ME 598 Report

Modelling of Generator system in Simulink

Primary Author:	Siddharth Rajagopal
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UNIVERSITY of WASHINGTON

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I. Introduction

An electric generator system with a series hybrid vehicle configuration has been implemented in the UW EcoCar 3 Camaro. This setup uses an electric generator that converts mechanical energy received from the IC Engine to electrical energy. The electrical energy generated is stored in batteries which is then used to drive the motors that move the wheels.

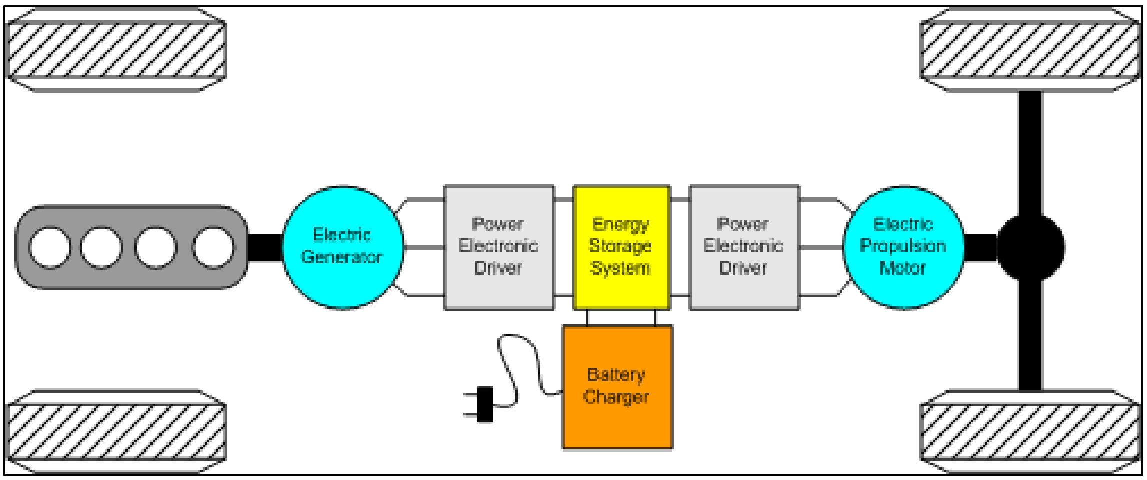
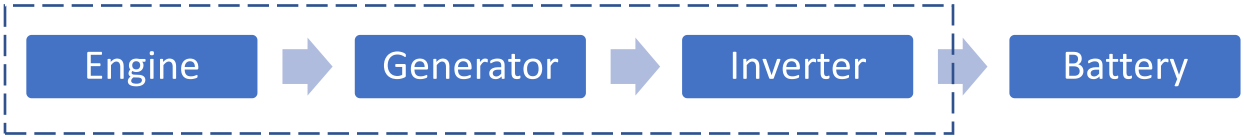


Figure 1 : Series hybrid vehicle set-up [1]

In this research project, a simplified mathematical model of the actual generator system is made and implemented using Simulink for simulation. The resulting outputs of this simulation are used for further analysis of the model.

The significance of such a model is that it helps in offline-analysis of the generator system without making actual changes on the vehicle. It helps in predicting the results that the actual system would perform thus can significantly reduce the testing time on the vehicle. The scope to modify the model with by adding extra components in Simulink aids in implementing desirable properties to the system.

II. Actual Model



a. IC Engine:

The car uses a 0.8L IC Engine that has been procured from the *Honda VFR 800* motorcycle. The stock fuel system has been modified to run on E-85 as fuel. The injector map and timing has been modified to compensate for the change in fuel and air-fuel ratio. Thus, the output characteristics will be different from the stock engine.

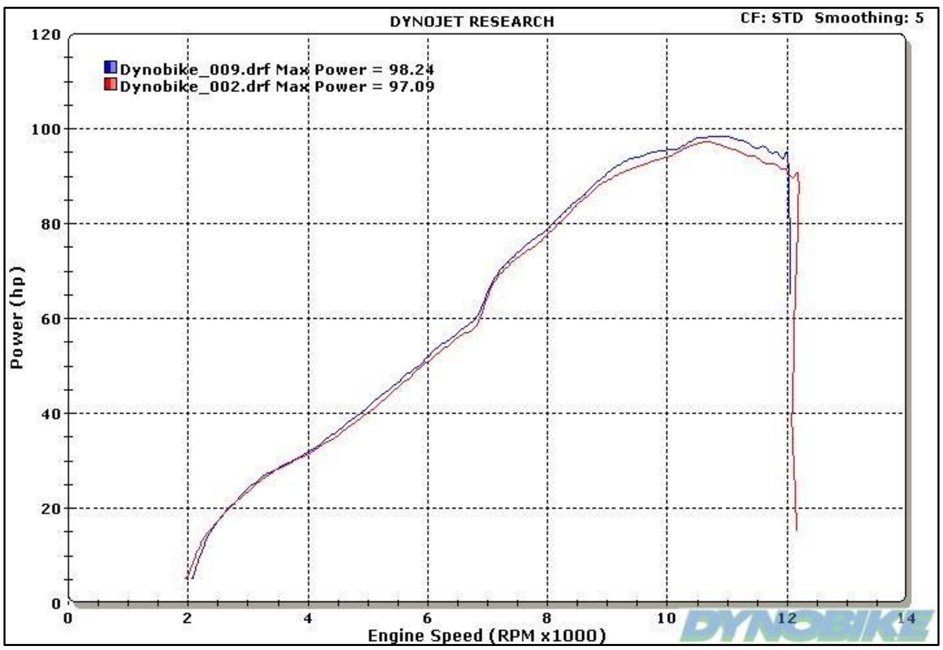


Figure 2 : Sample dyno jet graph of stock engine before fuel system change [2]

The peak torque from engine is around 77 N-m at 10,500 rpm. The output of the engine is coupled to the stock gear box in the Honda VFR 800 and is permanently engaged in the 4th-gear. The gear ratio of the 4^{th}-gear is 1.291 [9].

b. Generator:

Bosch Separated Motor Generator 180 is coupled with the IC engine. It works on the principle of permanent magnet synchronous generator. A 3-phase voltage output is generated.

The *figure 3* shows the basic construction of a synchronous generator which has a wound salient two-pole rotor. This rotor winding is connected to a DC supply voltage producing a field current. The external DC excitation voltage produces an electromagnetic field around the coil with static North and South poles. When the generator's rotor shaft is turned by the IC engine, the rotor poles will also move producing a rotating magnetic field as the North and South poles rotate at the same angular velocity as that of engine output, (assuming direct drive). As the rotor rotates, its magnetic flux cuts the individual stator coils one by one and by Faraday's law, an EMF and therefore a current is induced in each stator coil. In a permanent magnet synchronous generator (PMSG), the excitation field is created using permanent magnets in the rotor.

