Parallel Hybrid Electric Vehicle Powertrain Modeling and Control For John Deere-9370R Tractor

BY

BHARATH RAJ REDDY DERE

B.S., Osmania University, India, 2014

THESIS

Submitted as partial fulfillment of the requirements
for the degree of Master of Science in Mechanical Engineering
in the Graduate College of the
University of Illinois at Chicago, 2017

Chicago, Illinois

Defense Committee:

Prof. Sabri Cetin, Advisor
Prof. Jeremiah Abiade
Prof. Arunkumar Subramanian

This thesis is dedicated to my parents, without whom it would never have been accomplished.

ACKNOWLEDGEMENT

I take this opportunity to express my heartfelt gratitude and sincere thanks to my advisor Professor Sabri Cetin, who has been a source of inspiration throughout the work for providing conceptual ideas, directions, valuables active guidance advice with utmost patience and moral encouragement for the entire thesis work. Additionally, I would like to thank my committee members Professor Jeremiah Abiade and Professor Arunkumar Subramanian for their interest in my work.

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NOMENCLATURE

HEV	Hybrid Electric Vehicle
SOC%	State of Charge
PI	Proportional Integral
HIL	Hardware in the Loop
ICE	Internal Combustion Engine
CVT	Continuous Variable Transmission
CMA	Compact Modular Architecture
PID	Proportional, Integral and Derivative Controller
Kp	Proportional Gain
Ki	Integral Gain
Kd	Derivative Gain
V	Vehicle Speed
Vd	Vehicle Speed Demand
Teng	Engine Torque
Ne	Engine Speed RPM
Tm	Motor Torque
Tmd	Motor Torque Demand
Nm	Newton – meter
Tout	Output Torque of the Transmission
Tturb	Turbine Output Torque
Timp	Impeller Input Torque

SUMMARY

The objective of this paper is to study the suitability of the parallel hybrid electric vehicle (HEV) type powertrain for a real tractor - the John Deere 9370 R tractor. The HEV powertrain model is developed in MATLAB and Simulink environment using its add-ons such as control systems and Simscape libraries. The HEV powertrain model contains two power sources: 1. the engine is modeled using power vs. speed and torque vs. speed look-up tables, and 2. the electrical system is modeled using Simulink library. A single motor is utilized for the both purposes, to start the engine and to supply additional power to the wheels when required. This motor also works as a generator and charges the Li – ion battery in two modes known as cruise mode and parking/ charging mode. The power split device as we see in the modern HEVs such as Toyota Prius is replaced by a clutch and gear mechanism to add the torques through a pair of parallel shafts, like transaxle of Ford Escape HEV model. The lock-up clutch of the torque converter and the motor clutch engages according to the power requirement at wheels and the battery state of charge (SOC%). The gear mechanism is synchronous cone and hub type, as we see in the manual gear box, is used to switch power flows in three ways like power sources to wheels, engine to the generator, and motor to the engine to start the engine. In the case of off-road applications, we require different torque outputs at the drawbar and wheels of the tractor. Hence, a 5 – speed automatic transmission is used in between the sources and final drive.

Furthermore, the model is controlled using three PI – controllers, a vehicle speed PI – controller, which is a central controller of the system and two sub PI – controllers to control engine speed and motor torque. The model is tested in 3 three simulations. Firstly, the response of the system is studied to a step input signal. Secondly, the effect of the road grade angle on the performance of the system is investigated. Finally, the efficiency of PI controllers is observed by studying the behavior of the system using a drive cycle.

1. INTRODUCTION

The tractors are the popular off-road vehicles, particularly, its application in agricultural industry is remarkable. These are used for a variety of purposes such as pulling or pushing agricultural machinery, plowing, tilling, harrowing, and planting, etc., where this research is focused on the powertrain performance while performing the transport duties like an articulating truck do. The significant challenges in these applications are accelerating the tractor and climbing hills where hybrid electric vehicles (HEV) have advantages such as extra power assistance during accelerating the vehicle and climbing on hills. Moreover, the power assistance from the motor during acceleration also improves the fuel economy of the vehicle. By considering the satisfactory performance of the HEVs on the roads, we can implement HEV-type powertrain in tractors to increase the drawbar pull power on high-grade roads and acceleration capacity of the tractor.

The goal of this research is to develop an HEV-type powertrain model for the tractor, to study its performance and suitability to heavy equipment vehicles. This model mainly includes a controller, engine dynamics, electrical system, torque converter, gear and clutch mechanism, transmission, and vehicle dynamics. The fuel consumption model is not included in this research due to unavailability of the fuel consumption details. The MATLAB and Simulink environments are chosen to design powertrain model, because of its suitability to develop control systems and to carry out the real-time simulations (for example, hardware in the loop (HIL) simulations). The complete powertrain model is shown in the fig. 3.1. Furthermore, three PI – controllers are used along with two state flow charts to control overall powertrain model, where PI – controllers are developed to monitor the vehicle speed, engine speed, and motor torque. And the event driven logics are drawn up in Stateflow to choose among the different operating modes of the vehicle and to select the gears according to vehicle speed.

The performance of the powertrain model is analyzed by three simulations. The response of the system is studied using a step input signal of the vehicle speed to observe the accelerating performance. Then the effect of the road grade angle on the vehicle speed is investigated by analyzing the output response of the system at the tractor weight of 44,000 pounds and PI – controller efficiency is calibrated by using a drive cycle. Finally, the drawbar pull power values are compared with the John Deere 9370 R tractor drawbar pull power at three velocities to validate the developed powertrain model.

2. LITERATURE REVIEW

2.1. Tractor subsystems:

1. Chassis or body: The chassis or body is known as a skeleton of an automobile, which affects the vehicle dynamics, aerodynamics, fuel efficiency, and passenger comfort. The new trend is using lighter weight chassis, which improve the performance of the vehicle.

2. Diesel Engine: The engine is the heart of any vehicle, which is the power source for every operation of the vehicle. The piston type, liquid cooled, and gasoline/ diesel powered internal combustion engine is known as a conventional engine. The typical ICE use chemical energy that is developed by burning diesel to produce mechanical power. Most of the ICE's has four strokes which are known as intake, compression, power and emission strokes. The power developed during the power stroke is transmitted through the piston to the crankshaft. The cam shaft coordinates with the crankshaft and regulates the fuel injection to the cylinder, and during the 4^{th} stroke of the piston, the emissions are sent out of the cylinder to initiate the next cycle. [1] The ideal fuel-air ratio is considered as 1.4. In this research work a 6 – cylinder diesel engine is modeled as a look-up table by collecting data from torque vs. engine speed, and power vs. engine speed curves (as shown in the fig 3.17.). This lookup table is also known as engine map.

