Bangladesh University of Engineering and Technology

Department of Electrical and Electronic Engineering

Course no.: EEE 206
Course Title: Energy Conversion Laboratory

Design of a regulation and feedback control system for a synchronous generator with Simulink

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Project Introduction

Our project utilizes built-in Simulink models to regulate steady state operation of a synchronous generator which is connected to several types of loads. By using multiple feedback systems, we control the governor set points and other operating parameters of the synchronous generator to regulate it and keep close to the normal rating values.

We modeled the loads as a typical power consumption system. The following variables are monitored using several sensors and used in regulating with proposed feedback control system

- Line voltage
- Line frequency
- Power factor

By monitoring aforementioned variables in a dashboard, we change following parameters to regulate the system –

- Governor's set points
  - Torque of the prime mover
  - Speed of the prime mover's rotation
- Excitation/Field current
- Capacitor Bank Switch
- Power Overload Toggle Switch

In our project, we have used a 'Synchronous Machine Round Rotor' Simulink model which has 555 MVA rated power, $60Hz$ rated frequency, $24kV$ rated line voltage. We chose the solver type 'Backward Euler Method', and sample time $1ms$ with discrete simulation mode.

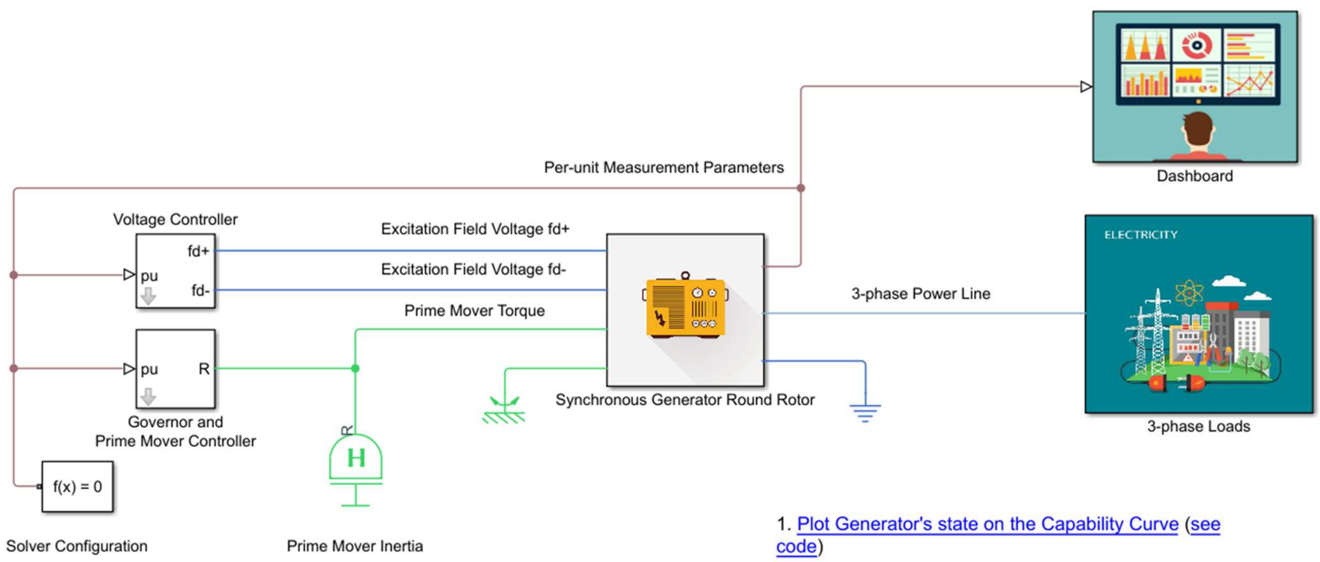
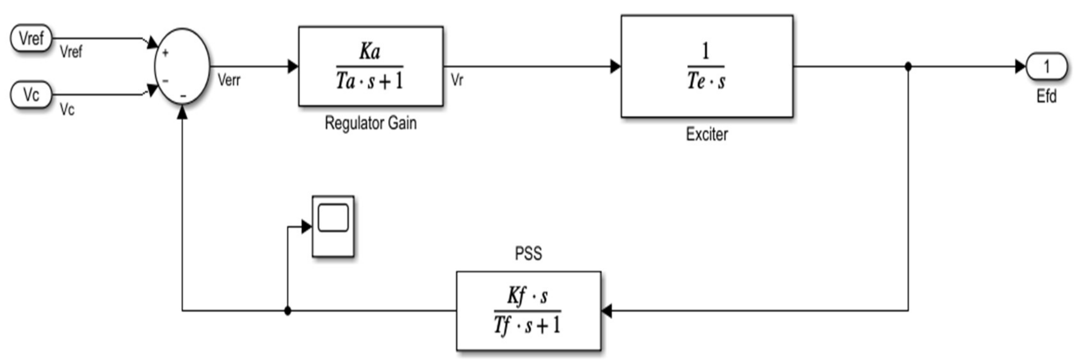


Figure 1: Schematic Diagram of the main project page

Terminal Voltage Controller

While the generator is operating at rated voltage, then sudden load change may significantly reduce or increase the terminal voltage which is not desirable. That's why we need voltage regulation to keep the voltage to rated value even if the load varies. To control the terminal-voltage with the changing loads we have implemented **"Excitation System"**. The main components of an excitation system are automatic voltage regulator (AVR), exciter & system stabilizer.

