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Approach to Design of a PID Controller for an AVR System and Stability Analysis Through Co-simulation Using MATLAB and DIgSILENT PowerFactory

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Abstract

Nowadays we are observing day by day the exponential growth of the power network and the different subsystems that this involves, therefore, it is necessary to model or simulate those systems trying to emulate their actual behavior accurately, some of these systems require modeling physical, mechanical, or electrical variables at the same time; considering this, a multidomain analysis is necessary. There is specialized software according to those domains or the specific task required like MATLAB / Simulink, which is a great tool for analyzing control systems, as well as DIgSILENT PowerFactory for modeling electrical power systems. That is why it is intended to get the best from both application software in a co-simulation to accomplish the objectives of this study. This document presents the design and tuning of a PID controller for the excitation system AVR using the Control System Designer toolbox from MATLAB; this system is subsequently tested under load with the synchronous machine running online with the power system, this is done through a co-simulation, interfacing MATLAB and DIgSILENT PowerFactory. Then we analyze the behavior of the system when is subjected to small signal disturbances to evaluate the performance of the controller and the voltage stability behavior of the power system. Finally, the reached Co-Simulation study proves to be a useful and powerful methodology to study the dynamics of the power system in this case, and it is presented as a possible solution for the simulation of future energy systems that integrate multiple domains.

Keywords: DIgSILENT PowerFactory, MATLAB - Simulink, Automatic Voltage Regulator (AVR), Excitation System, Excitation Control, PID controller, Co-simulation, DSL (DIgSILENT Simulation language)

1. INTRODUCTION

The excitation system in a synchronous generator is the set of elements in charge of maintaining the output voltage of the generator at a certain value or threshold; this voltage level is related to the reactive power flow that variates with changes in the load. “A change in the real power demand affects essentially the frequency, whereas a change in the reactive power affects mainly the voltage magnitude. The interaction between voltage and frequency controls is generally weak enough to justify their analysis separately”[1]. An excitation system can be composed of several parts according to its design, some of them are amplifiers, sensors, exciter, etc., and the element in charge of the control, commonly known as the Automatic Voltage Regulator (AVR), which adjust the excitation field voltage and current, and thus regulate the output voltage at the output terminals of the generator. There are three main categories for AVRs models: DC generator, AC generator, Solid-state rectifiers [2].

Most excitation systems fall into one of these three categories, where the source of the energy to power the excitation field varies. In Fig.1, we found the typical configuration for the excitation system.

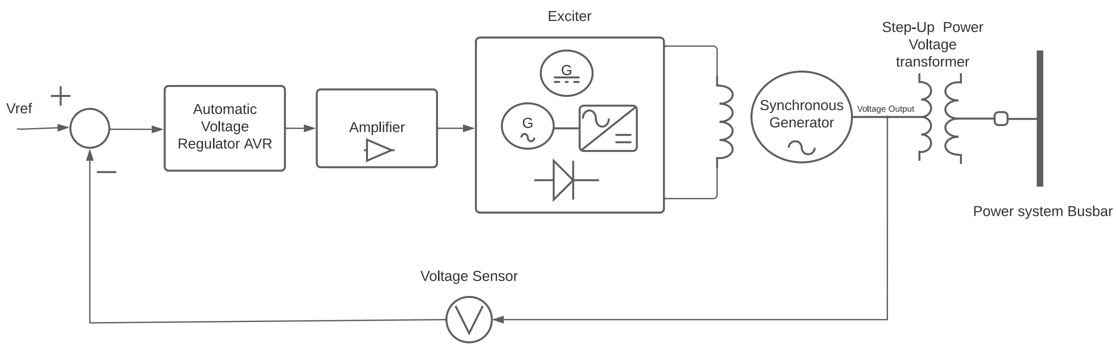


Figure 1: Excitation control system in a synchronous generator.

The power system is subjected to several types of stability due to its natural dynamic behavior, one of them is voltage stability which is related to the flow of reactive power. The lack of reactive power in the system is reflected in voltage drops and can lead the system to an unstable state, which in a severe case could cause major blackouts. In recent years, several of the main collapses were related to voltage instability [3]. In a power system, the sources of reactive power are generators, capacitors, and reactors[1]. Reactors, also help the system to reduce or regulate the excess of reactive power and thus decrease the voltage level. There are several generalized components used in the operation of a power system that helps to regulate the voltage level and flow of reactive power in the system such as Capacitor Banks, On Load Tap Changer (OLTC), Flexible

AC Transmission System (FACTS), Static VAR Compensation (SVC), and STATCOM among others[1], these components are placed at specific levels in the power system according to its characteristics and purpose.

Considering the importance of voltage stability and the necessity to control this variable in an accurate way as possible, to meet a reliable and stable power system, we will focus on the primary source of reactive power; the synchronous generator and its respective control in terms of voltage, the AVR. The above through the implementation of a PID controller, this type of controller has been widely utilized for this kind of application due to its good performance and robustness [4]. Nowadays "The proportional–integral-derivative (PID) controller continues to be the main component in industrial control systems. The reason of this popularity is for its simple structure which can be easily understood and implemented"[5]. Currently, there are several techniques and algorithms to adjust the parameters of this kind of controller, these methods include but not limited to, heuristic, rule-based, Ziegler-Nichols, Cohen-coon, model-based, fuzzy logic, etc., and optimization algorithms as those mentioned in [4].

Currently, there are several documents and studies with different techniques and approaches that focus on the design and tuning of the PID controller for the AVR. In [6] particle swarm optimization (PSO) algorithm is presented, the paper demonstrated in detail how to employ the PSO method to search efficiently the optimal PID controller parameters of an AVR system. In [7] ant colony optimization is implemented; real time control experiments were used to probe the response of the algorithm. In [8] the design of the Proportional-Integral-Derivative (PID) controller was made by using Cuckoo Search (CS) algorithm with a new time-domain performance criterion. The performance of the proposed (CS) based PID controller was compared to the PID controllers tuned by the different evolutionary algorithms using various objective functions proposed in the literature. The disturbance rejection and robustness performance of the tuned controller against parametric uncertainties were obtained, separately. In [9] and to improve the robustness of the system towards the relatively severe disturbances caused from both load side and set point side, the 2DOF state feedback PI-controller which was tuned with a metaheuristic optimization algorithm is propose. In [10] a method based on the usage of the Equilibrium Optimizer (EO) algorithm for the determination of the optimal values of the (PID) controller parameters for the (AVR) system were proposed, to probe the ability of the proposed PID controller to react to unexpected disturbances, step disturbance has been added to the control system loop. These papers give us a clear overview of how to design a PID controller and how to find the optimal values for its different parameters by focusing on obtaining the constants applying different methods.

On the other hand, some papers addressing the performance of the controller in the power system such as[11], a novel robust controller of automatic voltage regulator (AVR) in terms of H infinity (H∞) and structured singular value decomposition has been presented to provide the robust performance of the (AVR). Where, the behavior of the intended robust controller was shown in two benchmarks: a single machine connected to a 230kV network, and a four-machine two-area test system, but in this system the simulation was applied with the purpose of comparing the performance of the system with some other optimized PID, PIDD fractional order PID (FOPID), fuzzy+ PID and Interval Type-2 fuzzy logic controllers by heuristic optimization algorithms, the power system and the disturbance were both simulated in MATLAB. Another paper addressing the simulation of the excitation control system, but this time analyzing a post fault situation is in [12], the paper shows how an unstable operating condition, after the occurrence of two simultaneous events, at an oil refinery electric power system, may have been avoided by simply adjusting the automatic voltage regulator gain in one of its synchronous generators. The simulation of the power system for this analysis was made separately. Also, in [13] the steady state voltage stability with AVR voltage constraints in a power system is presented, voltage instability associated with the AVR voltage saturation phenomena is evaluated. For this purpose, a new methodology based on the predictor–corrector method was introduced to trace the total system equilibrium of the power system model. To summarize, from [12] and [14] we can see the importance of applying dynamic simulations involving the power system to assess the behavior of the excitation system control prior to its implementation. In [14] the commissioning and field tuning of ABB Unitrol P AVR, and PSS of a 160 MW steam turbine were conducted, AVR parameters such as time constants and gain were set to the values identified from simulation studies, then, some viable field tests were performed such as changes in the voltage setpoint. After that, comparisons between field measurements and simulations were made. Restrictions applied to perform other field tests.

Taking as reference the IEEE std 421.2, where provided criteria, definitions, and test objectives for excitation control systems are given, within these tests, the dynamic behavior of the excitation system must be assessed through the analysis of large signal performance, small signal performance, and the effects of the limiters on the stability of the power system. Nonetheless, many field tests on units under normal operating conditions are constrained to comply with the operating and security requirements of the power system. The need for models that accurately simulate the operation of excitation control systems during disturbances demands effective test methods[15]. However, considering the literature analyzed, it is observed that there is a gap between the design stage and the final validation-simulation and analysis of the performance of the designed controller working in the power system, and under the constraints of power system where the excitation system will be implemented. This simulation is necessary to evaluate the robustness of the designed controller to obtain a better approximation of the dynamic behavior of the excitation control system as well as the stability of the power system when facing possible real faults or disturbances in which the controller should operate without difficulty, considering that constraints limits of the excitation system must be taken into account.

