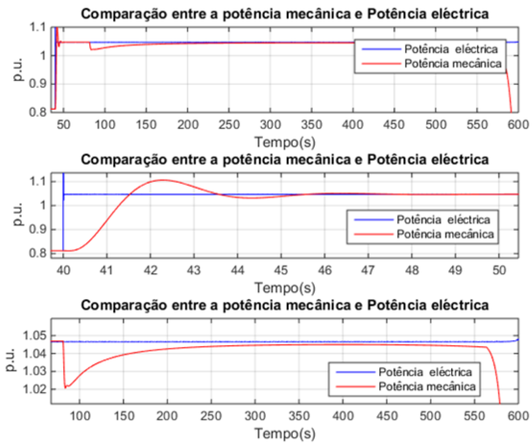

Figure 26: Mechanial and Electrical Power Comparison

As Figure 26 shows, the integral component of the temperature control, when attempting to match the mechanical to the electrical power, forces the speed to be reduced to values that do not guarantee the synchronism. Hence the system goes into instability.

5. Conclusions

After being created and tested, connected to a simplified model of a synchronous machine and simulated to analyze the behavior of the control loops, we conclude that the Rowen model is a reliable solution that allows an accurate and simple study of the stability of a generator turbine group inserted into an electric power network. The control loops respond well to the requirements imposed on the turbine, ensuring that it always works safely. To increase its stability limits, manipulations to the parameters of the load-speed, acceleration and temperature controls can be attempted.

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