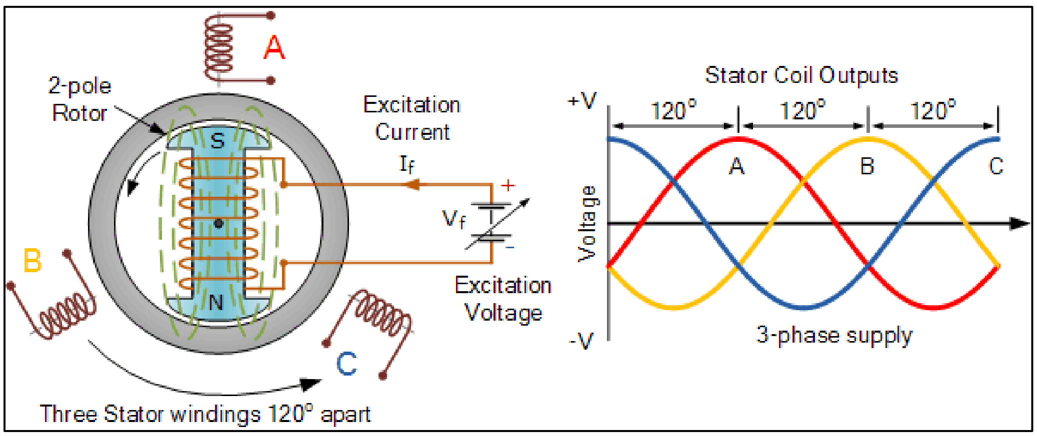


Figure 3 : Basic construction of a Synchronous Generator [3]

c. Inverter:

The 3-phase DC output of the generator is connected to a Bosch INVCON giving a 2-phase DC output which can then be stored in the battery.

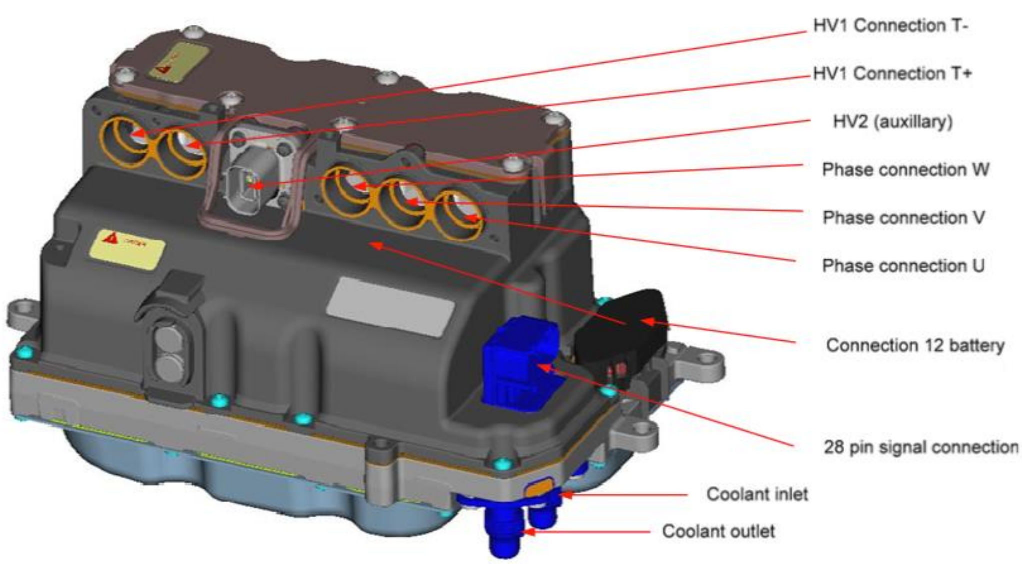


Figure 4 : Physical model of the inverter

III. Mathematical Modeling

The paper by *P. Pillay et al.*[4] provides a modeling procedure and analysis of a 3-phase permanent magnet synchronous motor drive. An equivalent circuit representing a 3-phase permanent magnet synchronous motor by *Dehkordi et al.* [5] presents the following traditional dq0 approach :

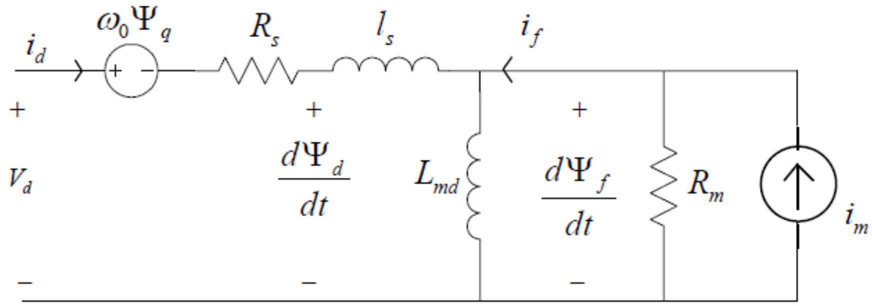


Figure 5a: dq0 Equivalent circuit model of the PMSM - D axis

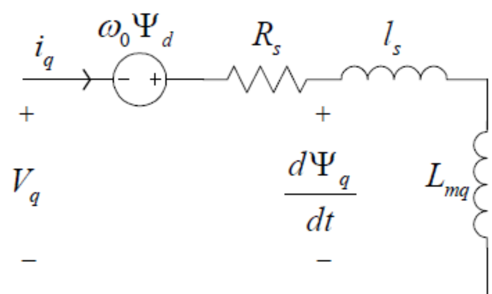


Figure 5b: dq0 Equivalent circuit model of the PMSM - Q axis

The equations for the dq0 model of the Permanent Magnet Synchronous Machine are:

$$\frac{d\Psi_d}{dt} = V_d - R_s i_d - \omega\Psi_q$$

$$\frac{d\Psi_f}{dt} = R_m i_m - R_m i_f$$

$$\frac{d\Psi_q}{dt} = V_q - R_s i_q + \omega\Psi_d$$

$$\begin{bmatrix} \Psi_d \\ \Psi_f \\ \Psi_q \end{bmatrix} = \begin{bmatrix} L_s + L_m & L_m & 0 \\ L_m & L_m & 0 \\ 0 & 0 & L_s + L_m \end{bmatrix} \begin{bmatrix} i_d \\ i_f \\ i_q \end{bmatrix}$$

d , q and f are notations representing the direct axis, quadrature axis and field respectively. R_s is the armature resistance. i_m is the current source from the rotor magnet located at the stator direct axis. R_m is the resistance connected across the direct-axis mutual inductance L_{md}. L_{mq} is the mutual inductance of q-axis. The leakage between d and q axis is given by l_s. ω represents the angular velocity. Ψ is the magnetic flux.

To use the 3-phase models by *P. Pillay et al*.[4] and *Dehkordi et al.*[5] and for simulation, the mutual inductances of the axes and flux are required, which are not readily available. Therefore, a simpler approach is implemented by using a single-phase DC generator equation assuming that it would also include the inverter system.