Based on the above, the whole excitation control system, including the power system must be evaluated before field implementation[15]. That is why in this paper this assessment, which involves the simulation and analysis is made by using a technique that becomes more relevant every day such as a Co-Simulation. This method opens the door to propose and implement more complex and/or robust control model simulations as necessary, or to create models that involve multi-domain analysis or variables that could not be simulated before, either due to the limitation of each software acting separately or due to the complexity to do so[16]. Co-Simulation then gives us the ability to extend our models. “Interfacing of the simulation tool to an external program/mathematical tool extends the capability of the simulation tool in a more effective execution of the simulation, particularly in an area where the external program/algorithm provides more advanced technique and flexibility”[17]. Knowing this and considering the benefits of MATLAB to design control systems, as well as DIgSILENT for power systems, a co-simulation is proposed in this document for the study of the excitation control system.

The purpose of this document consists in design a PID controller using the Control System Designer toolbox from MATLAB and tuning it by utilizing classical methods such as root locus and gain-phase margin analysis, making the necessary adjustments to meet a satisfactory performance considering reference parameters in IEEE std 421.2 [15]. Then, we simulate the power system in DIgSILENT PowerFactory where the generator will be running online. The control of the AVR is going to be in MATLAB/Simulink where the controller has been designed, and by interfacing both software’s we will evaluate the behavior and robustness of our AVR when subject to small disturbances trying to emulate a realistic scenario. We will do this using the methodology proposed below.

From here on, this document is organized as follows; In section 2, we show the methodology proposed to design the PID controller and to tune it by using a classical tuning method such as root locus and gain-phase margin analysis. Also, presents a brief description of the general procedure to interface MATLAB and DIgSILENT PowerFactory. In section 3, Simulation results, first for the PID control system designed, and then considering the response of the power excitation system when the generator is running online. Finally, in section section 4, conclusions are given.

2. DESIGN AND METHODOLOGY

Using the MATLAB toolbox APP Control System Designer, we are going to design and tune the AVR controller; this is a particularly useful graphical tool that allows us to observe and tune the behavior of the system in the time and the frequency domain simultaneously. By using this tool, the root locus and the loop shaping of the system as well as the structure of the controller can be manipulate to obtain the desired response. This study was made by following the next proposed methodology which can be applied to other control systems for this kind of applications:

2.1. Identify the dynamic model of the excitation system

This is done by linearizing the dynamics of the generator and the different components involved, AVR, exciter, sensors, etc., to determine its behavior or response when subjected to a certain stimulus, in our case, it is widely used for simplicity the space state representation model in the frequency domain. The model and the example used for this study is shown in Fig.2, which is a variation of the one presented in [1]. The model of our excitation system considers common values for this configuration as shown in Table 1 [4], these parameters may vary according to the manufacturer of each component.

Table 1: Common values for AVR basic components[4]

Component	K(time constant)	T(Gain constant)
$Amplifier$	10$\leq$ Ka $\leq$ 40	0.02 $\leq T_a \leq$ 0.1
$Exciter$	1 $\leq$ Ke $\leq$ 10	0.4 $\leq T_e \leq$ 1
$Generator$	0.7 $\leq$ Kg $\leq$ 1	1 $\leq T_g \leq$ 2
$Sensor$	0.9 $\leq$ Kr $\leq$ 1.1	0.001 $\leq T_r \leq$ 0.06

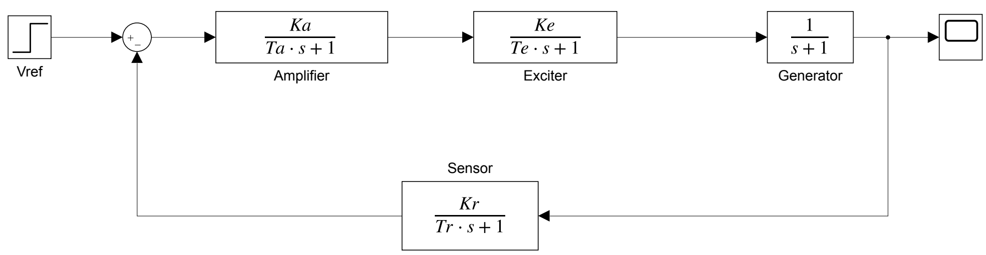


Figure 2: Closed Loop Excitation system without PID controller.

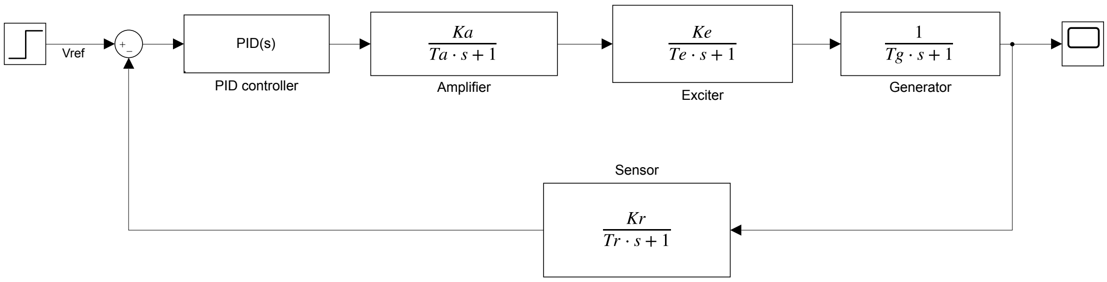


Figure 3: Closed Loop Excitation system including the PID controller.

2.2. Load the model into MATLAB

There are several ways to do this; it can be make it by drawing the system directly in Simulink, or by code definition. In this study case, the definition of the variables was made in the command window in MATLAB according to Table 2 values, then the model was drawn into Simulink, Fig.2. Once the system has been defined, the Control System Designer toolbox (CSD) can be executed.

Table 2: Values for AVR components used in our model

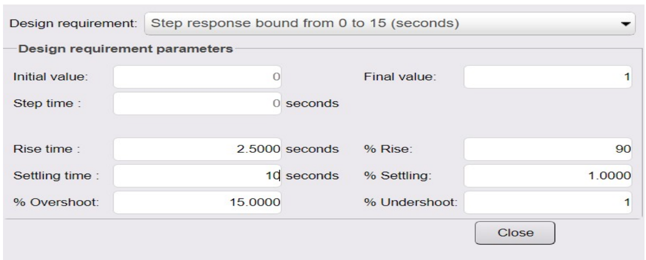
Component	K(time constant)	T(Gain constant)
Amplifier	Ka = 5, 20	T_a = 0.2
Exciter	Ke = 1	T_e = 0.5
Generator	Kg = 1	T_g = 1
Sensor	Kr = 1	T_r = 0.03

2.3. Select, check, and validate the architecture of the model

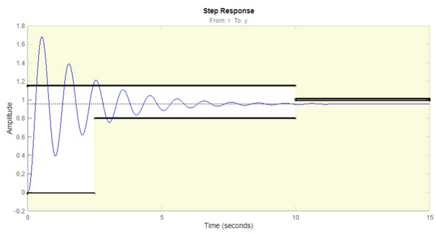
Choose the control architecture of the whole plant from the standard models in the MATLAB CSD toolbox according to the model of your plant. The blocks in the control architecture must match the ones in the excitation system model, including the generator. Link each block of the system with the respective value i.e., C, F, G, H blocks.

2.4. Designing the controller

The requirements and restrictions in each graphic of analysis, bode plot, root locus, and step response, must be set so that our controller can have a satisfactory performance i.e., controls the plant within the desired limits and for our purpose meets the basic requirements in [15]. Knowing this, the tuning process of the controller can be started by adjusting the gain, poles, and zeros, according to convenience and the restrictions of the system. This can be made manually or automatically using the app. For example, in Fig.4b. we observe the output voltage of the generator in the time domain, where the shaded region represents the restriction zone defined by rising time, settling time, and overshoot (%). These restrictions were configured according to Fig.4a. By observing Fig.4b, clearly shows the need to adjust the controller because the answer does not meet our requirements.



(a) CSD Design settings.



(b) Step response of the system from r to y in P.U.

Figure 4: CSD Design requirements for step response [18].

Once tuned the controller and obtained the desired response, we proceed to export the model to the workspace or create a new Simulink model directly from the Control System Designer. Since we had already created the model in Simulink it is preferable to export the controller variables to the workspace. Later we obtain the constants Kp, Ki, Kd, and the time constant Tf from the controller using the following function in MATLAB:

$$[K_p, K_i, K_d, T_f] = piddata(sys) \tag{1}$$

Having done this, we have the controller model ready as shown previously in Fig.3. All the constants are now known; once there, validate the model comparing the responses, Simulink (Fig.5) vs the designed in the CSD toolbox (Fig.14). If the two graphic answers match, it means that the model from the CSD application to Simulink has been correctly implemented, which is ultimately the model that we will use.