3. Power – train: The power train transmits the power from the engine to the wheels through torque converter/ clutch, transmission, driveshaft, differential gear systems, and final drive. The automatic transmission is already available in most of the vehicles, and electronic transmission control systems and continuously variable transmission (CVT) are being

developed. The differential gear produces required speed and torque at the wheels, “where wheels and pneumatic tires provide traction between the vehicle and road surface.” [2]

4. Steering: The steering is a subsystem which causes the lateral motion of the vehicles. The rotation of the steering wheel changes the orientation of the front or back wheels accordingly controls the vehicle direction. For example, rack and pinion steering system, power assisted steering system, and four-wheel steering system is commonly known types.

5. Suspension: The primary functions of this subsystems are 1) by observing the jerks provides a smooth ride and comfort the passengers, 2) maintains the contact between the wheels and road surfaces. The most common suspension systems are independent strut type suspension, semi-rigid axle suspension, and active/semi-active suspension systems.

6. Brake: The brakes has two purposes in an automobile, to lower the vehicle speed or to completely stop the vehicle motion. Drum and disc type brakes are widely used braking systems to all kind of transportation systems.

7. Other Accessories: The automobile includes many sensors, actuators, and other instrumentation. The effect of this device mostly neglected because they require very little power hence doesn’t affect engine performance.

In this research work, the vehicle model doesn’t include steering and suspension subsystems, which deal with the lateral and vertical motion of the vehicle respectively.

2.2. Hybrid Electric Vehicles (HEV's):

The HEV's takes the advantages of the both conventional ICE and electric cars, where the ICE is not efficient to provide the required torque in the case of high-grade roads, the electric battery supplies additional power to the vehicles to produce desired performance. And, "improves the fuel economy by engine right-sizing, load-leveling, and regenerative braking." [3]

Series, parallel, and power split HEVs are very popular in the present market. "In the series power flow, as shown in Fig.1.4(B), the motor power is provided by either a battery, or a generator transforming the engine power into electrical energy, or both. Then motor transfer received power from this two sources to the drive wheels. Since the engine operation is independent of the vehicle speed and road load, it can operate near its optimal condition almost all the time. A disadvantage of such configuration, however, is that the efficiency of the electric machine(s) will reduce the overall power-train efficiency. The parallel configuration, as shown in Fig. 1(A), includes two separate power paths: the mechanical path and the electrical path. Each power path can drive the vehicle individually or collaboratively. The main drawback of the parallel configuration is that a single electric machine is typically used both as a generator and as a motor. The electric power assistance must be constrained to avoid draining the battery, and frequent role-reversal may be necessary." [4] Whereas, the power split type HEV's, as shown in Fig. 1.4(c), covers the disadvantages of the both series and parallel type. Where part of the engine power is transferred to the generator to charge the battery by using a planetary gear mechanism and a major percentage of engine power is used to drive the wheels. The engine and motor work together in extended power mode (for example, as in Volvo CMA cars). [5]

In the case of tractors and heavy equipment vehicles, where different torque outputs are needed at the drawbar, which can be done by using transmission in between the sources and final drive. Therefore, it won't be a good choice to use power split type hybrid electric model. As the efficiency of the electric machines reduces the overall power – train efficiency, the series type hybrid electric cannot be used for pulling heavy loads. By considering this two applications, the parallel type hybrid model will be a right choice.

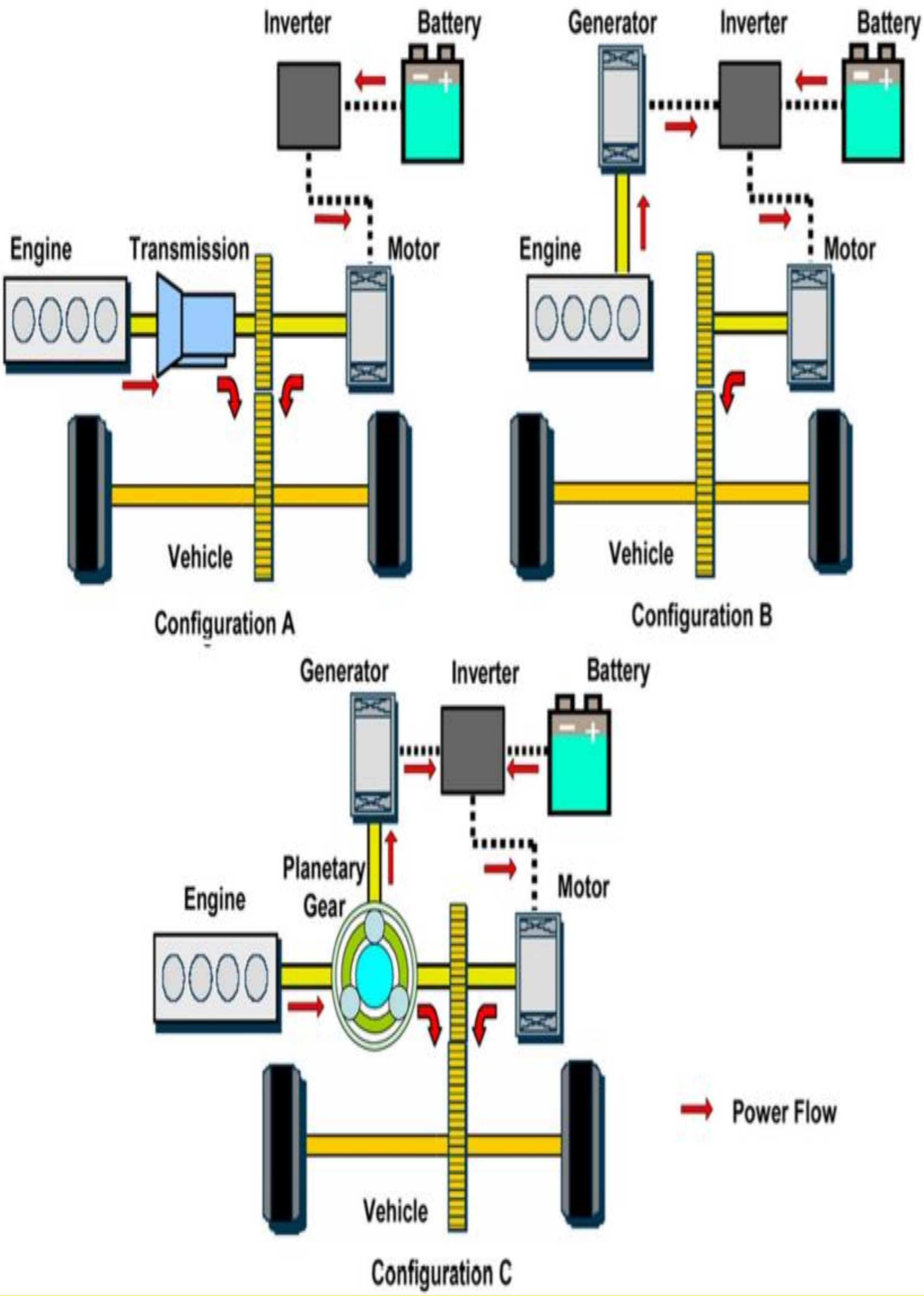

Figure 2.1. Power flow in HEV's A) parallel, B) series, and c) power split. [3]

2.3. PID Controller:

Feedback control is a control mechanism that uses information from measurements by sensing the output, and this output signal is used to control the input signal of the system. These are mainly classified into positive feedback and negative feedback controllers. The negative feedback is used to decrease the size of the input, and this feedback signal develops the more stable input. Most widely used feedback controller in process control is PID controller. This controller can be thought of as a controller that takes the present, the past, and the future of the error into consideration. This controller composes three controllers: Proportional controller (PC), Integral controller (IC) and Derivative controller (DC). Hence, the term PID stands for Proportional -Integral – Derivative.