Physical signal from the generator is converted to the Simulink signal by PS-Simulink Converter. Then V_T (terminal voltage) is sensed and is usually reduced to a dc quantity. For that purpose, we are using a transducer. A Voltage Transducer gives DC current or voltage output that is proportional to the AC input voltage. It can be represented by a single equivalent time constant, Tr (Terminal voltage sensing time delay). Generally, this time constant is very small & the transfer function $\frac{1}{1+Tr*s}$ represents voltage compensation, ac to dc rectification and also filtering process altogether. Output of the transducer, Vc is the principal input to excitation system & the reference voltage is also passed as an input. Reference voltage input is 1pu as it's the desired rated voltage. The excitation model is basically designed on the basis of IEEE standardized dc excitation model DC1A.



Voltage regulator gain Ka and time constant Ta
Exciter Time constant Te
Stabilization feedback gain Kf and time constant Tf
PSS= Power System Stabilizer

Figure 2: Functional Diagram of the Voltage Controller

In the exciter model V_C is subtracted from the set point reference, V_{ref} & also the stabilizing feedback signal Vf is subtracted to produce an error signal, Verr. Our main purpose is to reduce this error so that terminal voltage can hold a stable value near the reference voltage. The error is amplified (can be amplified by a magnetic amplifier, rotating amplifier, or electronic amplifier) & the amplifier is represented by its gain Ka and a time constant Ta & the transfer function is

$\frac{Ka}{1+Ta*s}$ .The voltage regulator output Vr is used to control the field voltage Efd with a time constant Te. A signal derived from generator field voltage is normally used to provide excitation system stabilization (Vf) via the rate feedback block with gain Kf and time constant Tf. Finally, the Physical Signal or the field voltage, Efd is used as an input in the built-in Synchronous Machine Field Circuit from which we can get fd+ and fd-, the field voltage inputs of the synchronous generator.

How Regulator works:

If the voltage decreases below the preset level, then the produced error voltage is positive. The AVR boots the power to the exciter rotor by amplifying the error voltage which is in turn passed through the rest of the excitation system and results in an increase in terminal voltage. If the voltage at the terminals increases above the preset level the AVR reduces the power, having the opposite effect.

Why Feedback Stabilization?

While using AVR such a quick recovery of the generator terminal voltage will force a negative effect on the damping. Power system stabilizer (PSS) is used in synchronous generator excitation control system for damping electromechanical oscillations. The effect of time delays on the stability of a generator excitation control system compensated by time constant Tf. Considering the time delay existence between the output signal Vf and the control signal Vc, Tf is modelled. In most designs Tf=10Ta and the stabilizer is modelled by the transfer function $\frac{Kf*s}{1+Tf*s}$.

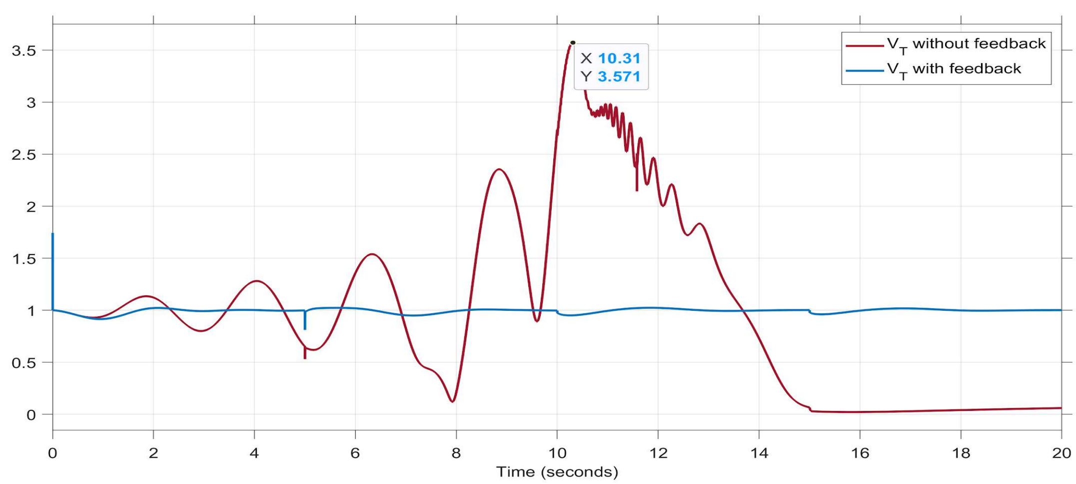
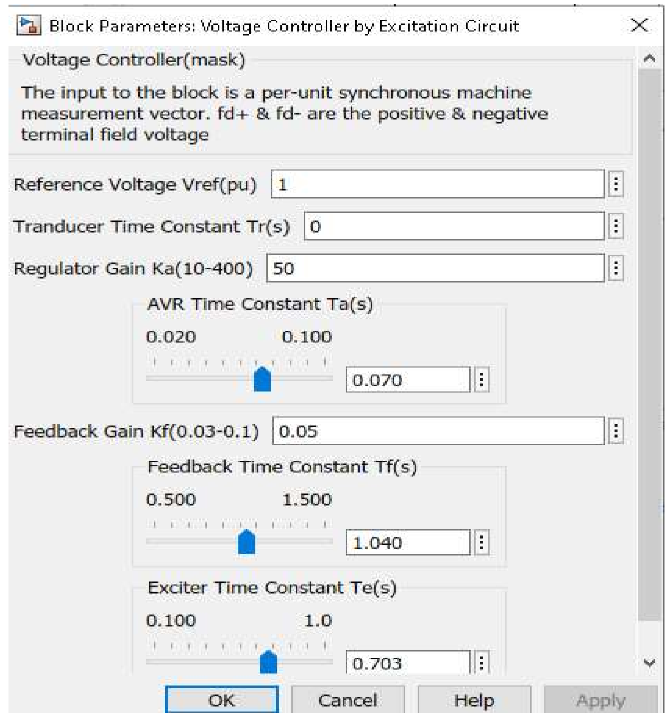