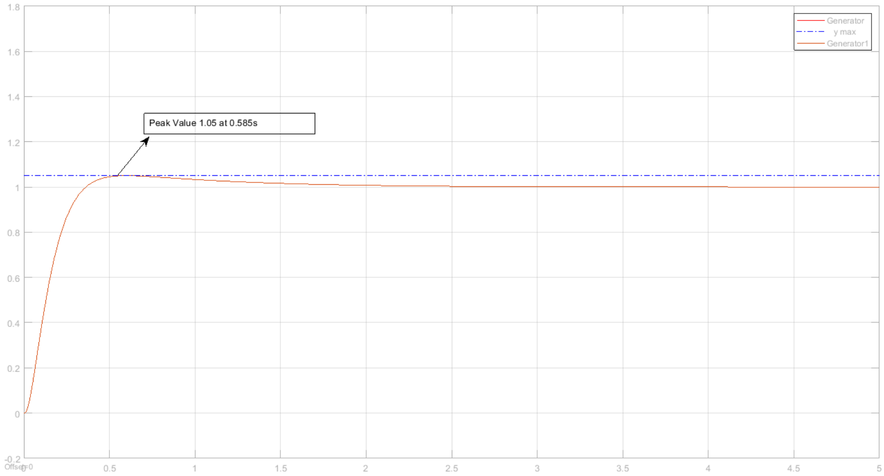


Figure 5: Simulink Step response of the system from r to y in p.u.

2.5. Implement the interface between MATLAB and DIgSILENT

We need to readjust our AVR control model given that the power system – generator is going to be running in DIgSILENT PowerFactory working under the power system constraints, whereas the AVR control will be set in MATLAB Fig.6. In Fig.7, we can observe the final AVR control model implemented in Simulink. As we can see, there is no synchronous generator block in this figure just the AVR control.

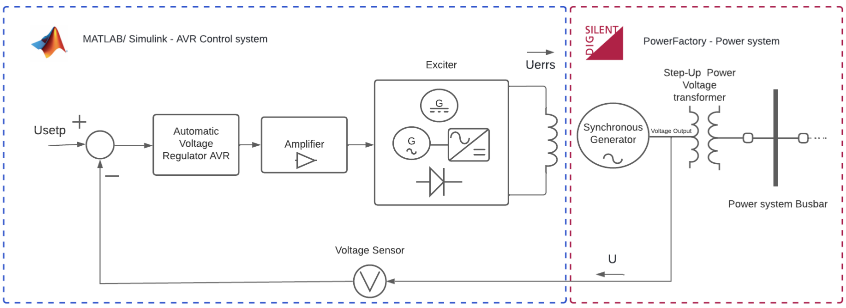


Figure 6: Co-Simulation process between DIgSILENT and MATLAB.

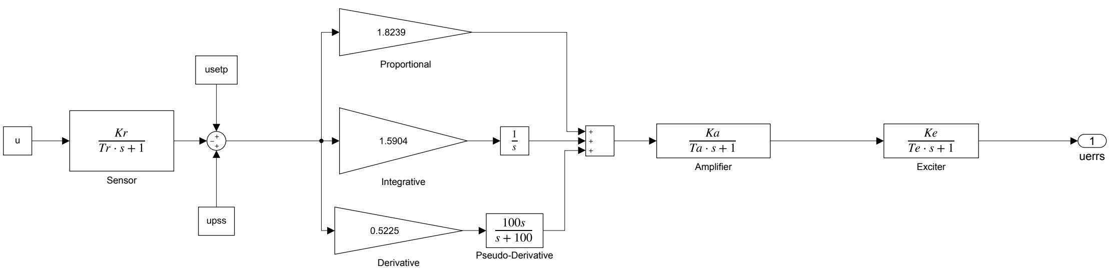


Figure 7: Final model of the excitation system in Simulink

To interface DIgSILENT PowerFactory and MATLAB we use the procedure described in the user manual, MATLAB Interface [19]. The process for data interchange between this two software's, in general terms consist in the one described in Fig.8.

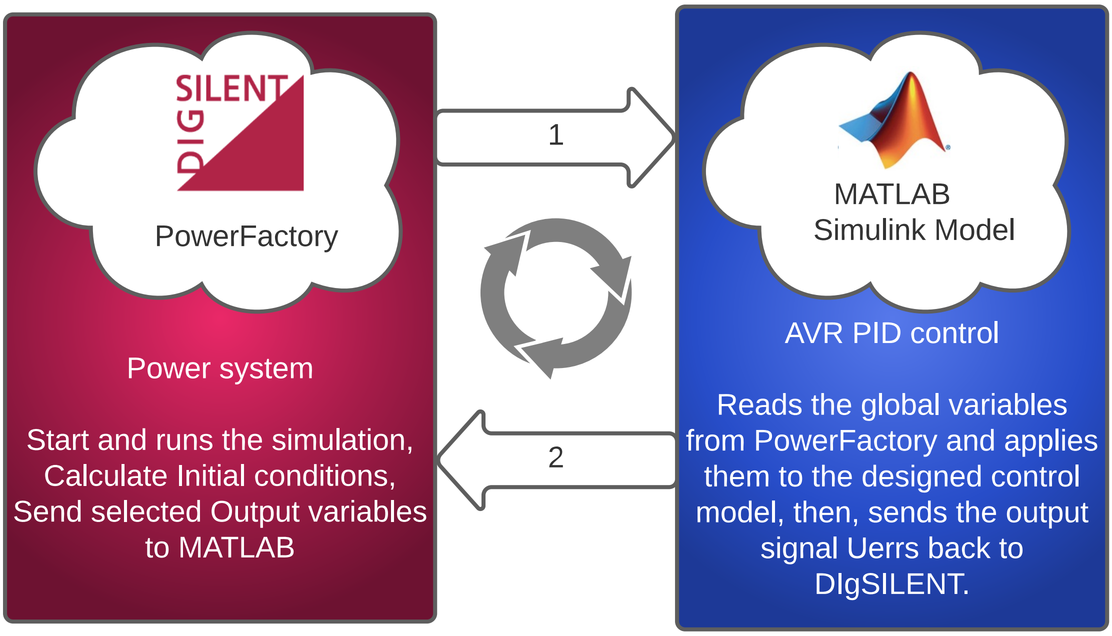


Figure 8: Data exchange process between DIgSILENT and MATLAB.

After analyzing the designed AVR system, we created a frame in DIgSILENT see Fig.11, indicating the information to be sent from DIgSILENT to MATLAB and vice versa. Also, we defined in MATLAB the function in Fig.9 [19], representing the variables of the system.

```
function [t, x, y] = AVR_PID
global u usetp upss Ka Ta Ke Te Kr Tr x1 x2 x3 x4 x5 %Variables and state
variables

options = simget('AVR_PID_model'); % Get the variables from Simulink
options = simset('InitialState', [x1,x2,x3,x4,x5]);%initial condition of
the state variables
[t, x, y] = sim('AVR_PID_model', [], options);% Creates the Output
```

Figure 9: Function defined for data exchange between DIgSILENT and MATLAB[19].

2.5.1 Validating the Model:

Additionally, from the AVR model created in MATLAB and to validate the correct implementation of the Co-Simulation, we created the same model in PowerFactory using DSL (DIgSILENT Simulation Language), see Fig.10.

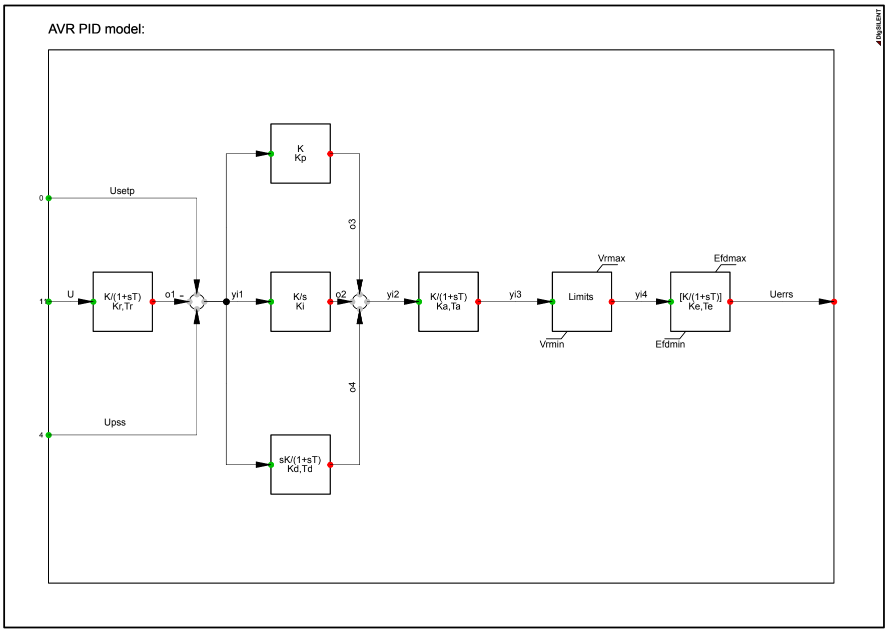


Figure 10: AVR model implemented in PowerFactory using DSL.