In a Proportional controller, the input signal is multiplied by a constant, known as proportional gain (Kp). In this case, “the steady state error depends inversely upon the proportional gain. High proportional gain results in a significant change in the output for a given change in the error and can lead to an instability of the system. In contrast, a small gain results in a small output response to a large input error resulting in little control action for significant disturbances.” [6]

An Integral controller is “proportional to both the magnitude of the error and the duration of the error. The integral action in a PID controller is the sum of the instantaneous error over time and gives the accumulated offset that should have been corrected previously.” [6] Therefore, “an integral control (Ki-integral gain) will have the effect of minimizing the steady-state error, but it may make the transient response worse.” [7]

In the Derivative controller, “a derivative of the process error is calculated by determining the slope of the error over time and multiplying this rate of change by the derivative gain (Kd). The derivative term slows the rate of change of the controller output with time.” [6] “A derivative control (Kd) will have the effect of increasing the stability of the system, reducing the overshoot, and improving the transient response.” [7]

We can also use this controller in combinations such as PI and PD controllers, comparatively, which provide better control on the output response of the system than individual controllers. In this research work, the PI type controller is used, where derivative controller doesn’t have a significant effect on the system’s response.

2.4. MATLAB®/ Simulink®:

MATLAB is the standard software tool used for control system design by engineers. The other MATLAB software package domains such as Simulink, Stateflow, Simscape and auto-code generation (Simulink Coder) are used as part of control system design, prototype development, and harder in loop (HIL) testing. A similar language to C is used as a programming language in MATLAB, which is called as MATLAB script language. MATLAB interface is used to write the control and simulation programs. The control logic can also be represented using graphical tools in Simulink and Stateflow environments. Stateflow is a complementary domain that is most suitable for modeling event – driven supervisory logic aspects of a control software, whereas Simulink is most appropriate for more mathematical aspects of it, such as PID control algorithms. The Simulink® Coder auto-code generation tool is used to automatically convert Simulink®, Stateflow, and MATLAB® files to C language files, compiled with a C-compiler, and deployed on a target microcontroller hardware. There are many, and growing, numbers of target microcontroller/DSP hardware supported by MATLAB® and its tools.

3. PARALLEL HYBRID TYPE TRACTOR POWERTRAIN MODELLING

The parallel hybrid electric tractor powertrain is modeled in the Simulink environment, which includes a controller to control the functions of the different subsystems, an internal combustion engine (ICE) as a primary energy source, a motor/ generator as a secondary power source/ sink. It also includes a torque converter with a lock-up clutch, which transfers the driving force from the power sources through a gear mechanism and automatic transmission system to longitudinal vehicle dynamics.

The fuel consumption dynamics, brake cylinder dynamics, suspension system dynamics and lateral vehicle dynamics are not considered for this model to reduce the complexity of the design. In this powertrain model, the motor also assists as an auxiliary motor in engine starting, hence the state of charge (SOC%) of the battery is always maintained at 30%. The control logic is developed using event driven logic (State-flow chart) to choose b/w different energy paths. The throttle angle is controlled by PI- controller using engine rpm as a feedback. The motor and generator torques are controlled by using different PI- control units, where the speed of the motor/ generator is used as a feedback signal. The clutch and gear mechanism, which uses a synchronous cone and hub system to switch from motor to generator, is mounted before the transmission and after the lock-up and motor clutches. Fig 3.1 illustrates the complete powertrain Simulink model of the tractor.

3.1. Controller Block

The controller block is a central controller of the vehicle, which coordinate b/w different subsystems controllers. The fig 3.2, depicts the controller block and its sub control blocks. The controller block includes:

a) Event Driven State Flow Chart.
b) Vehicle Speed Controller (PI logic controller)
c) Battery Charge Controller
d) Motor Torque Controller (PI logic controller)
e) Generator Torque Controller (PI logic controller)
f) Motor/ Generator switch
g) ICE Speed Controller (PI logic controller)