Figure 3: Terminal voltage profile with & without Feedback

In the graphs we can see, for increasing lagging load terminal voltage shows too much oscillation without the feedback stabilizer while the controller with feedback block damps out the oscillations and keeps the voltage near the reference value. Without feedback, the peak of oscillation becomes 3.571 times the rated value & finally it becomes close to zero due to increasing lagging conditions.

All the gain & time constant parameters are taken as inputs in the masking system and these values are provided according to “IEEE Recommended Practice for Excitation System Models for Power System Stability Studies IEEE volume 421 chapter 5”.



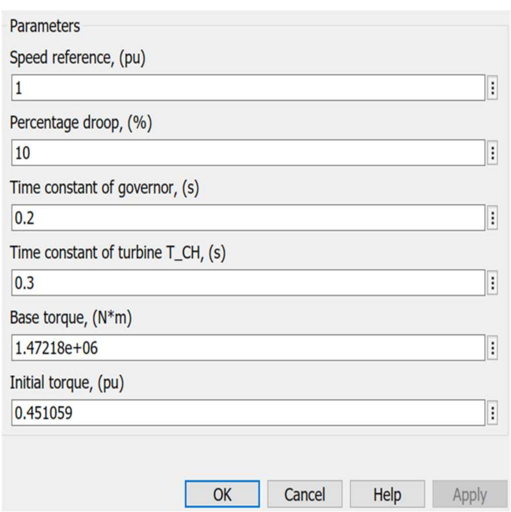


Figure 4: Parameters this sub-blocks takes

Frequency Controller

All prime movers have a characteristic droop behavior in speed as load torque on its shaft is increased. This droop tendency directly affects the output electrical frequency which is undesirable. A governor mechanism is implemented in the **Governor and Prime Mover Controller** sub-block which will adjust the torque output of the prime mover as a response to the increasing electrical load. Our input signal to this block is the per unit rotor velocity – which directly correlates to electric line frequency– and output signal is the Physical Simulink torque signal.