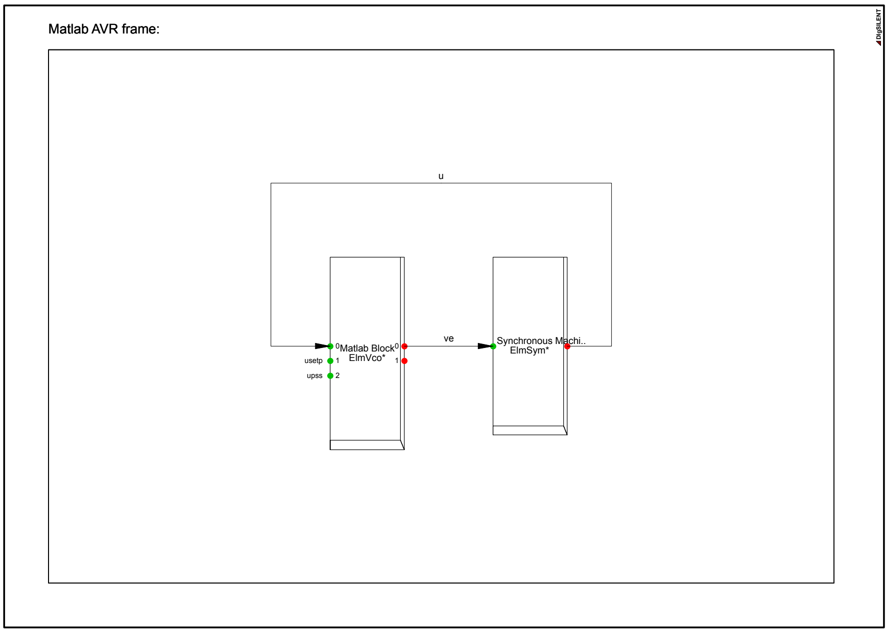


Figure 11: MATLAB AVR frame model in PowerFactory using DSL[19].

Once the two models with the same parameters have been implemented, we can compare the response from both the DIgSILENT and the MATLAB AVR control models by simulating some disturbances in the power system and expecting the same response as shown later in Fig.20.

2.6. Assessment of the designed controller

Field tests and final product acceptance tests are always necessary since it is where the real behavior of the equipment is observed. However, in this case as the above mentioned is not feasible; It is intended to simulate the behavior of the designed AVR, first, using just the Simulink model with no load in the generator, section 3.1, and then coupling the generator to the power system using DIgSILENT PowerFactory software, section 3.2; this to obtain and analyze a better approach when the generator is working under load, in simulated near-real conditions. At this point and to test our controller we implement the classical IEEE nine bus system, Fig.12 [20], this system has three generators, each one of them it's going to have our designed AVR controller. Once there, we are going to simulate some small signal stability voltage events.

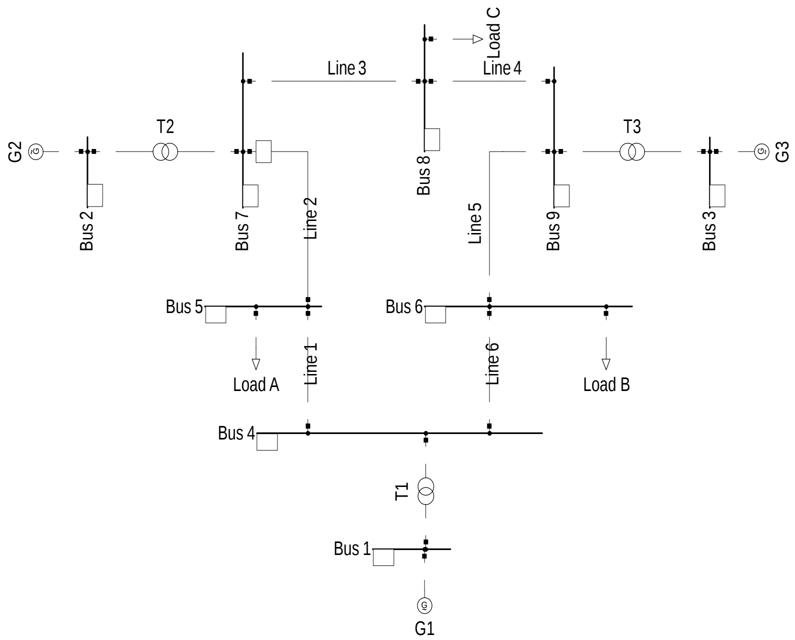


Figure 12: IEEE Nine Bus System – Model under test in DIgSILENT PowerFactory.

3. SIMULATION RESULTS

3.1. Designing the controller.

3.1.1 Case 1:

In this case, we simulate the excitation system without controllers, and just using the Simulink model in Fig.2, we start varying Ka to see the response of the system to a step input. As shown in Fig.13, while increasing Ka gain, we reduce the steady-state error and improve the rise time, but the system loses stability. If we continue increasing Ka, the system will get completely oscillatory and unstable. The need to implement a controller is evidenced.

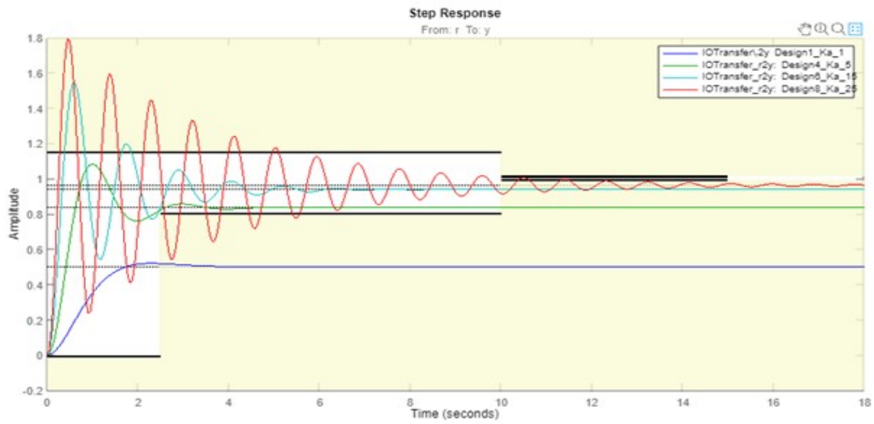


Figure 13: CSD Step response of the system varying Ka gain 1,5,15,25 [18].

3.1.2 Case 2:

In this case, we simulate the excitation system including the PID controller see Fig.3, we have adjusted the root locus graphic moving the poles of the system and considering the limits and the generally accepted values, such as gain margin, phase margin, overshoot, Mp, and damping ratio. We tested and generated several designs; however, we chose to use the one shown in Fig.14. This one model presents a good response according to the requirements in [15].

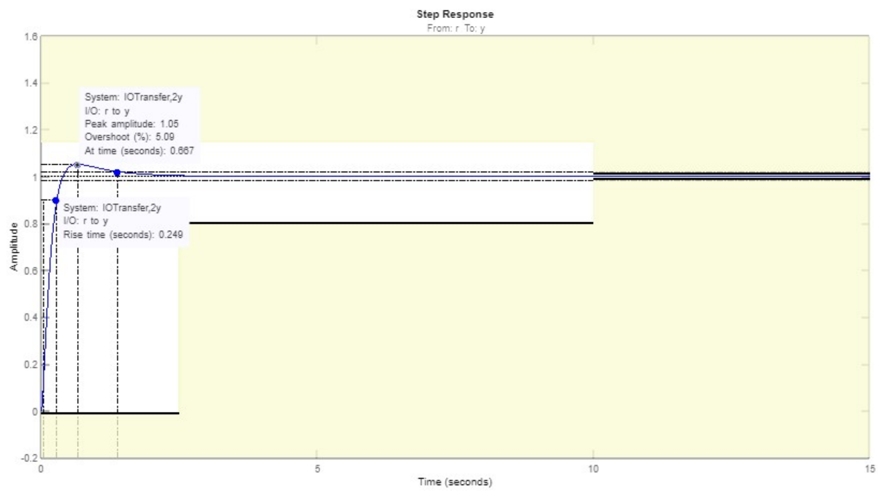
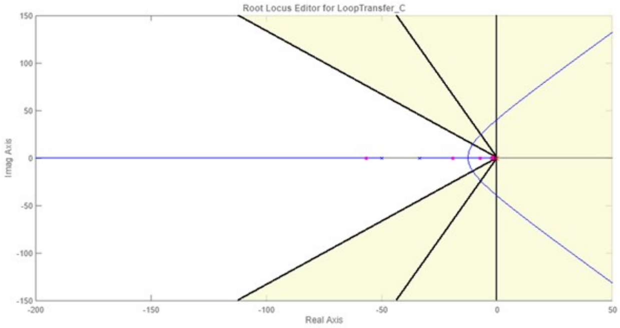


Figure 14: CSD Step response of the system with the PID controller for Ka = 5 [18].

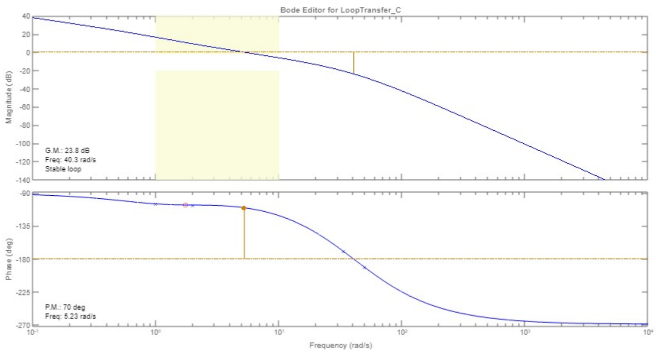
In Fig.15a, we set restrictions such as percent overshoot, settling time, and the damping ratio as well as the structure for the PID controller; In our case, we add to real zeros and one integrator at the origin to shape our PID controller. The characteristic values of this response can be seen below in Table 3.