Simplified DC Generator Model:

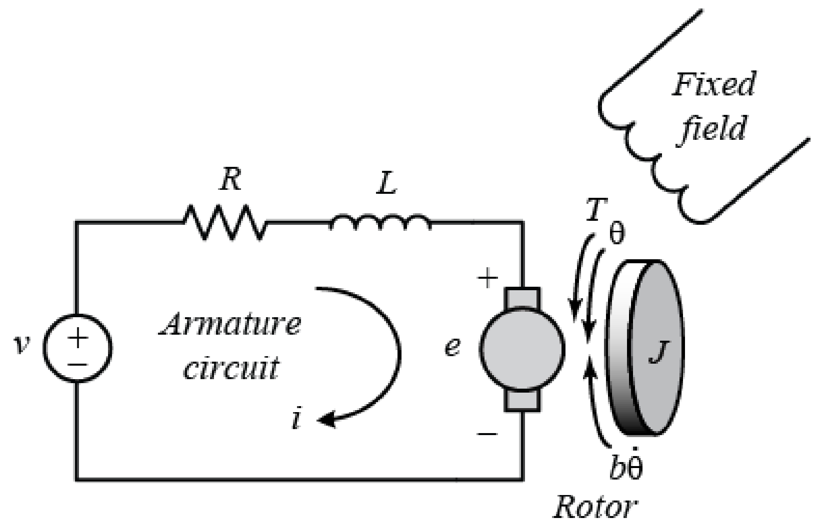


Figure 6: Electric circuit of the armature and free-body diagram of the rotor [6]

The differential equation governing the electrical characteristics of the electrical characteristics is derived based on study of papers by *J. S. Mayer et al.* [7] and *M. Fazil et al.*[8]

The armature current and the strength of the magnetic field is proportional to the torque input T_{in} to the DC generator. The magnetic field is assumed to be constant and, therefore, that the generator torque is proportional to only the armature current i by a constant factor K_t as shown in the equation below.

$$T_{in} = K_t \, i$$

From Newton's Second Law, the following governing equation is obtained,

$$J\ddot{\theta} + b\dot{\theta} = K_t \, i$$

where,

$\dot{\theta}$ = ω = angular velocity of the rotor shaft
b = motor viscous friction constant
$\ddot{\theta}$ = angular acceleration of the rotor shaft
J = moment of inertia of rotor

The current output is requested from the generator system by applying a load torque T_L on the generator. This load torque is applied on the rotating rotor by drawing energy from the battery in the direction opposite to the rotor's rotation. Since the torque T_{in} is greater than T_L, a reverse current i flows opposite to the direction of the applied battery current and thus charges the battery. So the set-up in *figure-5* is further modified to,

$$J\ddot{\theta} + b\dot{\theta} = T_{in} - T_L$$

The power generated is assumed to be proportional to the load torque applied,

$$P = T_L\dot{\theta}$$

The current generated can be obtained by dividing the power by the assumed constant voltage across the bus,

$$i_{out} = \frac{P}{V}$$

IV. Implementation in Simulink

a. Model of the IC engine and gearbox

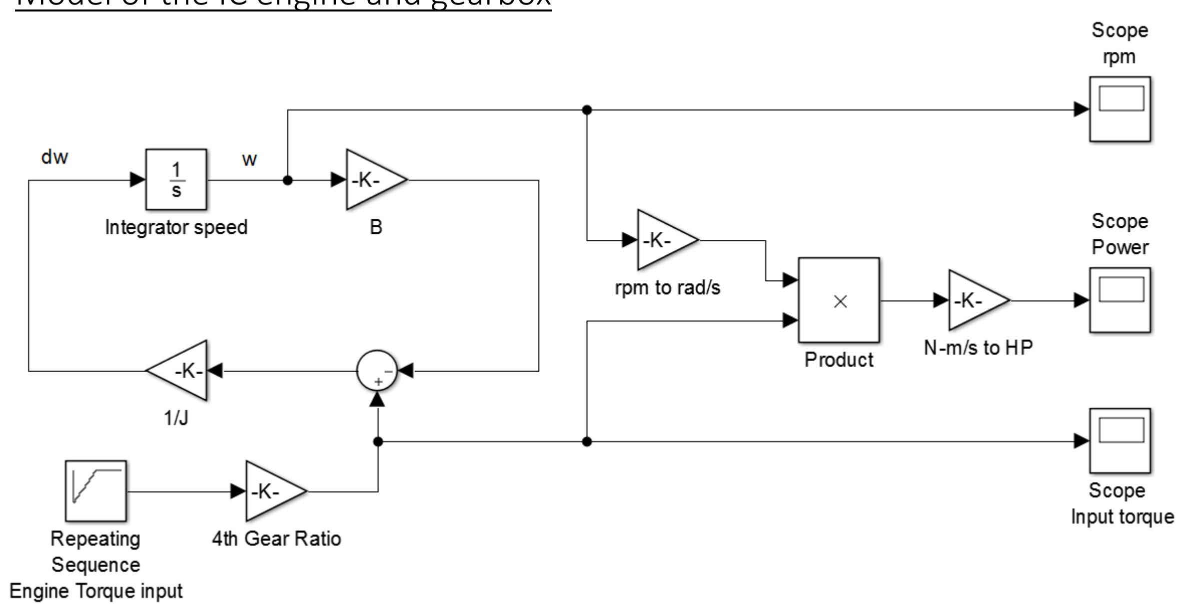


Figure 7 : Simulink Model of the Engine

An integrator block is used to solve the first order ordinary differential equation given by $J\dot{\omega} + b\omega = T_{in}$.

A linear torque pattern is generated in the simulation similar to the dyno-jet graph of the engine shown in *figure 2.* The torque is gradually increased to its peak of 77N-m in the form of repeating sequence input function of Simulink for 200 time steps. When coupled with the 4^{th} gear, peak torque becomes 99N-m.