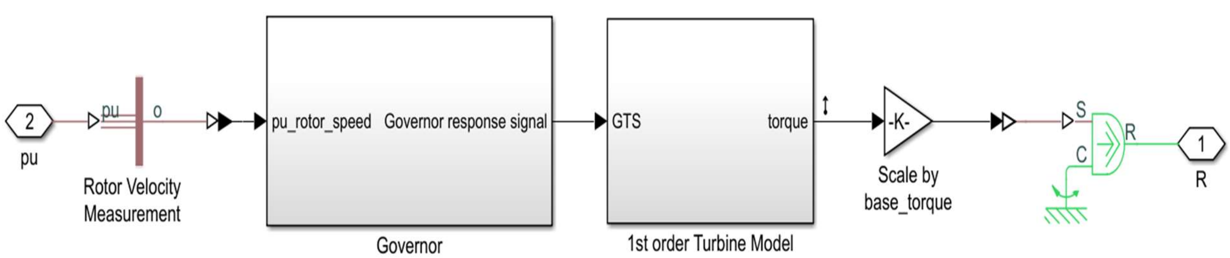


Figure 5: Higher level functional diagram of the sub-block

Governor Controller

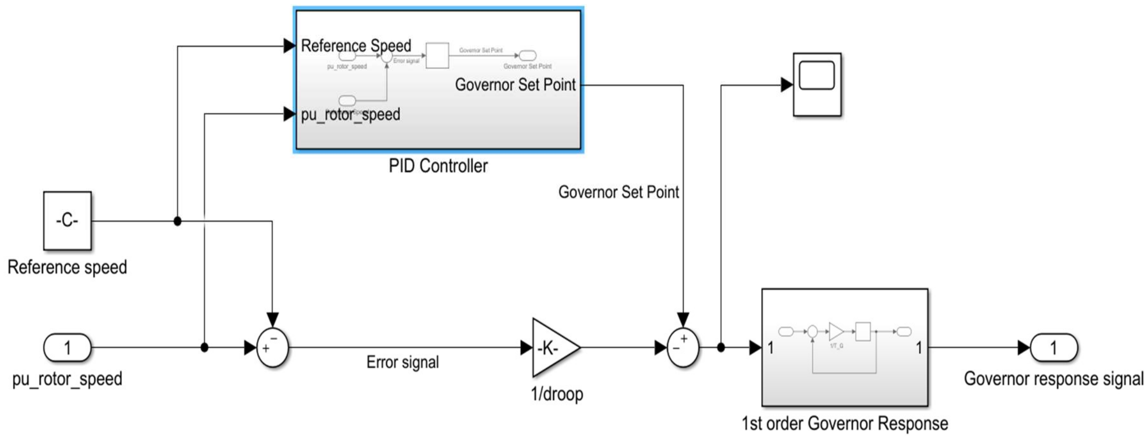


Figure 6: Functional diagram of governor controller

Following the basic concept of a feedback loop PID controller, inside this Governor Controller, we passed the error signal into the Simulink discrete PID controller, whose parameters we tuned with an in-built auto-tuner. The input signal –whose strength determines the torque applied on the shaft– enters the governor response subsystem , $G_{input} = G - \frac{\omega_{error}}{droop}$. If the droop percentage is low from a given user, then G_{input} will decrease, meaning a low regulation is needed to maintain the line frequency.

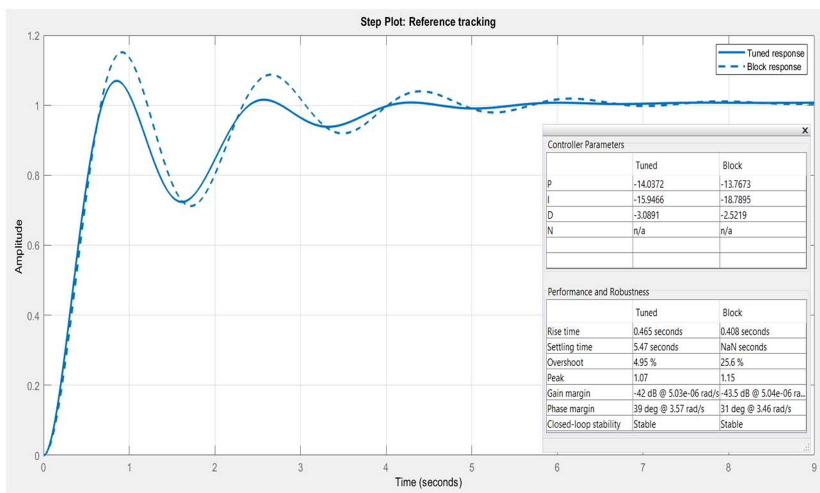


Figure 7: Step Response of PID controller

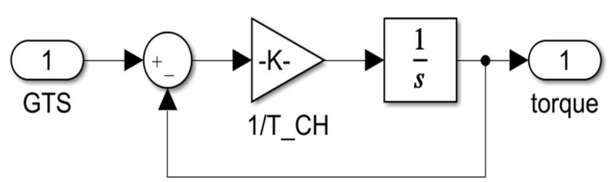
The governor response is modelled by a 1^{st} order transfer function with characteristic time constant.

$$\frac{G_{input}(s)}{G_{putput}(s)} = \frac{1}{1 + sT_G}$$

Turbine

The next block is just a simplified physical model of a turbine, which is defined by the transfer function –

$$\frac{Turbine_{input}(s)}{Turbine_{putput}(s)} = \frac{1}{1 + sT_{CH}}$$



As a comparison, we added a $0.02\ pu$ active load at $t = 20s$ and $t = 30s$ gradually, and better regulation of per unit rotor speed, ω_m, with the governor controller is quite evident, with only a tiny transient damped oscillation. We used $0.28\ pu$ shaft torque for constant governor set point.

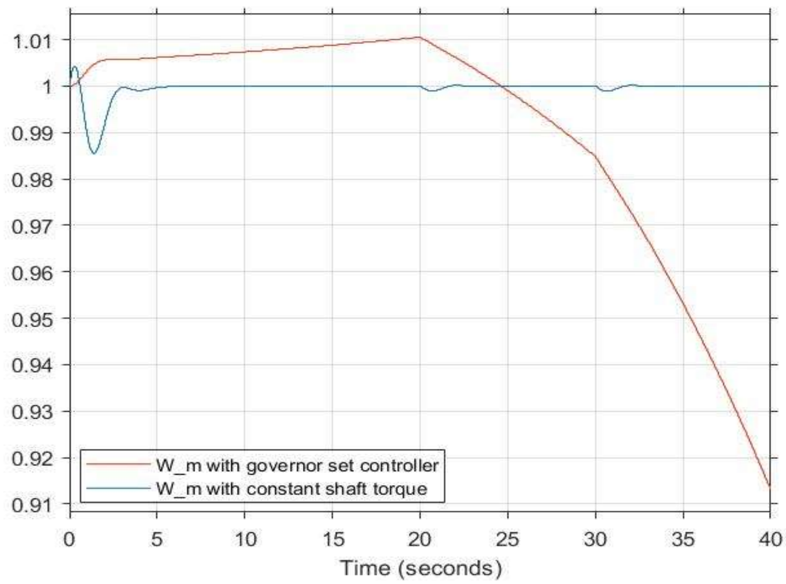


Figure 8: Per-unit Rotor Speed with and without Governor Set Controller

Synchronous Generator Block

In the **Synchronous Generator Round Rotor** subsystem, we have used Synchronous Machine Round Rotor Simulink model as our model generator. In this block, we have added a power factor correction block with a simple MATLAB function, which connects the capacitor bank to the circuit when the power factor of the system drops under lagging 0.9 and remains in that condition for at least 1 second so that this bank improves the power factor.