Table 3: Dynamic response values of the control system with the synchronous machine disconnected from the power system.

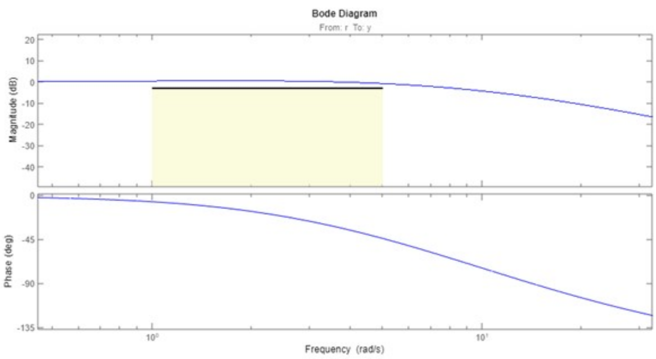
Variable	Value	Time seconds
$Amplitude(p.u)$	1.05	0.589
$Overshoot(\%)$	5.09	0.667
$Settling\ Time(p.u)$	1	1.39
$Rise\ time(\%)$	90	0.249



(a) Root Locus editor of the system for Loop Transfer C.

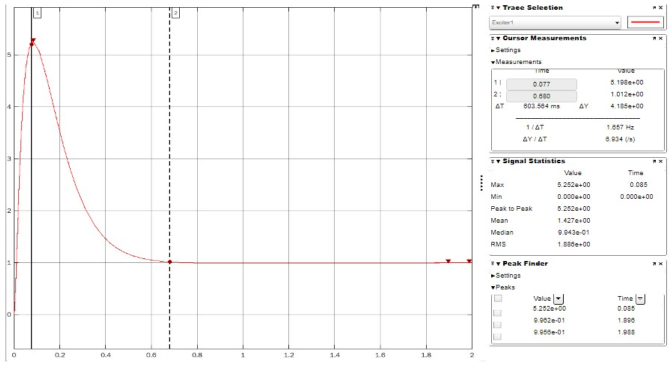


(b) Bode Plot editor for Loop Transfer C.



(c) Bode Plot of the system from r to y

Figure 15: CSD tuning of the PID controller [18].



(d) Voltage effort of the controller from r to u.

Figure 15: CSD tuning of the PID controller [18]. (cont.)

In Fig.15b, we set restrictions such as Gain Margin, Phase Margin, and Frequency.

Next, in the Table 4, we observe the characteristic frequency response of the system from Fig.15b and Fig.15c. Also, it is important to consider the effort of the controller to manage the excitation field. As shown in Fig.15d, in this case we have a peak of 5.2V, a low acceptable voltage value to control the excitation voltage in the generator.

Table 4: Frequency response values of the control system with the synchronous machine disconnected from the power system.

Variable	Value
$Gain\ margin$	23.8 dB
$Freq$	40.3 rad/s
$M_p(Peak\ Value)$	0.364 dB at 1.67 Hz
$Phase\ margin$	70 deg
$Damping\ ratio$	0.6

By manipulating the location of the roots and zeros we change the response of the system, as evidenced in the previous figures, this process is known as the tuning of the controller. In Table 5, we can see the final values found for our PID controller. For more detail about all the parameters and restrictions refer to [15]. Once all the values for our controller have been found, we show the final composition of the designed AVR in Fig.7.

Table 5: Constants Values Kp, Ki, Kd, Tf Found for the PID Controller.

Kp	Ki	Kd	T_f
1.8233	1.5904	0.5225	0

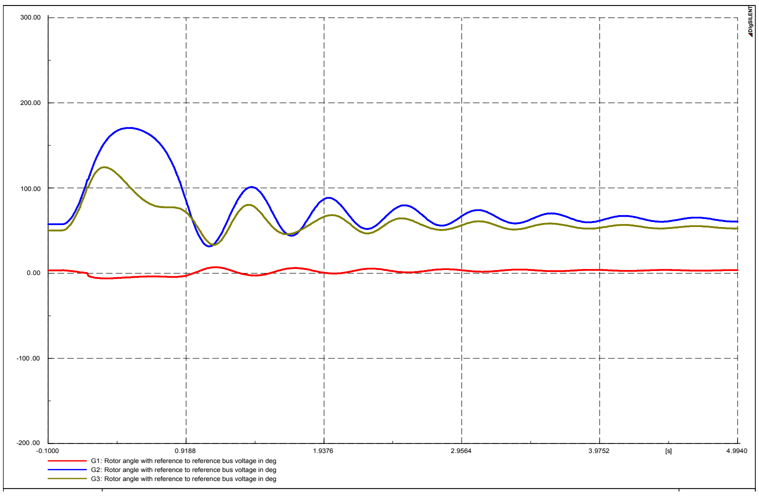
3.2. Testing the designed AVR controller

To identify the behavior and performance of the controller and analyze the power system stability, two simulation scenarios and six cases with different variations were established:

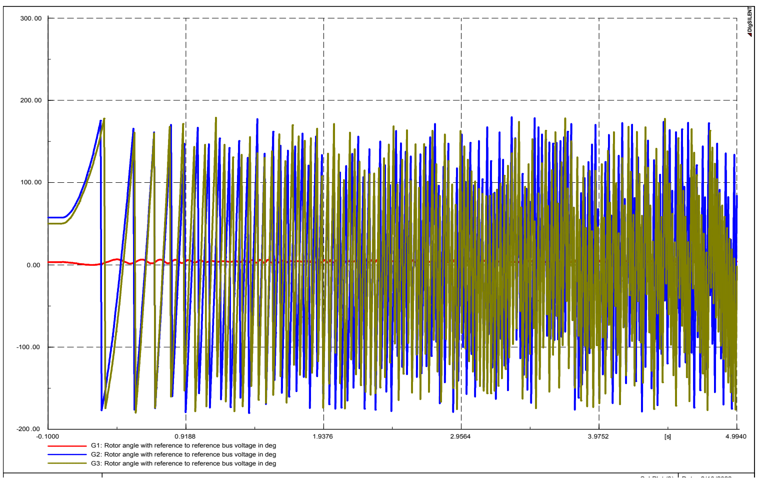
3.2.1 3.2.1 Critical time for fault clearance

3.2.2 Case 1, No AVR controllers,

in this case we simulate a 3 Phase short circuit at bus 8th at 0[s] to find the critical time to clear this fault before the system loses stability and the generators run out of step. For this system and under these conditions we found that the critical clearance time is 0.195ms, for a 3-phase fault with no impedance, Fig.16a. After this, if the fault is not cleared the system will collapse, Fig.16b.



(a) Before collapse case 1.

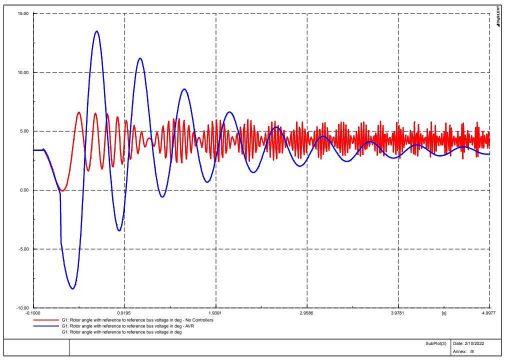


(b) After collapse case 1.

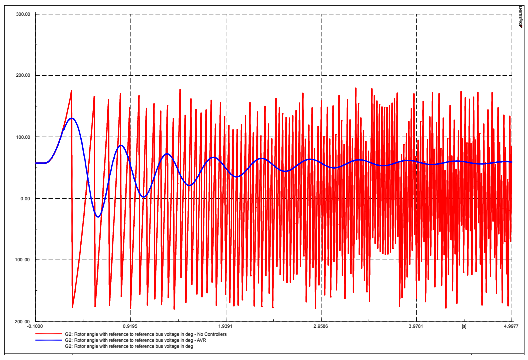
Figure 16: Rotor angle stability referenced to bus voltage for G1, G2, G3 case 1.

3.2.3 Case 2, Implementing AVR controllers,

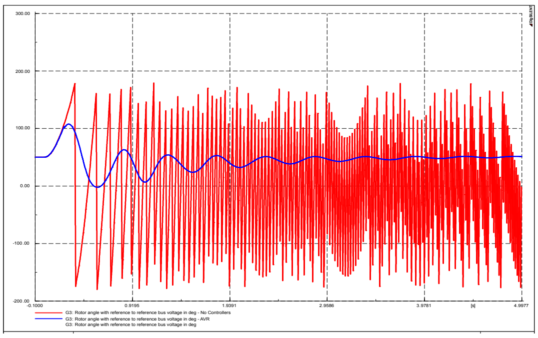
in this case we simulate the same previous 3-phase short circuit at 0[s], at the bus 8th to find the new critical time; but this time the AVR's are working. For this system and under these conditions we found that we improve a few [ms] the critical time; the new value is 0.253ms, after this if the fault is not cleared the system will collapse. For Fig.17a, Fig.17b, Fig.17c, the blue signal represents the behavior of the rotor angle for the three generators activating the AVR control, while the red one without the controllers. Even having controllers in all three generators will not prevent the collapse of the system if the fault is not cleared within the new critical time due to the magnitude of this 3-phase short-circuit, and the capability limits of each generator.