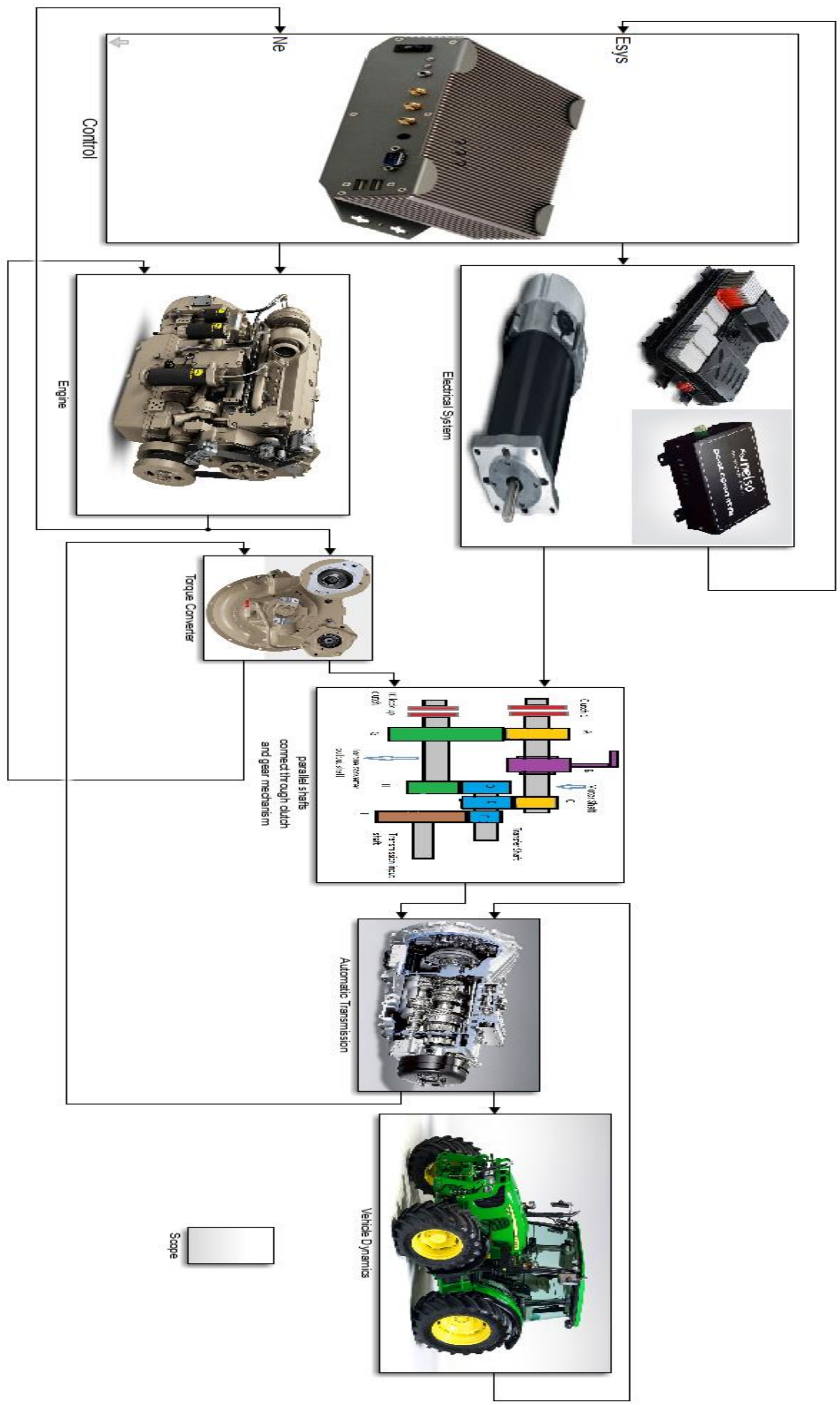

Figure 3.1. The Simulink model of the tractor powertrain.

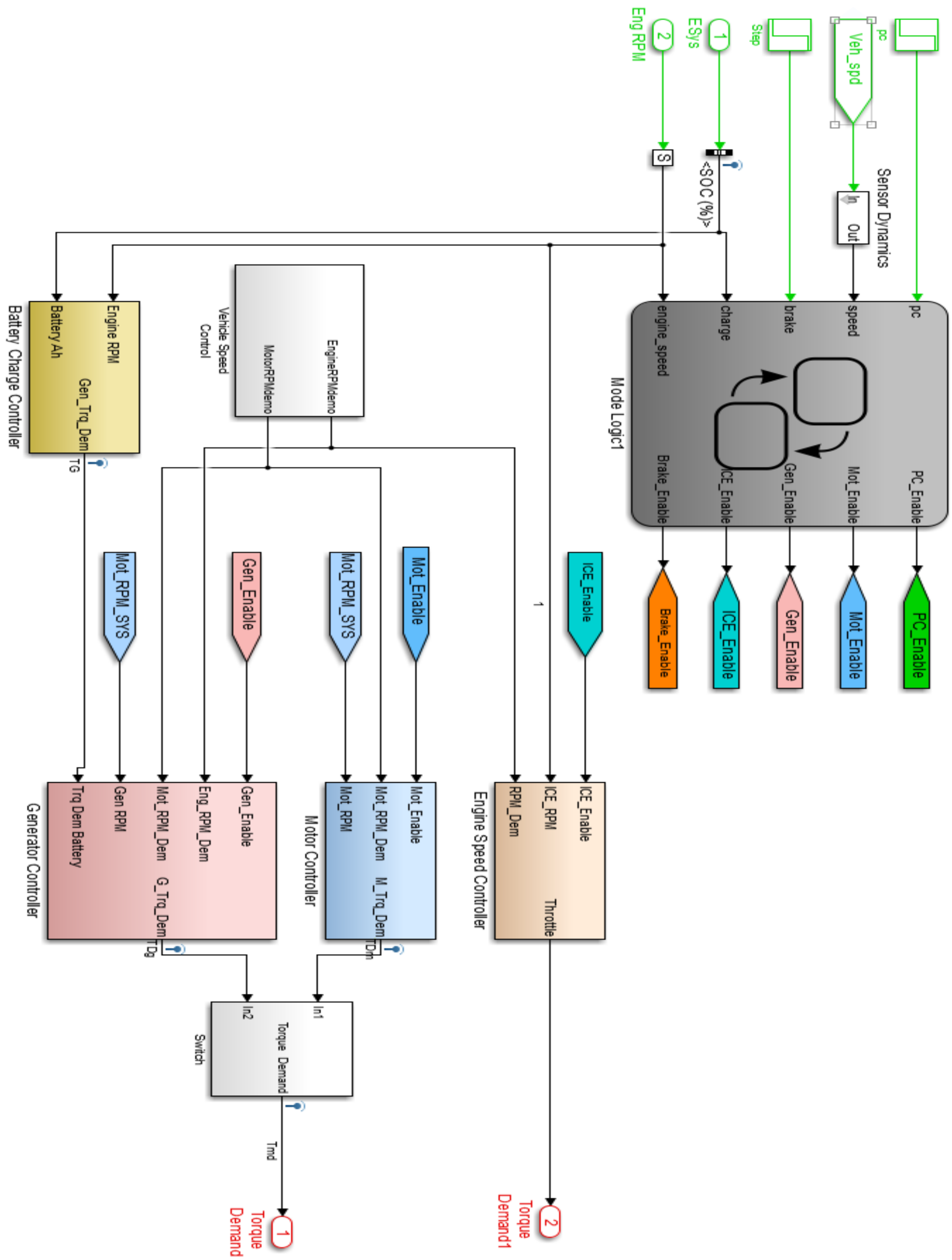

Figure 3.2. The controller block and its subsystem controller blocks.

Note: This controller block is modified and improved version of the original model in this work. The original model is taken from MATLAB/ Simulink examples. [8]

3.1.1. Event Driven State Flow Chart:

This block of the controller enables different subsystems by analyzing inputs from vehicle speed sensor, brake pedal input sensor, battery state of charge sensor, and engine speed sensor. The tractor is operated in 4 modes. The start mode activates the motor, and it generates required torque to the wheel by using power from the battery, when the SOC% is greater than 30%. If the SOC% is less than 30%, the motor gives an initial push to start the ICE and ICE runs the vehicle. The second mode is known as a driving mode, in this mode vehicle operates in two conditions. In the case of high power requirement at the wheels, for example, climbing the mountain. The vehicle is operated in acceleration state in which ICE and motor together assist the vehicle to reach the required performance at the wheels.

When the vehicle is on expressway or highway, it will be operated in the cruise mode, where the constant power is needed at the wheels. In this condition, a part of power from the ICE is taken by the generator to charge the battery. The power is drawn by the generator from ICE through a clutch and gear mechanism, which is explained in the later sessions. The third mode is the brake mode, the sensor at the brake pedal forwards the signal to the main controller block. Controller block decides whether to turn off the power sources or keep them on and sends a signal to the master cylinder to generate required brake power at the wheel, according to the received signal. The 4th mode of the vehicle is parking mode, in this mode ICE left turn on and this power will be used for charging the battery when SOC% is less than 30%. [9]

The old speed of the vehicle is calculated using a MATLAB function, and this old speed is compared with the current speed to know the vehicle condition, whether it is in the accelerating mode or cruise mode.