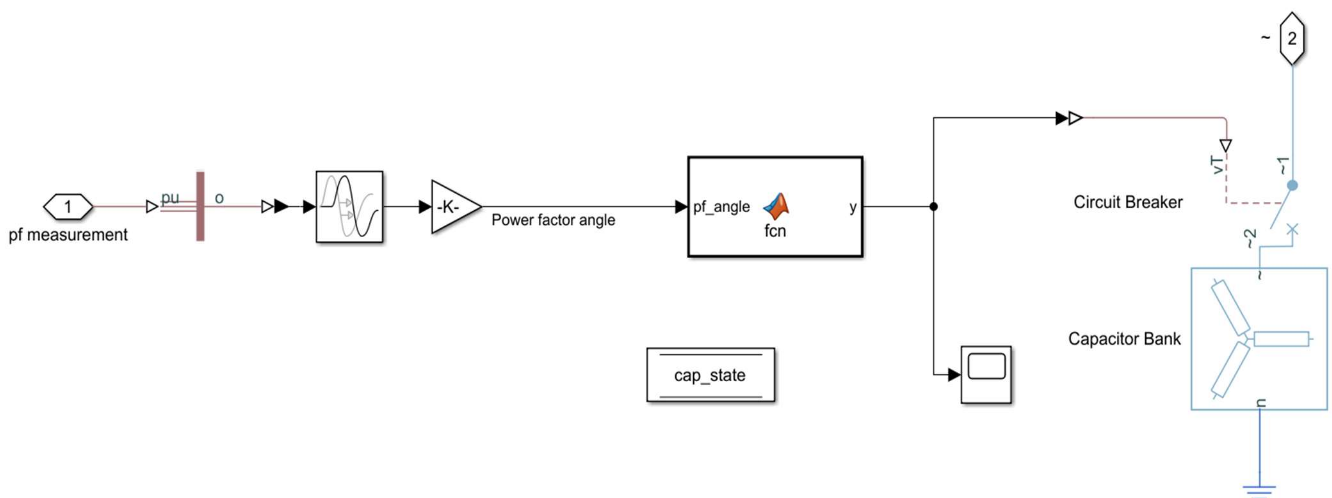


Figure 9: Power Factor Correction Sub-block

There is also a circuit breaker which disconnects the generator from the system in case of overload.

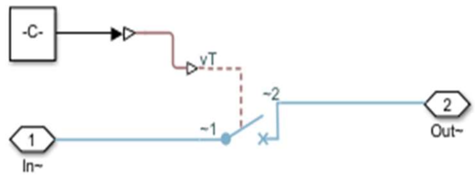


Figure 10: Voltage Controlled Circuit Breaker

MATLAB Function:

```
function y = fcn(pf_angle)


global cap_state;
global cut_off_pf;

cut_off_angle = acos(0.9)*180/pi;

if(cap_state == 1)
    if(pf_angle > cut_off_angle)
        cap_state = 0;
    end
else
    if(pf_angle < 0)
        cap_state = 1;
    end
end

y = cap_state;
```

3-Phase Loads

In the **3-Phase Loads** sub-block, a combination of seven types of loads were created. The initial 0.27pu real load that is connected to the generator is always active. Then depending on the user's choice, different types of loads can be connected to the generator. The load types are:

1. Increasing Unity: A load with unity power factor and increasing magnitude (VA)
2. Increasing Leading: A fully leading load with increasing magnitude (VA)
3. Increasing Lagging: A fully lagging load with increasing magnitude (VA)
4. Leading to Lagging: A load with increasing power factor.
5. Lagging to Leading: A load with decreasing power factor.
6. Varying Load: A load which VA is changing over time.
7. Overload: A load bigger than the rated load.