(a) G1



(b) G2



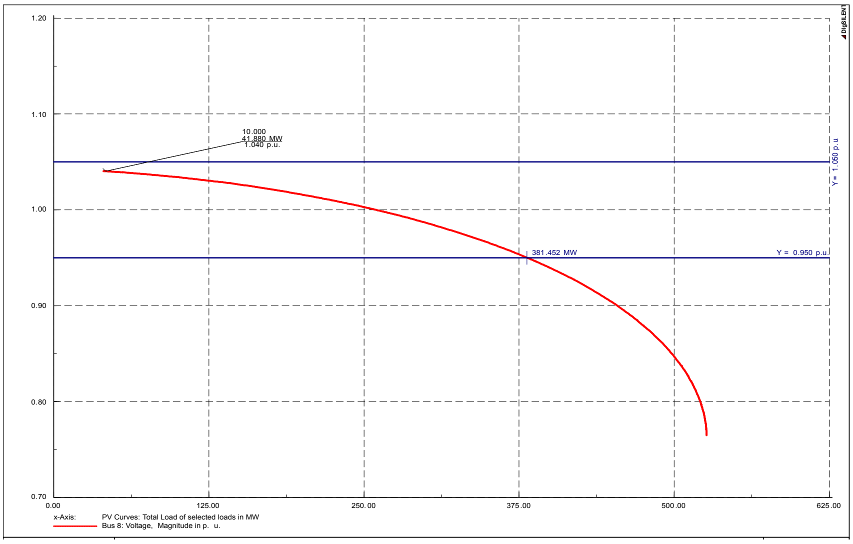
(c) G3

Figure 17: Rotor angle referenced to bus voltage; No controllers (Red), AVR(Blue) Case 2

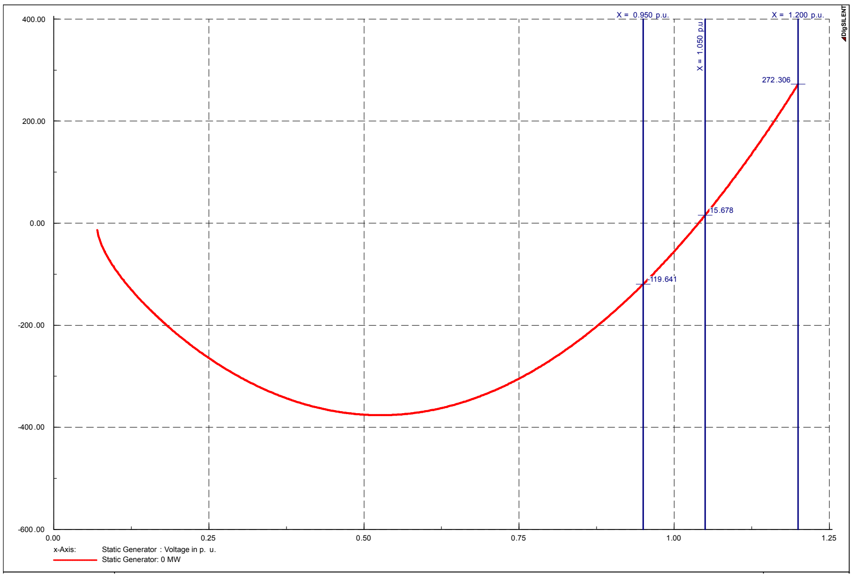
3.2.4 3.2.2 Load Event

3.2.5 PV and QV curves,

due to voltage regulation and depending on the operator rules its common that voltage level variates between 1.05 p.u. and 0.95 p.u. at transmission levels ±5%. To find the power consumption of the load C, at bus 8th to make the voltage variates to these levels, we apply the PV - Fig.18a, and QV - Fig.18b, curves method to find these values.



(a) PV curve at bus 8th.



(b) QV curve at bus 8th.

Figure 18: PV and QV curves.

According to Fig.18a and Fig.18b, we found that load C could variate within the limits of normal operation as shown in Table 6. Considering the voltage limits at the bus, we proceed to simulate both extreme operation scenarios within this range of voltage to see the response of our controller.

Table 6: P and Q values in load C, for normal Voltage operation limits.

	PV curve		QV curve	
Voltage level at bus 8th	MW	MVAr	MW	MVAr
1.05(p.u.)	41.80	35	100	-15,68
0.95(p.u.)	381	35	100	120

• First, we simulate the increase in reactive power without AVR controllers, as we can see in Fig.19, the voltage drops without recovering until the system reaches its new operation point this could take several seconds or even minutes.

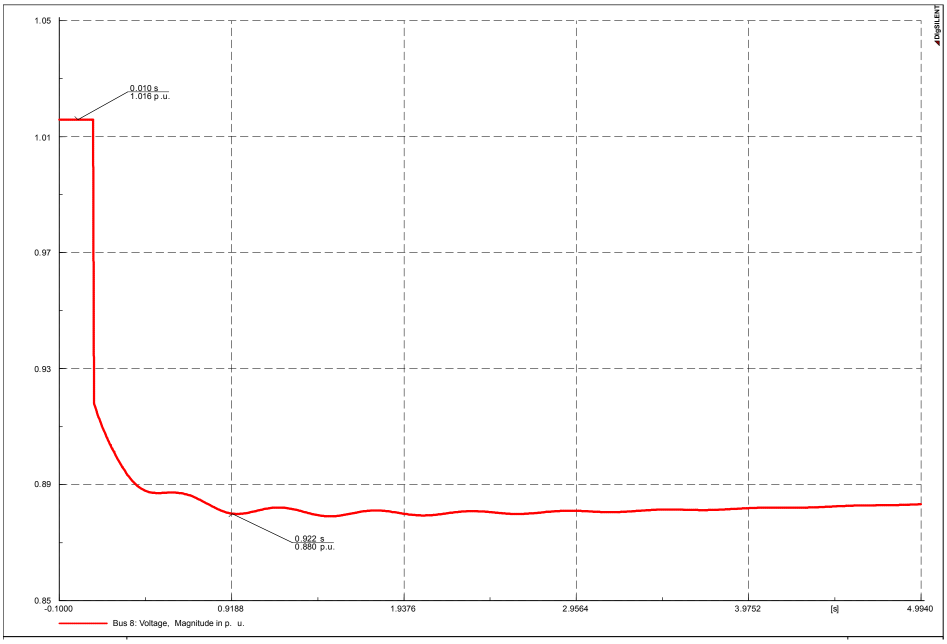


Figure 19: Bus 8th Voltage Magnitude simulating a load event without AVR's

For our purpose we choose to simulate an extreme and severe increase in the reactive power from 35 Mvar to 120 Mvar, to drop the voltage at bus 8th to its lowest operational limit 0.95 p.u.

• Next, as we can see in Fig.20, we run the same simulation but this time activating the AVR's controls

3.2.6 Case 3, Load event 0.95 p.u.,

We choose to simulate an extreme and severe increase in the reactive power from 35 Mvar to 120 Mvar, to drop the voltage at bus 8th to its lowest operational limit 0.95 p.u, when the reactive load at bus 8th is increased to 120 Mvar at 0.1s - load C, the bus voltage decreases from 1.016 p.u. to a minimum value of 0.9 p.u., but this time the controllers are taking action to restore the voltage magnitude to the new operation point, which after just a few seconds is 0.95 p.u. as calculated in the QV curve in Fig.18b, we found that although Ka = 5 works pretty good, by increasing this gain to 20 we get a better response, preventing the voltage from dropping even further. Also, in Fig.20, we validate the response of the two control models we had created for our AVR, the MATLAB control in Fig.7 and the DIgSILENT control in Fig.10, getting the same response for these two models, thus, validating the correct implementation of our excitation system. Although the controllers are working continuously sensing the output voltage of the machine, we can evidence its response as soon as this event takes place; the excitation system in each synchronous machine start increasing the field voltage and current to keep the output voltage of the generator at a stable value Fig.21. That response takes less than 5th seconds to reach a settling time, which it is in the range of accepted response values from [15]. This response must also consider the limits, voltage, current, temperature of the excitation system.