MATLAB function:

```
function y = oldspeed
speed_buffer(2:end) = speed_buffer(1:end-1);
speed_buffer(1) = speed;
y = mean(speed_buffer);
```

3.1.2. Vehicle Speed Controller:

The speed of the vehicle is controlled by using PI - control logic as shown in the fig. 3.4. We can also use a PID control logic with appropriate PID gains. The values of the integral and proportional gains are calculated by using trial and error method. The signal builder sends the input signal to the controller, and this model is tested using two different input signals such as

a. Step signal (30 KMPH to 60 KMPH at sampling time = 0.01s).
b. Driving cycle (to test the capability of Simulink model).

The low pass filter adds transport delay to vehicle speed controller from the vehicle speed sensor. The required power is divided in b/w motor and engine using lookup tables. These fractions of acceleration demand are sent as an engine speed demand to the ICE controller block and as a motor speed demand to the motor controller block.

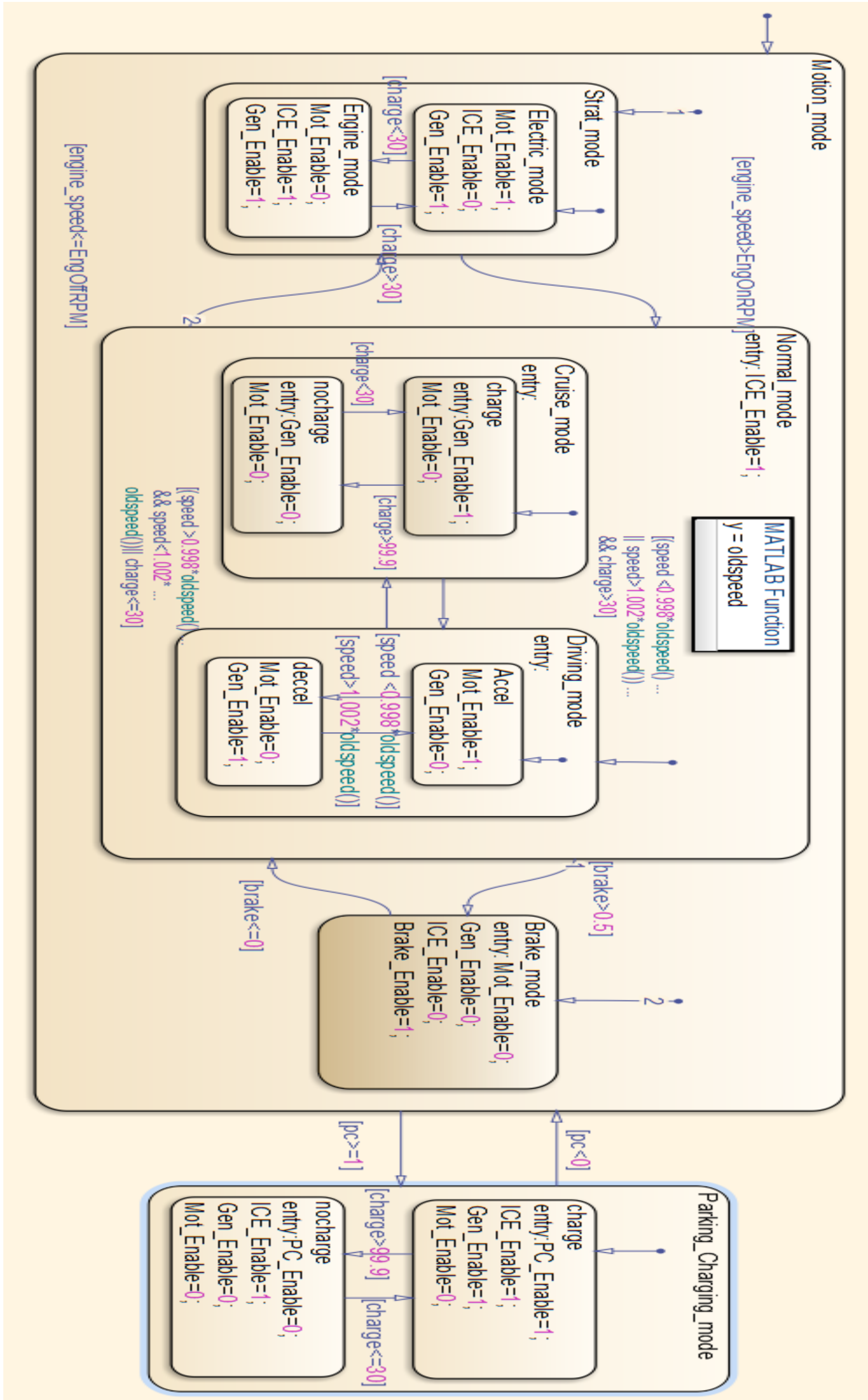

Figure 3.3. The event driven logic to decide among different modes.

Note: This mode logic is modified and improved version of the original model in this work. The original model is taken from MATLAB/ Simulink examples. [8]

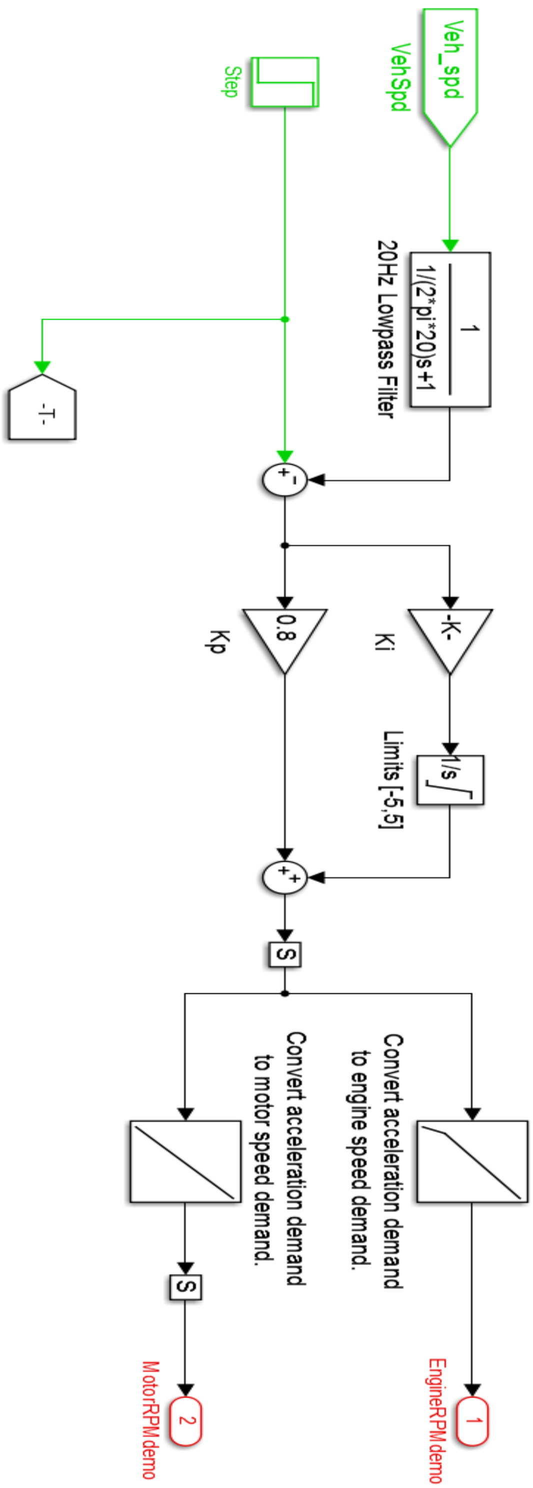

Figure 3.4. The PI- controller block to control the vehicle speed.