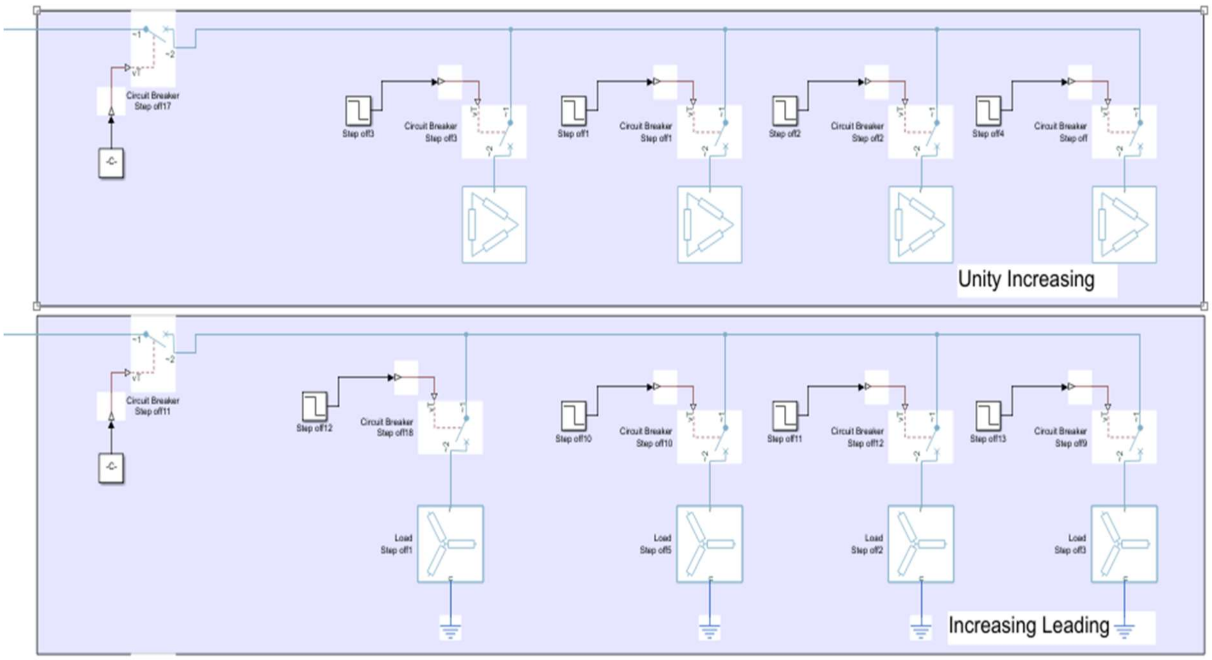


Figure 11: Sample Designed Loads in the 3-phase Loads Sub-block

When the user selects an option, a switch to that type of load is connected, while other loads remain disconnected. Switching technique is used to connect the load to the generator. Delta connected loads are used as loads. For leading loads, grounded Y connected loads have been used. A step signal is fed into an electronic switch to connect/disconnect a load to the generator. The step signals have different step times. Usually the load changes when t=10,15,20,25 seconds. The loads increase and decrease but never exceed the rated load (except the overload). The loads have been modeled such that they always consume a constant level of real and reactive power. A mask has been created so that the rated frequency, terminal voltage and frequency for the load can be customized by the operator.

Result Analysis

To demonstrate the results together and in real time, a dashboard is added to the system to display the per unit measurements through various graphs and gauges.

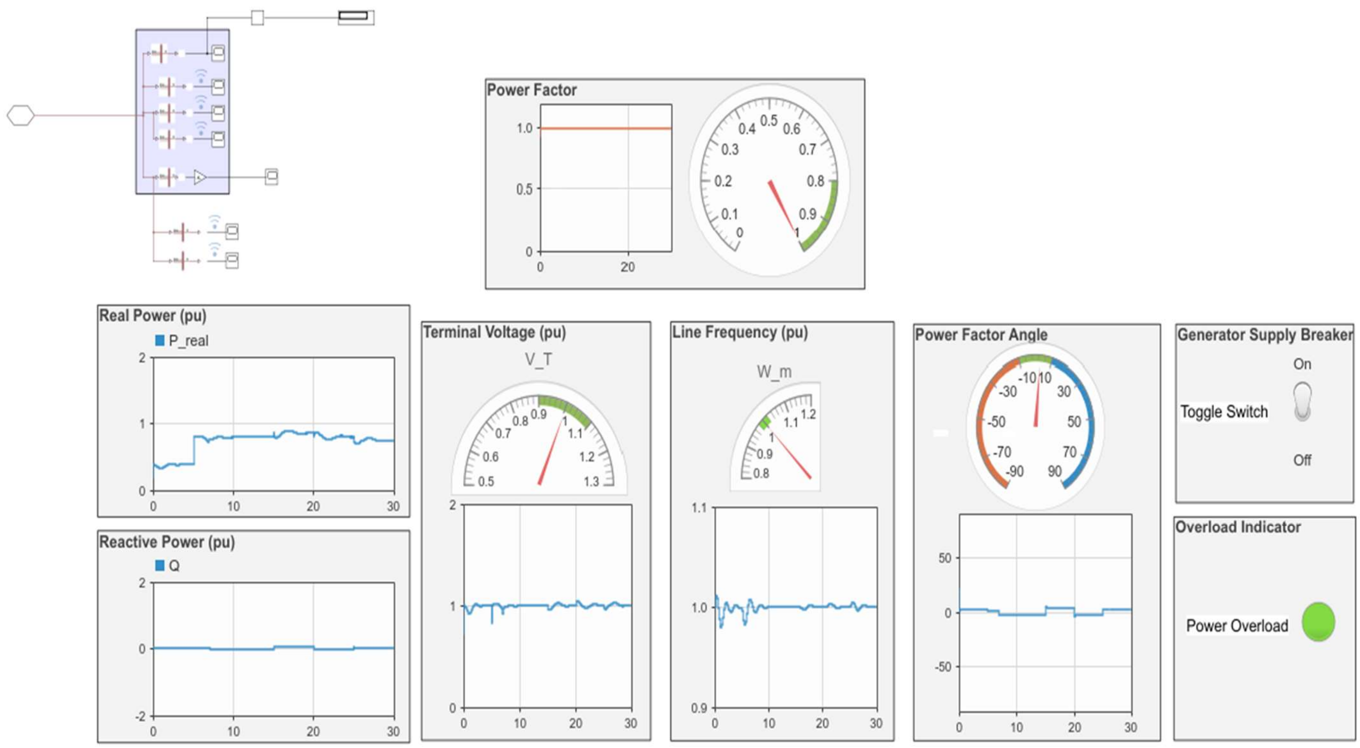


Figure 12: Synchronous Generator Control System Dashboard

When the generator is connected to a varying load (a representation of practical situation), the terminal voltage and frequency changes with load changes at 5,7,15,20 and 25 seconds. But the excitation system keeps them near desired level.