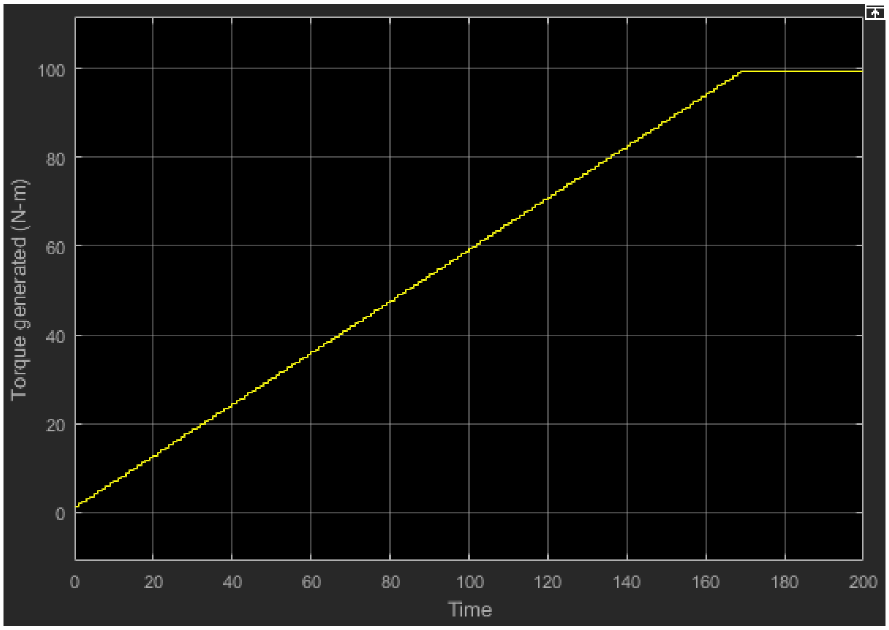


Figure 8: Torque generated at the gearbox output

The Inertia J of the system is kept at 932kg.cm^2 and the value of b is chosen such that the peak rpm at gearbox output is in accordance with rpm of the dyno-jet graph in *figure 2.*

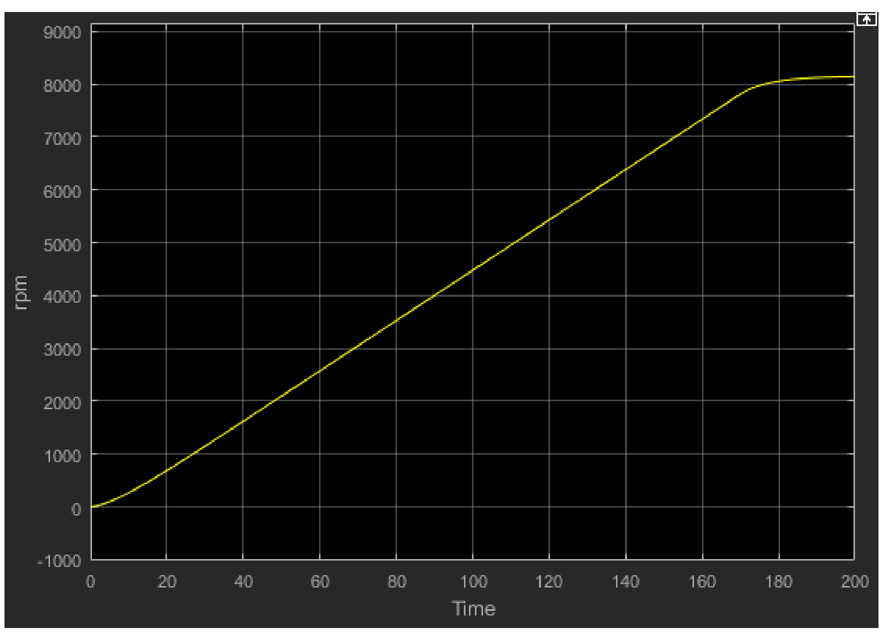


Figure 9: rpm of gearbox output

The power generated from the model resembles a linearized model of the graph of dyno-jet result shown in *figure 2.*

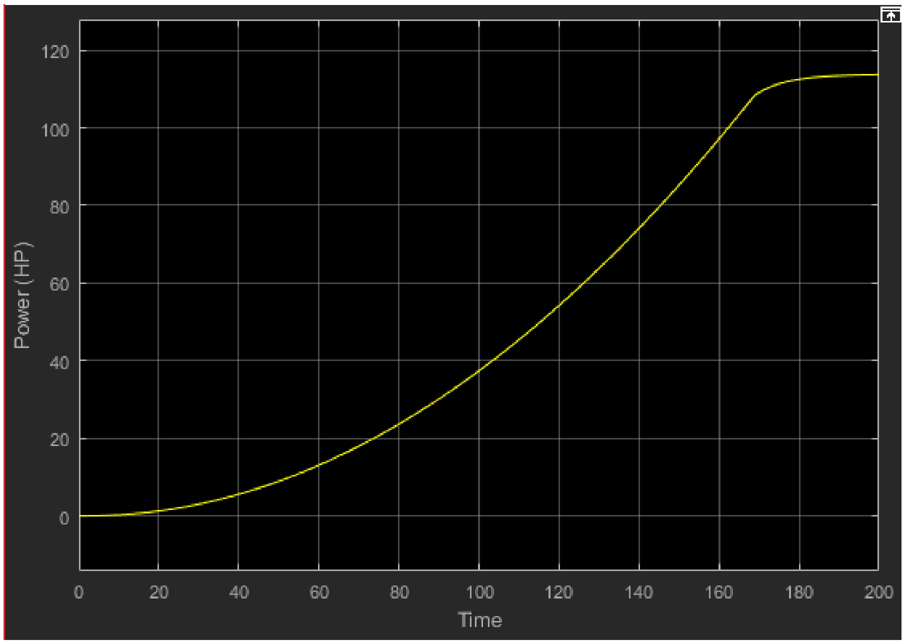


Figure 10 Power output at gearbox

b. Model of Generator loading torque

A loading torque is applied on the rotor against the direction of rotation of engine output to generate current i. The model has a varying voltage source input (from battery) which when applied on the generator creates the loading torque. This loading torque is directly proportional to the voltage applied.

The following first order differential equation is used to model the current applied that generates the loading torque:

$$L\frac{di}{dt} + Ri = V$$

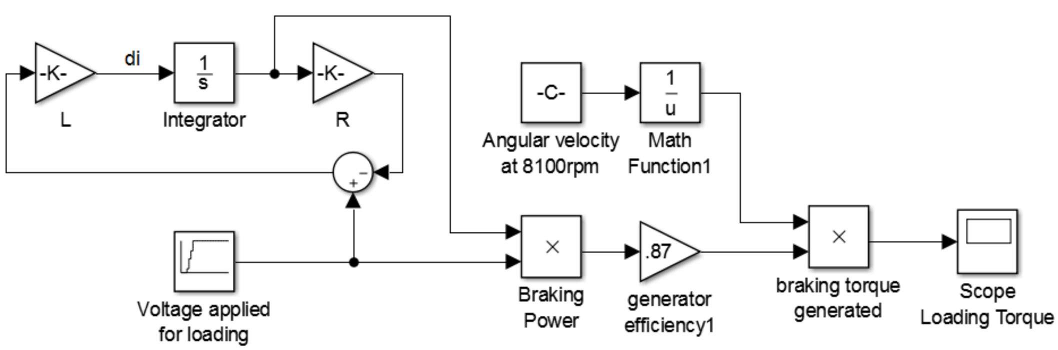


Figure 11: Modelling the loading on generator

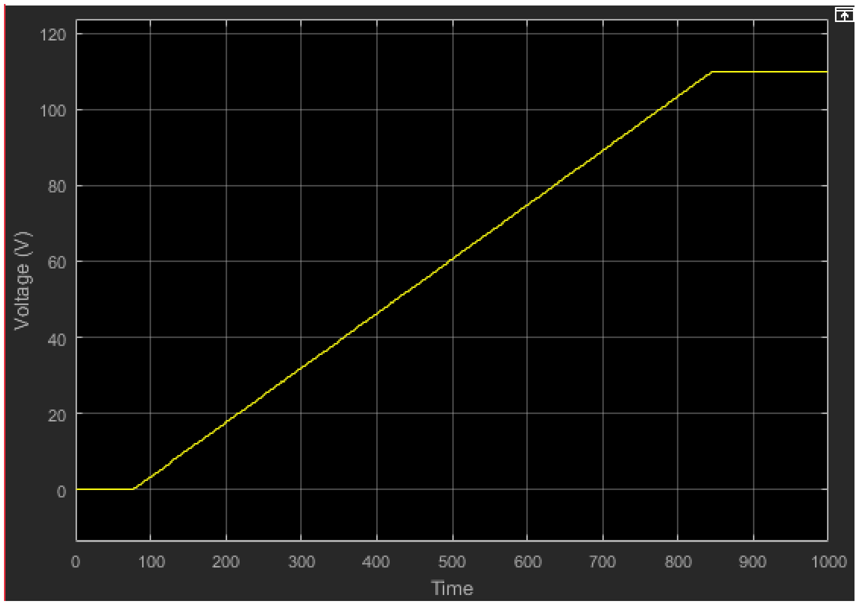


Figure 12 : Profile of applied voltage for generating loading torque

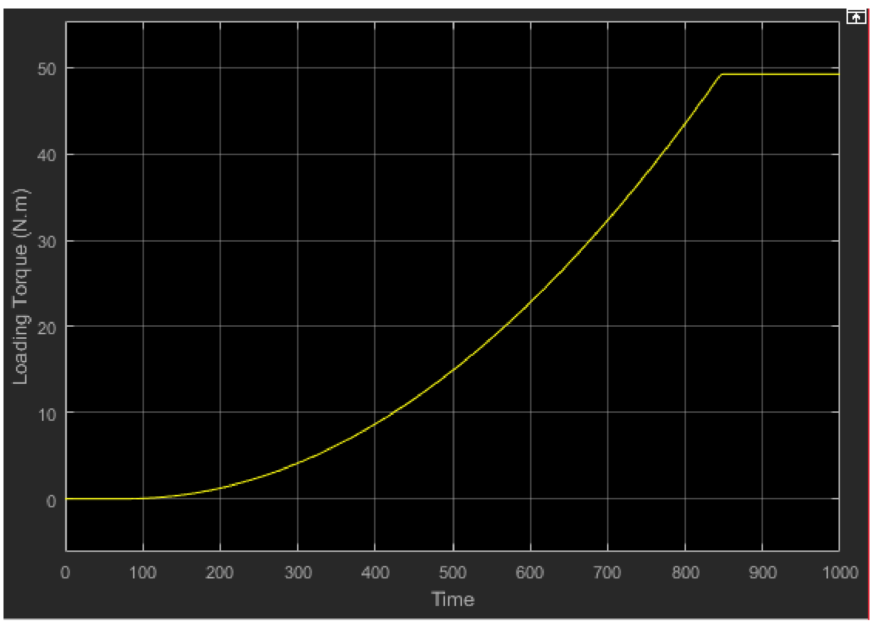


Figure 13 : Loading torque generated at constant angular velocity

c. Modelling the current output

The loading torque generated is subtracted from the engine torque to get the net load acting on the system. The output angular velocity is used to find the net power generated and the resulting current. The generator efficiency is assumed to be 87%. The assembled system with all three models is shown in *figure 13.* The change in angular velocity and net torque can be observed in *figure 14* and *figure15.* The voltage applied for loading has the same profile as shown in *figure 11.*