Note: This vehicle speed logic is modified and improved version of the original model in this work. The original model is taken from MATLAB/ Simulink examples. [8]

3.1.3. Battery Charge Controller:

This sub-block of controller estimates the state of charge of the battery and generates required generator torque to charge the battery. The lower limit of power taken from the ICE to charge the battery is decided by using engine speed and torque look-up table and battery charge percentage. The torque is reduced to 50% at engine – generator gear and a maximum of 20% power is drawn from the engine when low power is required at the wheel. The voltage output is managed in b/w – 100 V to + 100 V, which is then converted into torque demand output signal at a proportion of 100/400. The max torque output is 400 Nm. The output of this block is sent to the generator controller. Once the battery is fully charged (100% SOC), then no generation is required. The fig. 3.5, depicts the battery SOC% control logic.

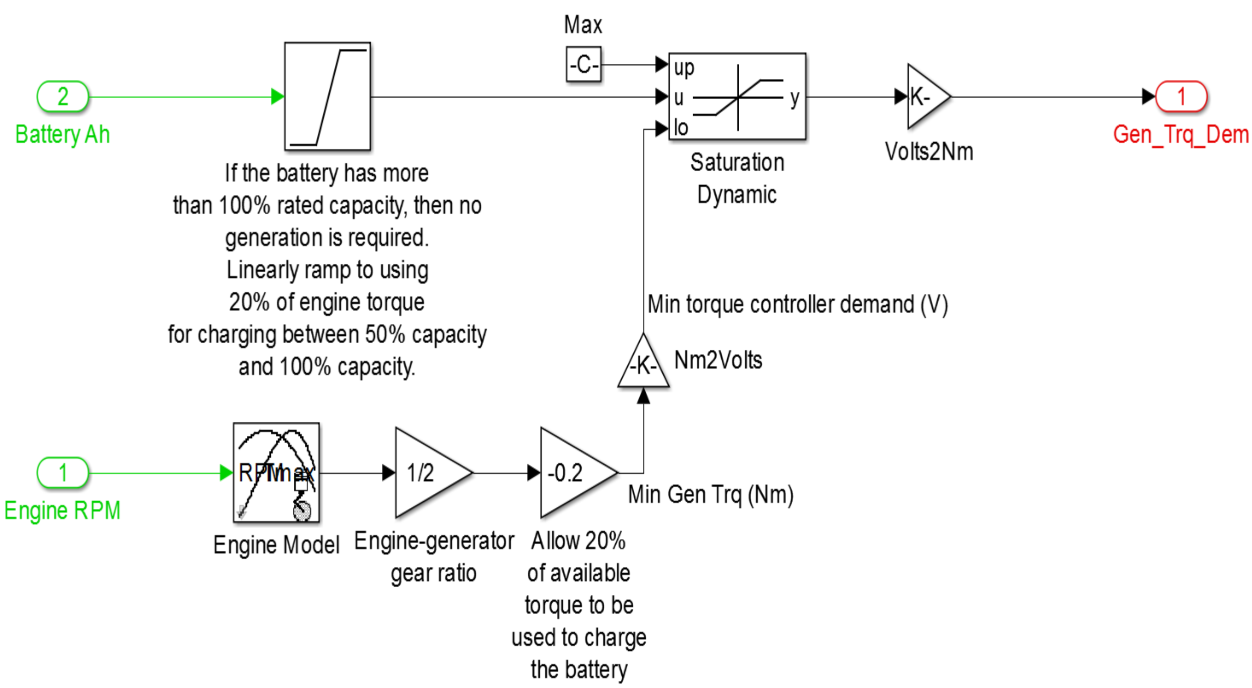

Figure 3.5. The battery charge controller.

Note: This logic is modified and improved version of the original model in this work. The original model is taken from MATLAB/ Simulink examples. [8]

3.1.4. Motor Controller:

The motor controller is a PI – type controller as shown in the fig.3.6., which controls the speed of the motor. The torque demand is calculated by using error signal between motor rpm demand and motor rpm. The motor rpm is converted into voltage signal first (at a proportion of 100/6500), and the error between this two voltage signals is processed through PI – control action. The generated control signal then converted into torque demand signal using a proportion of 400/100. The max motor speed is limited to 6500 rpm.

Note: the low pass filter indicates transport delay of the motor speed sensor.

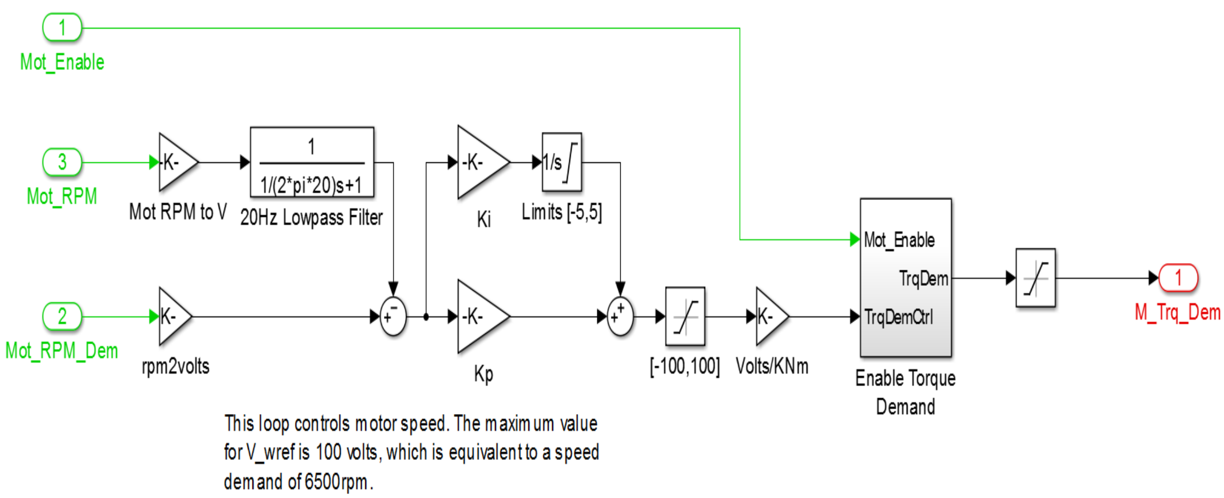

Figure 3.6. The motor PI – controller.