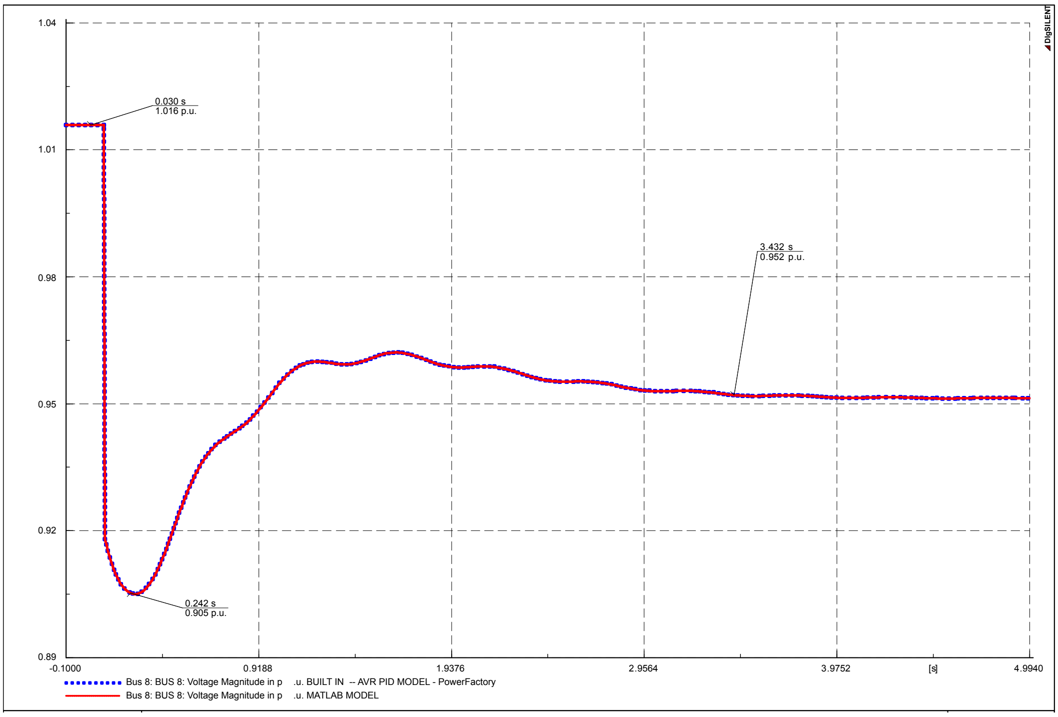


Figure 20: Bus 8th Voltage Magnitude simulating load event with AVRs (Blue - AVR PID MODEL - PowerFactory) (RED - MATLAB MODEL) Case 3.

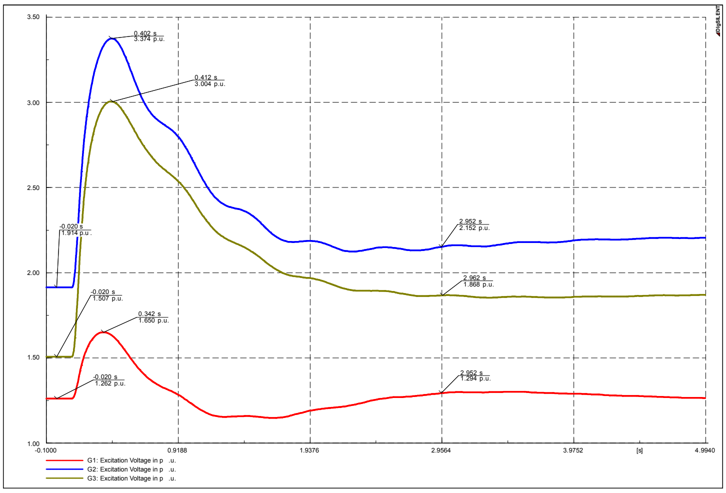


Figure 21: Excitation Voltage Response of the excitation system AVR's G1, G2, G3, for load event Case 3.

The signal U in Fig.22, in each AVR represent the output voltage at the terminals of the generators, which is the signal of major interest for us because represent the variable we are controlling. As we can observe the voltage level decreases at the time of the event, due to the increased demand of reactive power in the system. In this interconnected system, all the synchronous machines experiment this change and each one assumes this increase within its capabilities. As shown in the figure for this severe case the minimum voltage level as well as the settling time response it is within the range for excitation control systems for small signal dynamic performance indices, demonstrating the correct controller behavior.

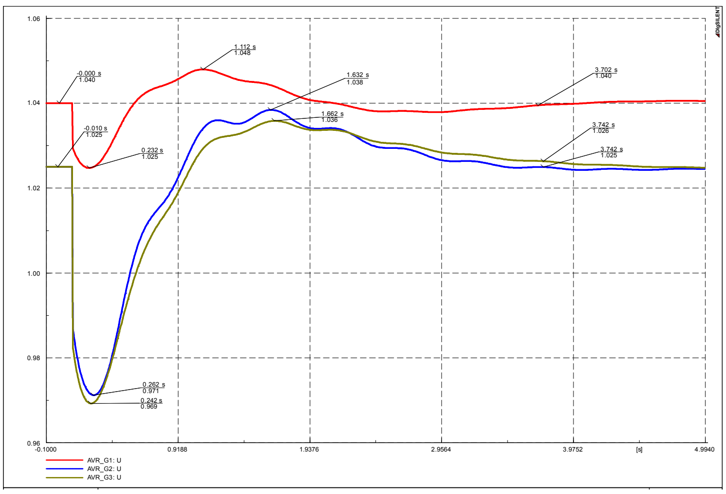


Figure 22: Voltage signal at terminals of the generator U - G1, G2, G3, for load event Case 3.

The signal Uerrs in Fig.23, in each AVR represent the output voltage of the controller before entering in the generator, this voltage level increases at the time of the event, giving the signal that the field voltage and current must be increased to meet the constant setpoint signal Usetp, despite the increase in reactive load on bus bar 8th.

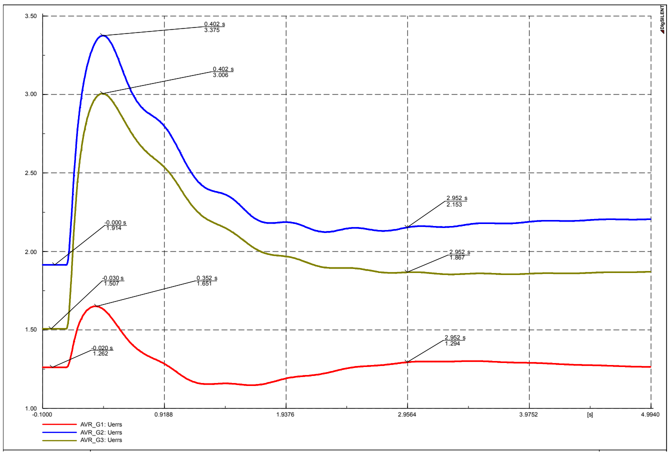


Figure 23: Response signal of the excitation system Uerrs AVR in G1, G2, G3, for load event Case 3.

The signal Usetp in Table 7, in each AVR represent the setpoint or the optimal voltage level of operation for the generator, this voltage value remains constant, and it is a parameter that we set initially as well as the active and reactive power in the synchronous machine.

We must consider the response of the excitation system as well. In this case, after the load event (Case 3) takes place all the synchronous generators start injecting reactive power into the system to maintain its setpoint at the generator terminals. We must take particular care with the limits of the excitation system, ceiling voltage and ceiling current, and the capability curve of the generator. According to Table 7, the excitation system of the generators G1, G2, G3 reaches at some point maximum values of 1.651 p.u., 3.3751 p.u., 3.0058 p.u., respectively from rated values. We most guarantee this or readjust our control system to avoid damage and preserve system stability.

3.2.7 Case 4, Load event 1.05 p.u.,

When the reactive load at bus 8th is injected to -15 Mvar at 0.1s - load C, the bus voltage increases from 1.016 p.u. to a maximum peak value of 1.08 p.u., the AVR controllers are taking action to restore the voltage magnitude to the new operation point, which after just a few seconds is 1.05 p.u. as calculated in the QV curve in Fig.18b.

Now, as shown in Fig.25, we evidence an inverse behavior to the one observed in Case

Table 7: Response Values of the excitation system, for load event (Case 3).

Case 3 Variable	G1 Ve p.u.	G2 Ve p.u.	G3 Ve p.u.
$Usetp$	1.040	1.025	1.025
$Excitation\ Max$	1.651	3.3751	3.0058
$Excitation\ Min$	1.1476	1.9138	1.5075
$Operational\ Capacity$	32.35%	88.66%	69.51%
$Reactive\ Power\ Q$	41.31 MVAr	51.52 MVAr	27.33 MVAr

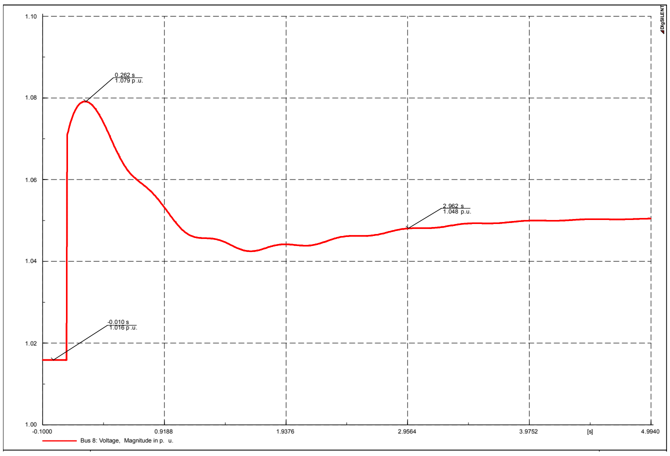


Figure 24: Bus 8th Voltage Magnitude simulating load event Case 4 with AVR's.