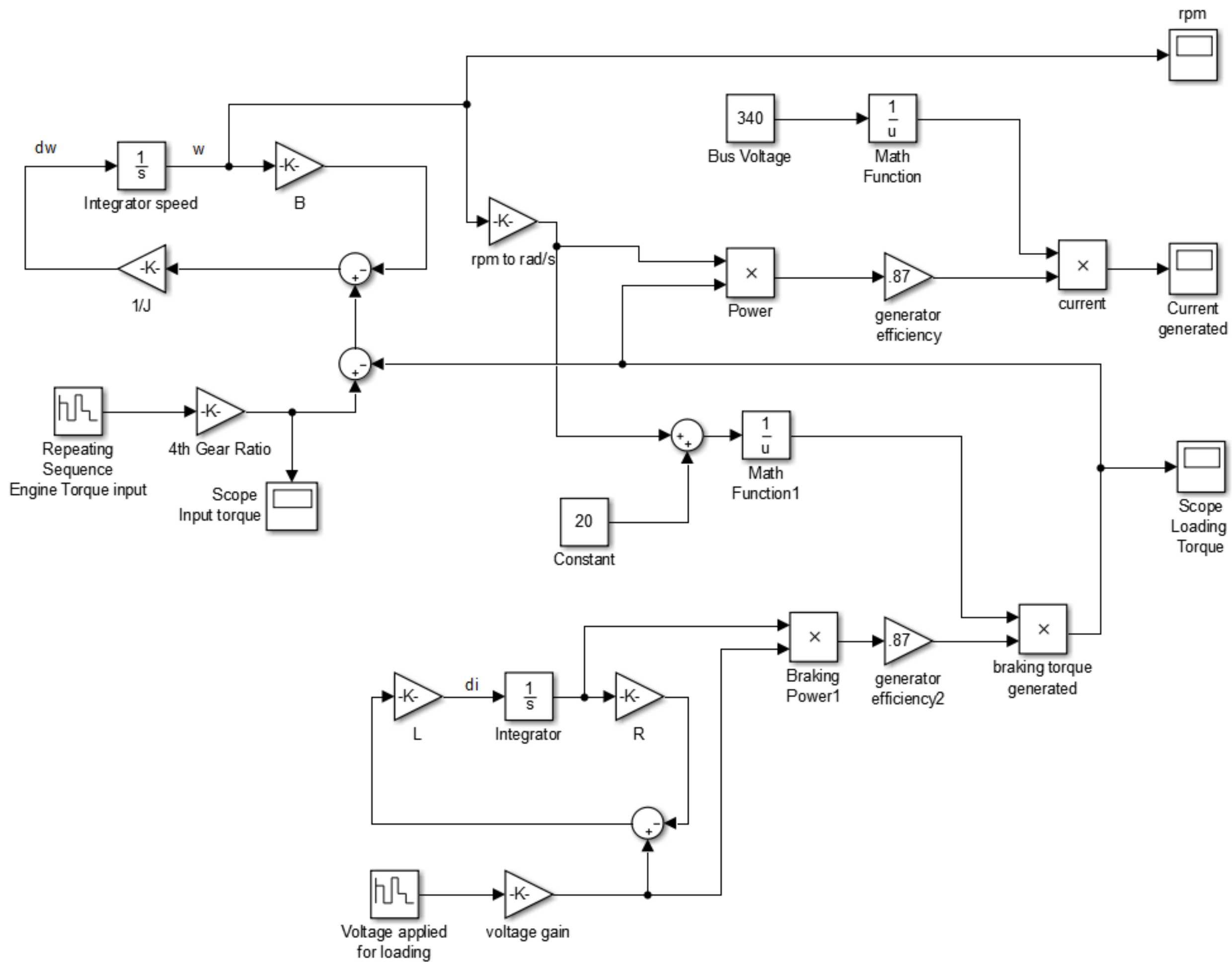


Figure 14 : Combined model for the generator system

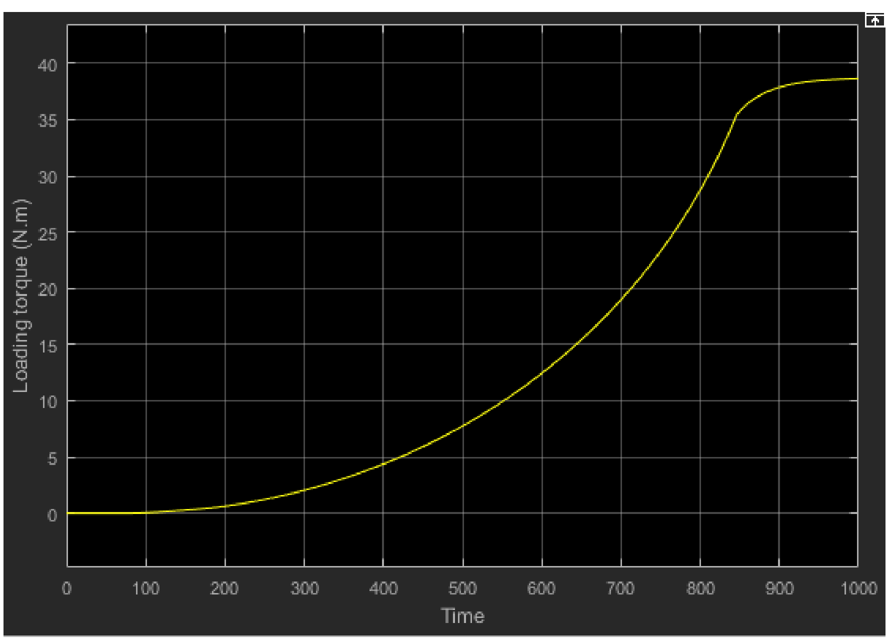


Figure 15 : Net torque profile of generator after loading is applied

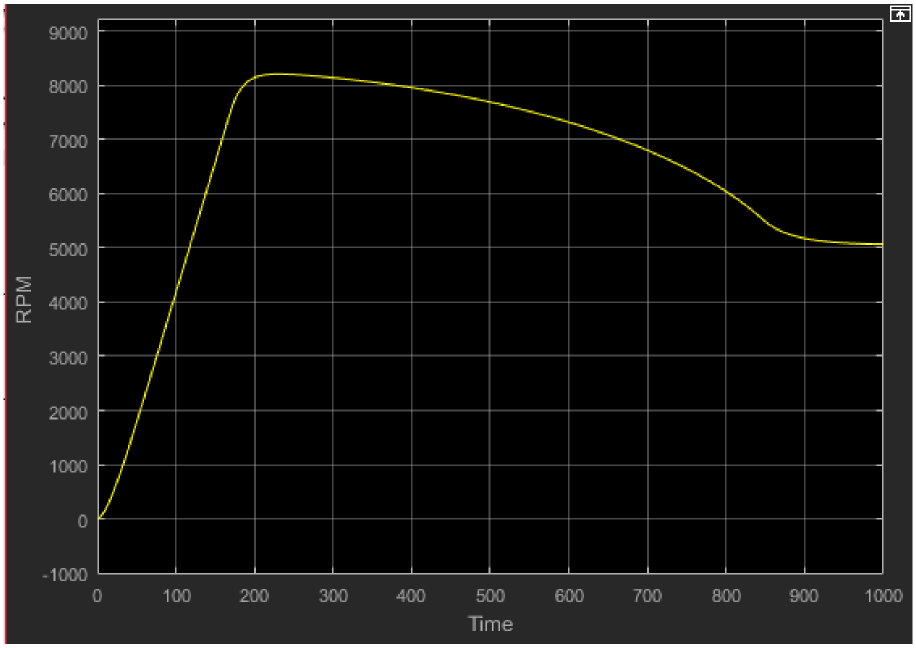


Figure 16 : RPM profile of generator after loading is applied

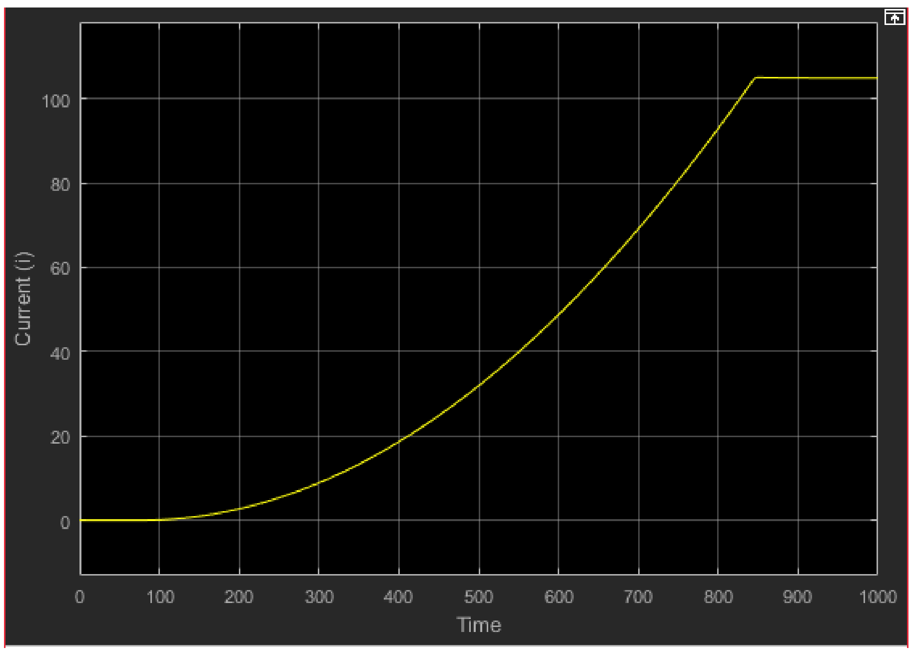


Figure 17 : Profile of current generated

d. Implementing a PID controller

PID control was studied from *Åström, K et al.* [10]. The PID controller looks at the present value of an error ε, the integral of the error over a time interval $\int \varepsilon$ and the rate of change of the error $\Delta\varepsilon$ to determine how much of a correction to apply. The controller continues to apply the correction until change is seen on the feedback. Depending on the error calculation update rate the corrective action can be adjusted at a fast rate. The PID controller forces feedback to match a setpoint.