From the graph, it can be observed that the voltage and frequency went through fluctuations, but after a oscillatory transient, it came back to its initial steady state. Change of line frequency is a harmful thing to happen in a power system but our excitation system kept the frequency to the rated level (1-pu).

Also, while adding heavy loads, terminal voltage changes heavily. At 5 sec, 0.4pu load was connected to the generator, that caused the terminal voltage to drop by 17%. But within several seconds the excitation regulation system brought it back to rated level.

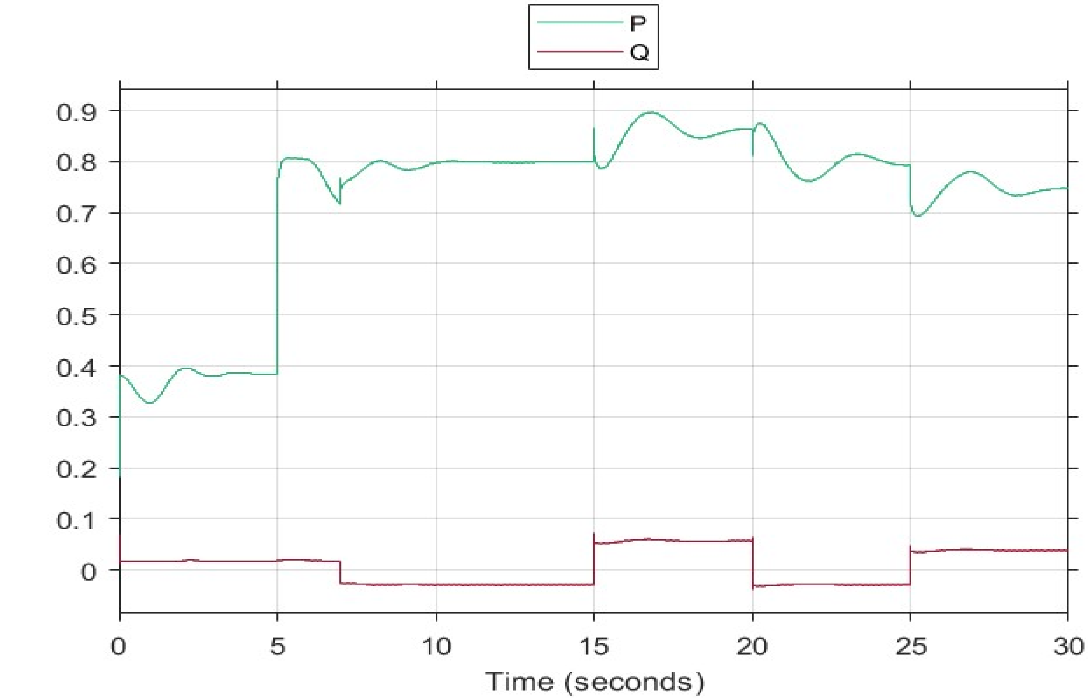


Figure 13: Per-unit Real and Reactive Power

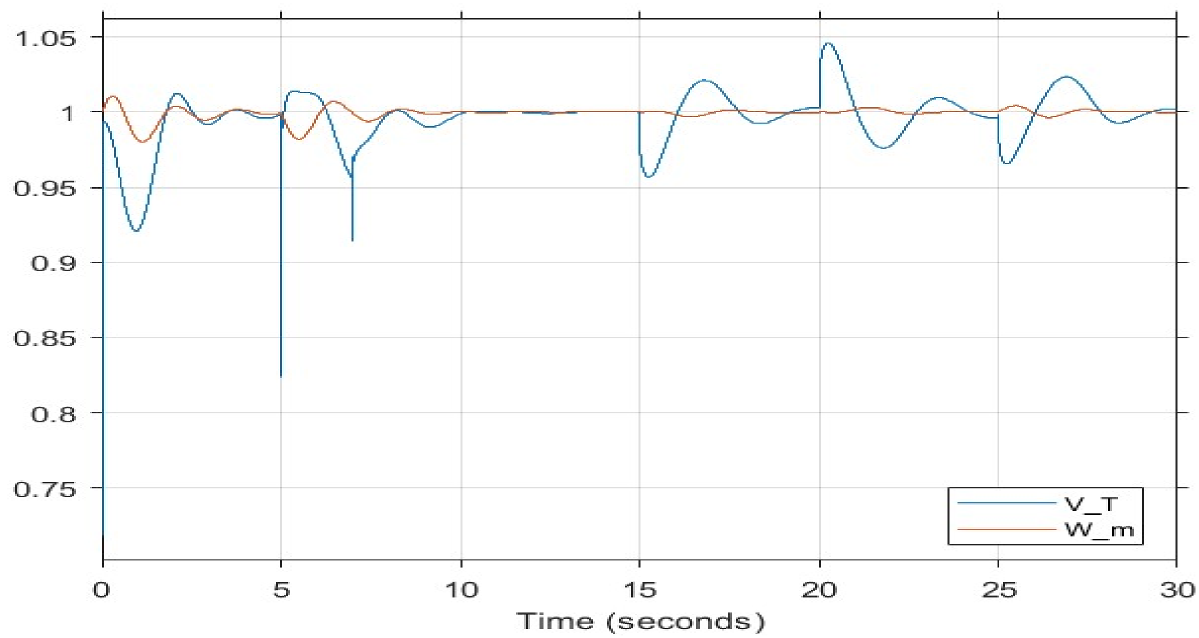


Figure 14: Per-unit Terminal Voltage and Line Frequency Profile

When the power factor of the load drops below 0.9 lagging, a capacitor bank corrects the power factor. A capacitor bank supplying 10% of the rated VA corrects the power factor so the power factor improves by 10%.

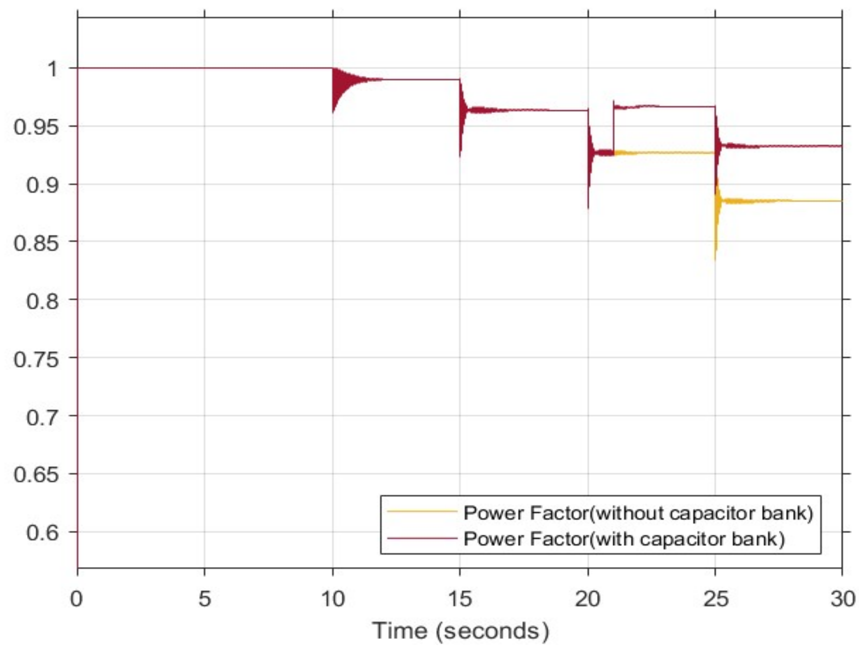


Figure 15: Power Factor Profile with and without Capacitor Bank