The enable torque demand block in the motor controller activates the motor after receiving motor enable signal from central controller unit in the real vehicle. In this model, it initiates sending output signal of the motor controller block to motor dynamics block. As shown in the fig.3.7., the low pass filter in this sub-block indicates the transport delay from the central control unit to the motor control unit.

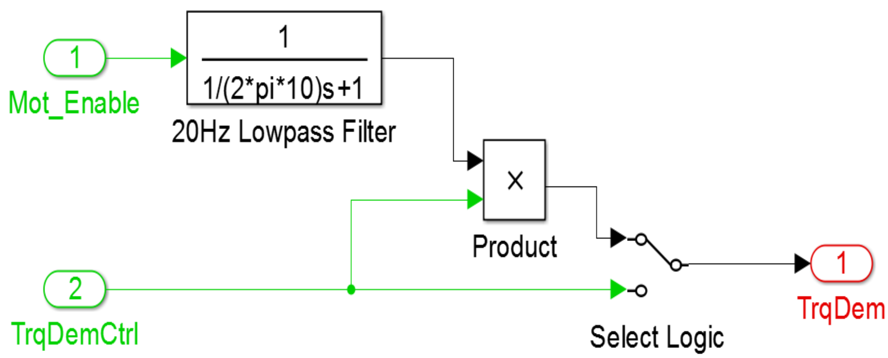

Figure 3.7. The activation block of the motor.

Note: This logic is modified and improved version of the original model in this work. The original model is taken from MATLAB/ Simulink examples. [8]

3.1.5. Generator Controller:

The generator controller as shown in the fig.3.8 generates generator torque demand when the generator is enabled. The controller generates the signal only when the engine is running, and engine speed is more than 800 rpm (which is an idle speed of the ICE). Generator RPM demand is calculated, so that engine RPM is controlled to zero or the idle speed. S block denotes the generator torque demand sensor.

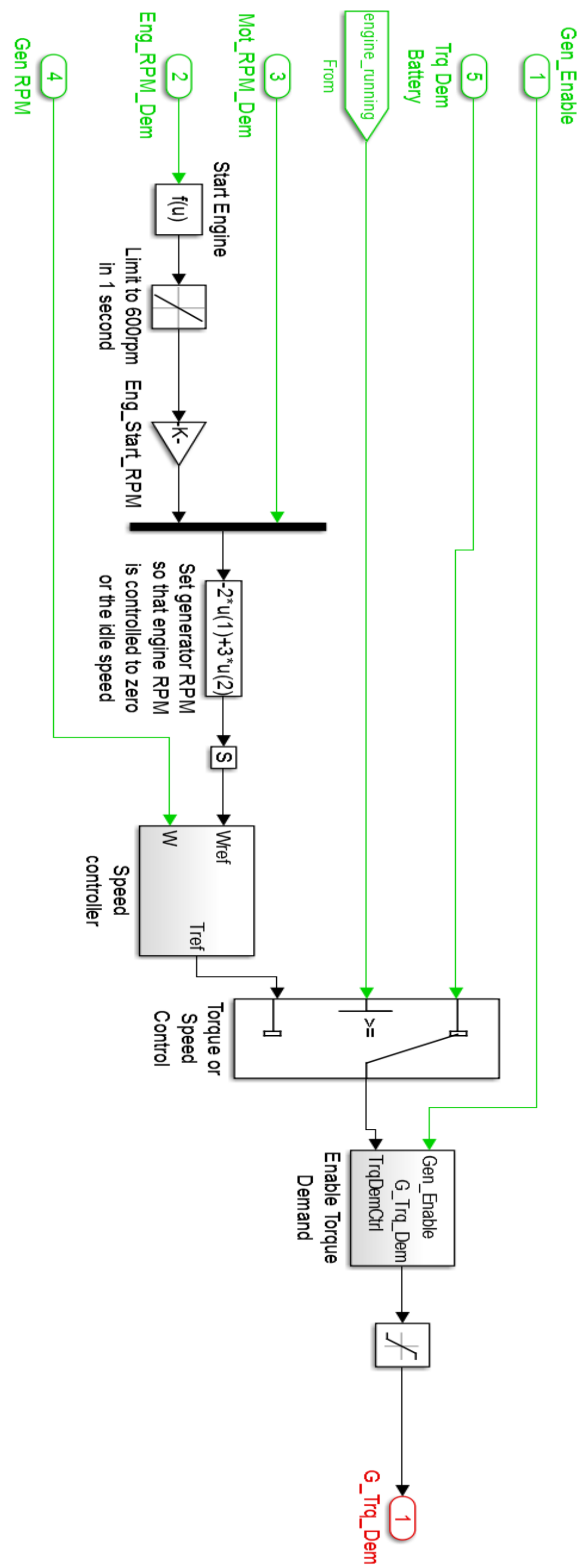

Figure 3.8. The Generator controller.

The generator speed control logic as shown in the fig.3.9 works same as the motor control logic and generates required generator torque signal. And the low pass filter indicates the transport delay from motor/ generator rpm sensor to the generator controller. The maximum speed of the generator is limited 10,000 rpm.

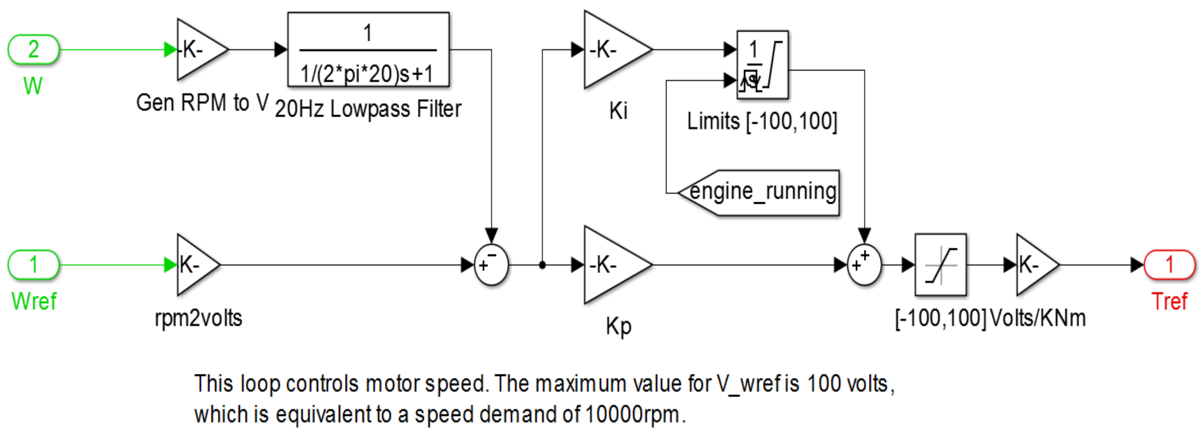

Figure 3.9. Generator speed control logic.