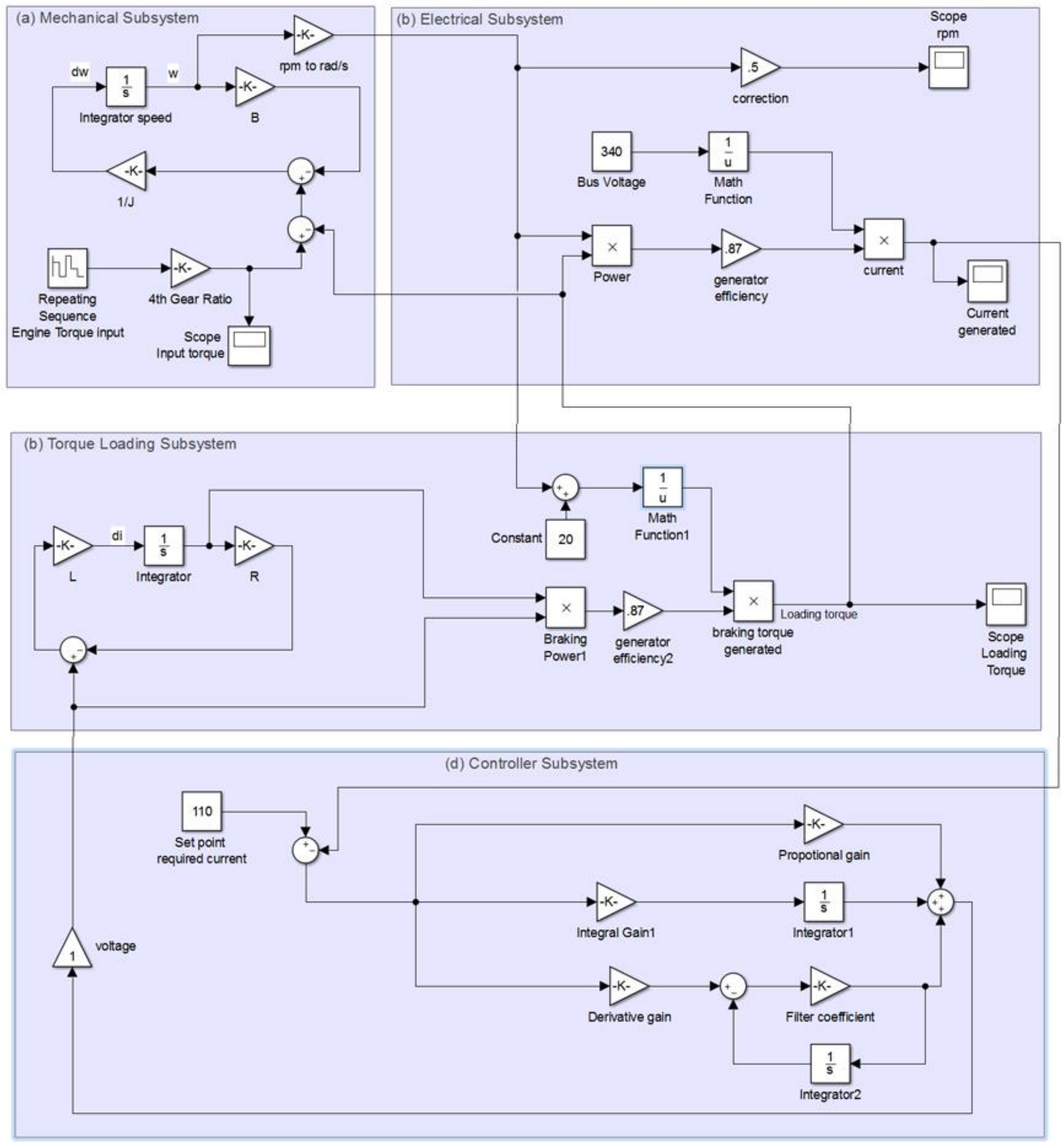


Figure 18 : System with feedback design

The set point current requirement is kept at 110A. Output current from the system is compared with the set current and a PID feedback is given to the torque loading system iteratively till the set current requirement is matched. Gains for the P, I and D were set to obtain a smooth curve. The input from engine is gradually increased to its peak of 77Nm for simulation. Following plots were observed from the system.

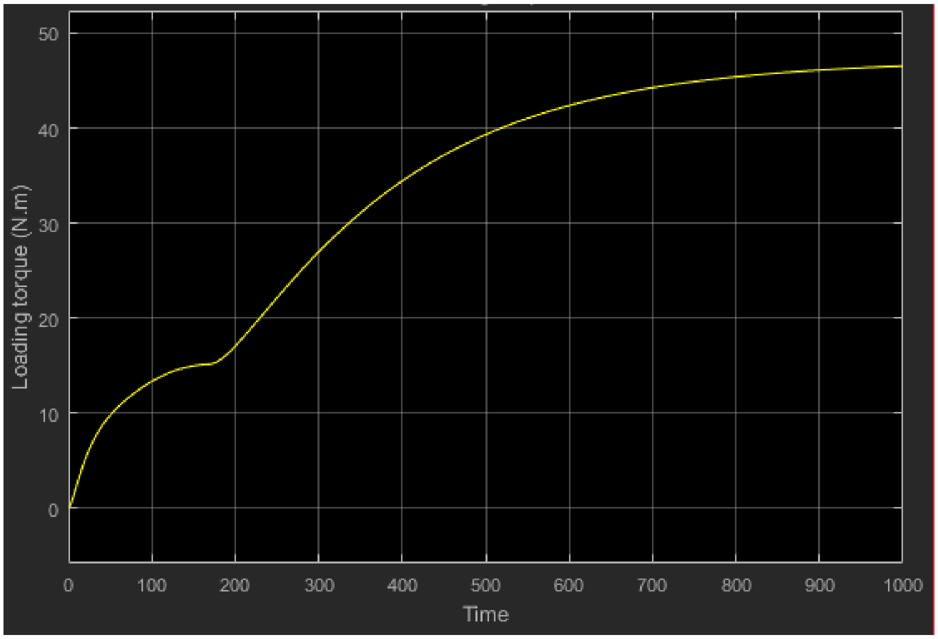


Figure 19 : Loading torque generated by PID control

It can be observed that the loading torque is gradually increased to the reach the required loading that generated 110A current and attains almost a constant value.