3, Fig.21; as soon as event Case 4 takes place, the excitation system in each synchronous machine start decreasing the field voltage and current to keep the output voltage of the generator at a stable value. The synchronous machines are not generating but absorbing the excess of reactive power in the power network and start working under excited. That response takes less than 5th seconds to reach a settling time, which it is in the range of accepted response values from [15]. This response must also consider the limits, voltage, current, temperature of the excitation system.

The signal U in Fig.26, in each AVR represent the output voltage at the terminals of the generators. As we can observe the voltage level increases at the time of the event, due to the decrease in demand of reactive power in the bus 8th and in the system in general. All the synchronous machines experiment this change and each one assumes this decrease within its capabilities, absorbing or generating reactive power to maintain its bus voltage at the setpoint. As shown in the figure for this severe case the maximum voltage level as well as the settling time response it is within the range for excitation control systems for small signal dynamic performance indices, demonstrating the correct controller behavior.

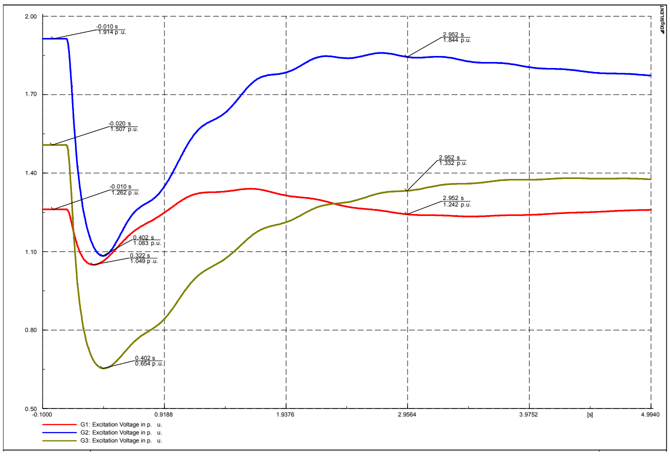


Figure 25: Excitation Voltage Response of the excitation system AVR's G1, G2, G3, for load event Case 4.

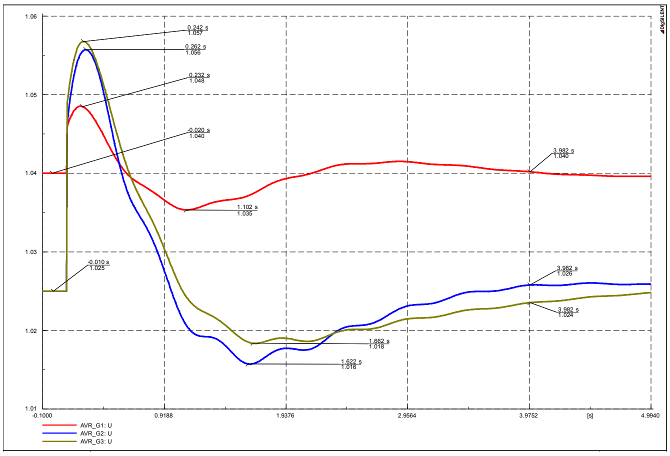


Figure 26: Voltage signal at terminals of the generator U - G1, G2, G3, for load event Case 4

The signal Uerrs in Fig.27, in each AVR represent the output voltage of the controller before entering in the generator, this voltage level decreases at the time of the event, giving the signal that the field voltage and current must be decreased to meet the constant setpoint signal Usetp.

The signal Usetp in Table 8, in each AVR represent the setpoint or the optimal voltage level of operation for the generator, this voltage value remains constant as we set it initially when modeling the power system. Now, let us analyze the response of the excitation system after the load event (Case 4) takes place. G1 continues injecting reactive power, while G2 and G3 starts absorbing the reactive power excess to maintain its setpoint at the generator terminals. According to Table 8, the excitation system of the generators G1, G2, G3 reaches at some point maximum values of 1.3403 p.u.,

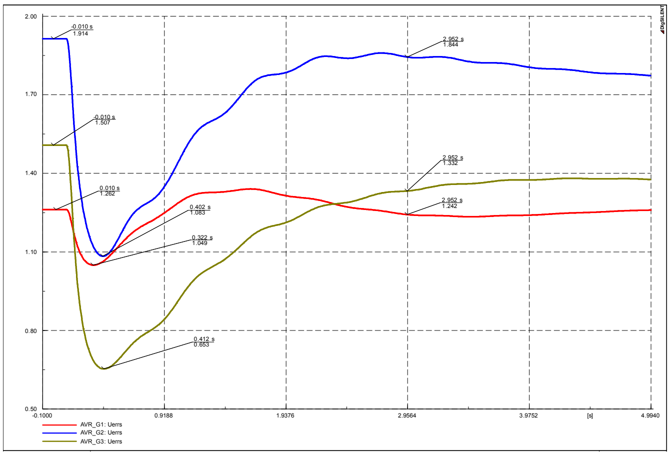


Figure 27: Response signal of the excitation system Uerrs AVR in G1, G2, G3, for load event Case 4

1.9138 p.u., 1.5075 p.u., respectively from rated values, but this time G2 and G3 are under excited to consume the excess of reactive power. We most guarantee this limit or readjust our control system to avoid damage and preserve system stability, especially in G3 where the minimum excitation voltage arrives to 0.6532 p.u.

Table 8: Response Values of the excitation system, for load event (Case 4).

Case 4 Variable	G1 Ve p.u.	G2 Ve p.u.	G3 Ve p.u.
$Usetp$	1.040	1.025	1.025
$Excitation\ Max$	1.3403	1.9138	1.5075
$Excitation\ Min$	1.0492	1.0834	0.6532
$Operational\ Capacity$	30.78%	85.50%	70.96%
$Reactive\ Power\ Q\ (Mvar)$	19.30	-16.86	-31.52

4. CONCLUSIONS

The design and tuning of an AVR were successfully carried out with a PID controller for the described power system and under the proposed methodology. Tests were carried out on this under small-signal simulations, which are necessary to study the dynamic response of the system, evidencing the fulfillment of basic parameters named in [15] for excitation systems. We comply with basic parameters based on transient response characteristics such as rise time, overshoot, peak time, settling time, among other characteristics evaluated, and represented in the result tables 3 y 4. Bearing in mind that the values in the guide are reference values and may vary depending on the system and its components.

By changing the controller gain from Ka=5 to Ka=20, we got a better controller response; this can be further increased. However, it should be borne in mind that by increasing or decreasing this, we observe how the system, although it tends to be faster, becomes unstable, in Fig.28, its shown the oscillatory response when increasing ka=100.

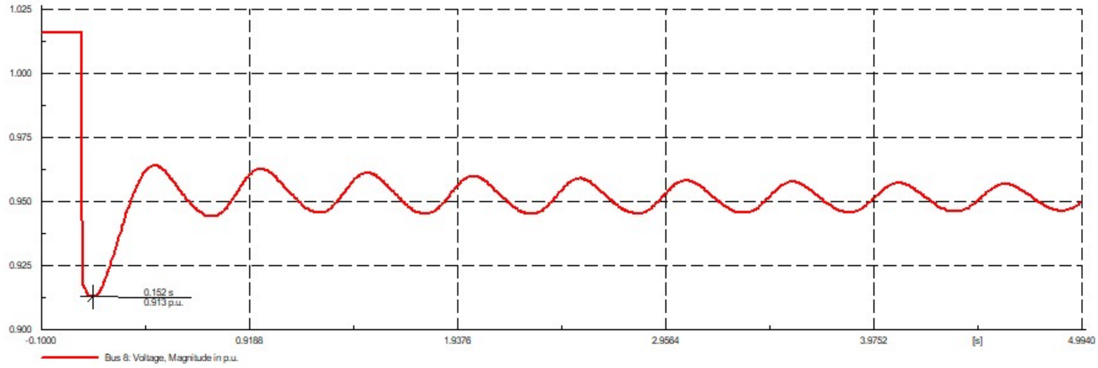


Figure 28: Bus 8th Voltage Magnitude simulating the same load event case 3, increasing the gain to Ka=100.

Currently, there are many standardized models for excitation systems, like those mentioned in [21]; however, the adjustment or identification of the system parameters will always be required. The implemented methodology is then presented as a possible solution as evidenced in this study works correctly for this system and can be used to study other control systems that involve power systems, such as the speed regulator in the generator, or to model other kinds of dynamic control systems. It can also be used for the identification of parameters in a control system.

Co-simulation thus proves to be a useful tool to carry out these types of studies, especially those where the use of various specialties or domains are involved, where there is software that stands out independently, but that, by working all together can deliver great results.

Finally, for the final acceptance of this type of control system, field tests are still necessary and required to complete the tuning process of the controller. In addition, it is required to complement the studies with other tests such as large-signal stability evaluating other cases of real operation, to meet the requirements of each operator of the electrical power system.

As future work, it is proposed to simulate and analyze the system by adding other esential control components such as the speed regulator- governor(frequency control), and a Power system stabilizer PSS with the aim to improve even further the stability of the power system. Modal analysis - Eigenvalues analysis is also propose as future work to analyse the oscillations of the power system.

5. ACKNOWLEDGEMENT

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