We have also generated the capability curve of the generator from model parameters (taking generator impedance $X_s = 1.81\ \Omega$) and plotted the corresponding states of the generator over various points in time with overloaded condition.

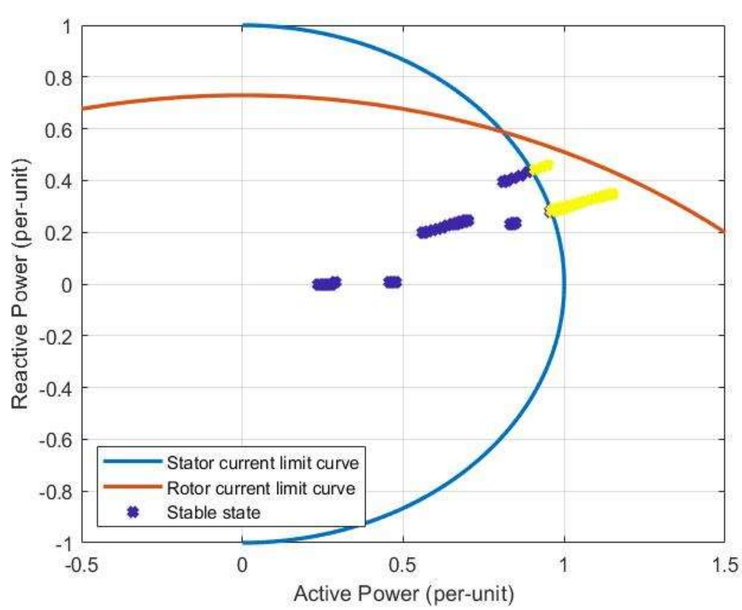


Figure 16: Capability curve (Yellow dots - unstable state, Blue dots - Stable state)

Conclusion

Goal of our project was to design regulation and feedback control systems of a synchronous generator. By using Simulink, we have tried to show how a generator stabilizes with changing load. This project of ours can be implemented in practical life. However, we have used a circuit breaker so that the generator disconnects when there is overload. So, in case of loads higher than the rated load, this generator will be disconnected. We were unable to design parallel operation of synchronous generators due to limited time. Also, we have considered seven types of load in this project. But among these loads, varying load is the most practical one. In case of increasing lagging load, the starting value of terminal voltage is around 1.8pu, which is quite higher than the rated terminal voltage (1pu). We have been unable to remove this extra value. Overall, it can be said that our project was successful with minor errors.