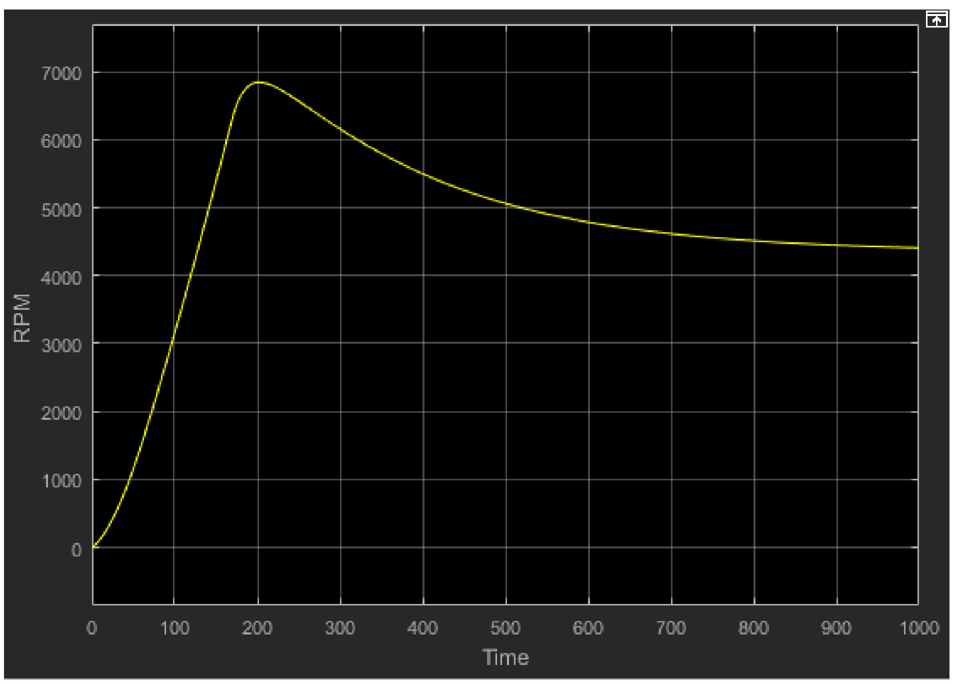


Figure 20 : RPM curve generated by PID control

The RPM curve gradually increases with increase in the input torque from engine and attains a peak at around 6900RPM after which it reduces as the loading torque increases from PID feedback. The RPM at 110A output current is around 4500RPM.

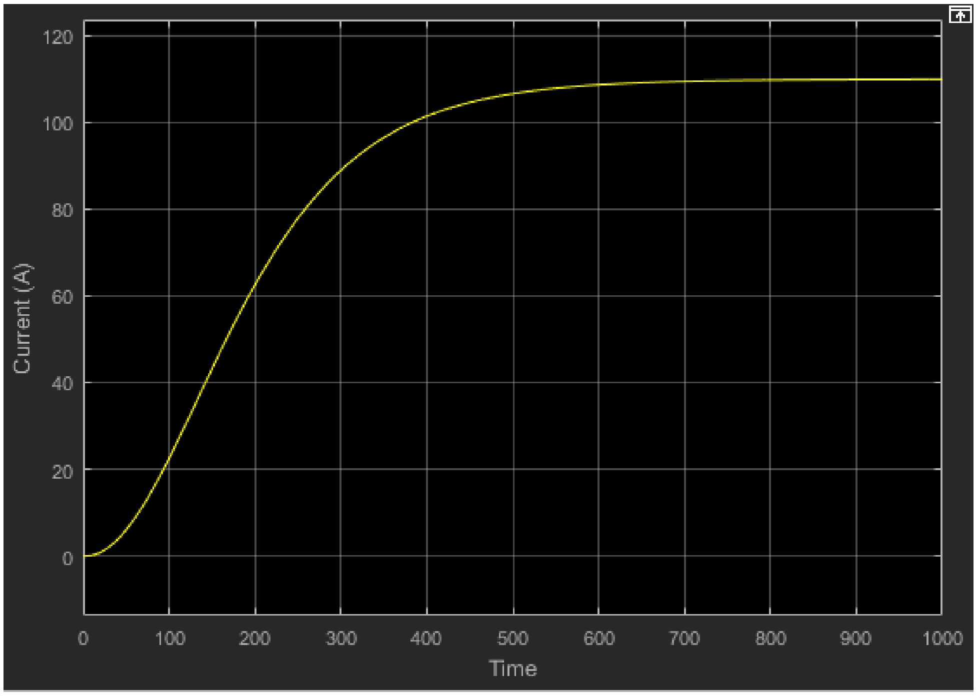


Figure 21 : Current curve generated by PID control for a set current of 110A

The current has the desired incremental increase and the loading torque increases as expected from the PID control.

V. Validation of the Simulink model

The Simulink model can be validated by comparing the results of the simulation with the actual model test results. Estimation techniques like Kalman filter or Unscented Kalman Filter can also be used to further optimize the model based on the measurements of the real system.

VI. Conclusion

The Simulink model is derived from a simplified mathematical model representing the actual dynamics of the system. The design has considered the input and output measurements of the real system and has tuned the model parameters to obtain matching results. Based on the validation results, the values of parameters of this model can be adjusted. This validated model can be used to simulate results under varying dynamic conditions. Compatibility of a new IC engine with the generator system can also be tested by changing the input torque in this model(a) to match with torque-rpm curve of the new engine. Thus, this Simulink model will help in reducing time for analysis and modification of the generator systems used in Series-Hybrid electric vehicles.

VII. References

[1] https://www.atec.ncsu.edu/innovation/electric-drive/

[2] http://dynobike.com/gallery/technical/Honda_VFR800_rhs_chart.htm

[3] http://www.alternative-energy-tutorials.com/wind-energy/synchronous-generator.html

[4] P. Pillay and R. Krishnan, "Modeling, simulation, and analysis of permanent-magnet motor drives. I. The permanent-magnet synchronous motor drive," in *IEEE Transactions on Industry Applications*, vol. 25, no. 2, pp. 265-273, Mar/Apr 1989.

[5] Dehkordi, A. B., A. M. Gole, and T. L. Maguire. "Permanent magnet synchronous machine model for real-time simulation." *International Conference on Power Systems Transients (IPST'05)*. 2005.

[6] http://ctms.engin.umich.edu/CTMS/index.php?example=MotorSpeed&section=SimulinkMo deling

[7] J. S. Mayer and O. Wasynczuk, "Analysis and modeling of a single-phase brushless DC motor drive system," in *IEEE Transactions on Energy Conversion*, vol. 4, no. 3, pp. 473-479, Sep 1989.

[8] M. Fazil and K. R. Rajagopal, "Nonlinear Dynamic Modeling of a Single-Phase Permanent-Magnet Brushless DC Motor Using 2-D Static Finite-Element Results," in *IEEE Transactions on Magnetics*, vol. 47, no. 4, pp. 781-786, April 2011.

[9] 2002 Honda VFR800/A Service Manual

[10] Åström, K., & Hägglund, Tore. (2006). Advanced PID control. Research Triangle Park, NC: ISA-The Instrumentation, Systems, and Automation Society.