Note: This logic is modified and improved version of the original model in this work. The original model is taken from MATLAB/ Simulink examples. [8]

3.1.6. Motor/ Generator Switch:

This controller unit switches the input signal to the motor in the real situation. In this model, it switches the input signal to the motor dynamics block. The motor torque demand signals are sent to the motor dynamics block when the motor is turned on. Otherwise, the generator torque demand signal passes through it, when the generator is turned on. This switch also initiates parking – charge mode and generator torque demand signal from the battery controller passes through it to the motor. This control unit coordinates with the clutch and gear mechanism in a real situation.

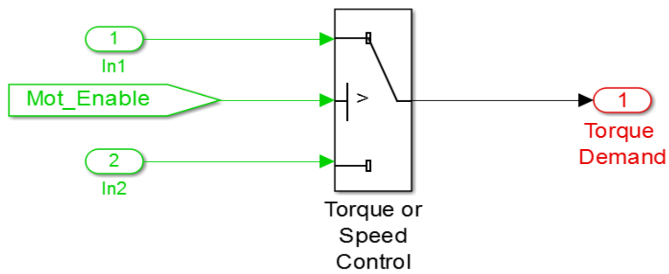

Figure 3.10. The switch block (switches in b/w the motor and generator torque demand signals).

3.1.7. ICE Controller:

The ICE controller block includes engine running block, which activates the ICE and passes the engine RPM demand signal through the switch. Otherwise, the engine is in off mode. The switch one assists the vehicle in the parking – charge mode by maintaining engine rpm little above the idle speed, where this power is transferred to the generator to charge the battery. Finally, the error between ICE rpm demand and ICE rpm is processed through PI – control logic, which generates a control signal. Then the generated control signal is converted into throttle opening fraction as shown in the fig.3.11., which will control the ICE.

The ICE enable block enables engine as required. The low pass filter indicates the transport delay from the central controller to the ICE controller unit.

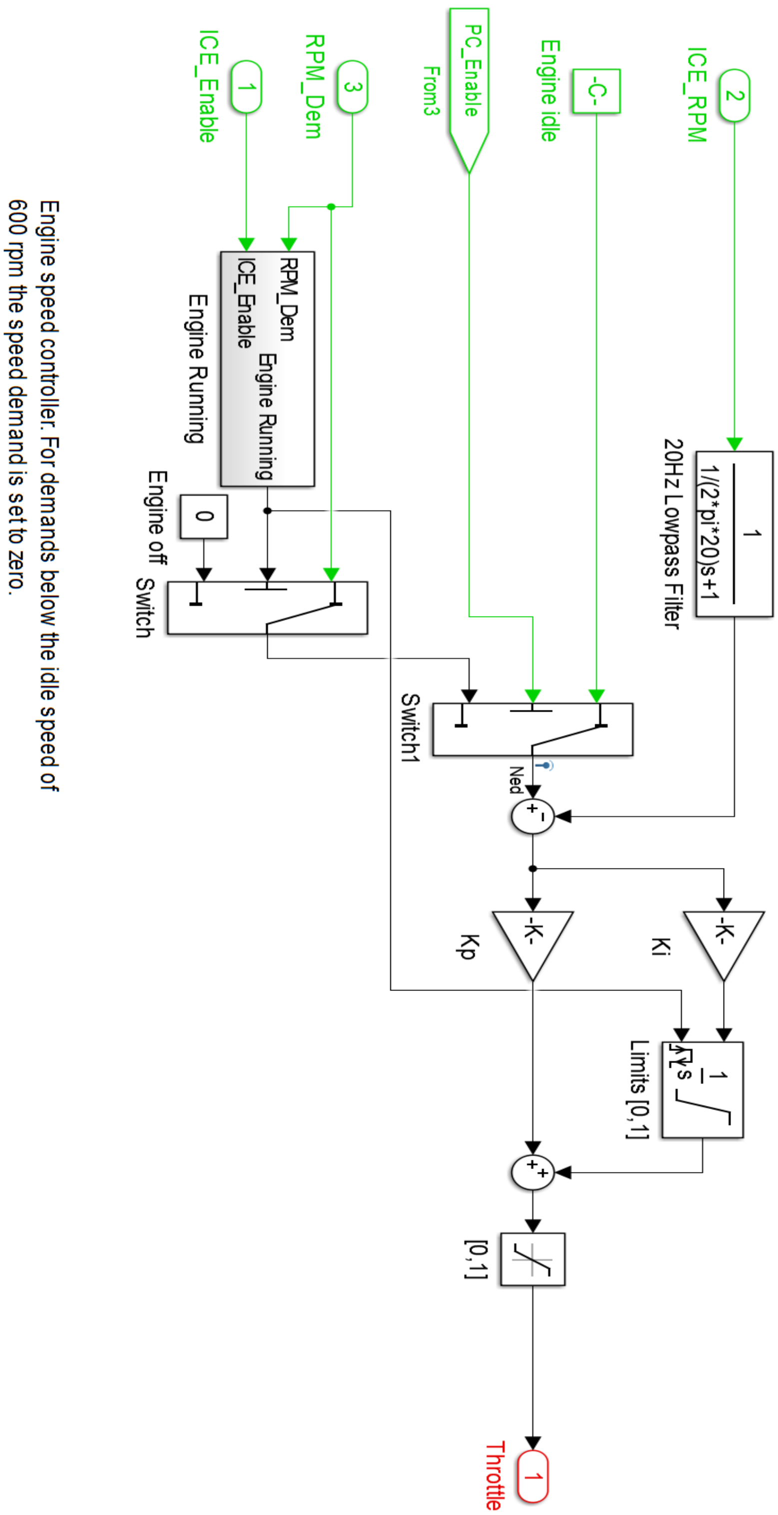

Figure 3.11. The ICE speed controller.

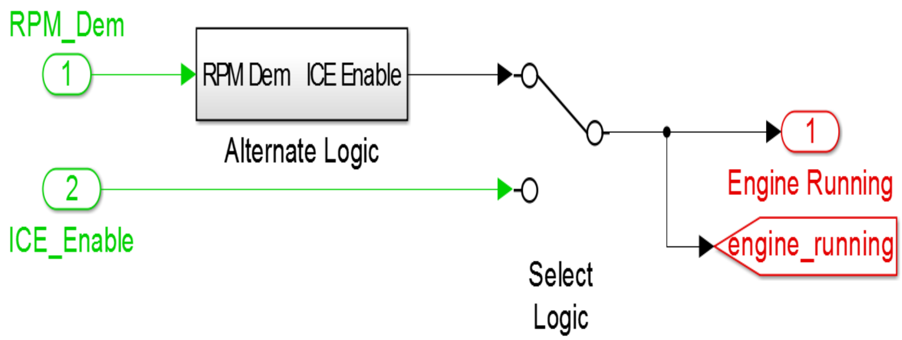

Figure 3.12. The activation block of the engine.

This logic is modified and improved version of the original model in this work. The original model is taken from MATLAB/ Simulink examples. [8]

3.2. Electrical system

The electrical part of a vehicle includes three major subsystems.

1. Synchronous Motor/ Generator.
2. DC – DC converter.
3. Li – ion battery.

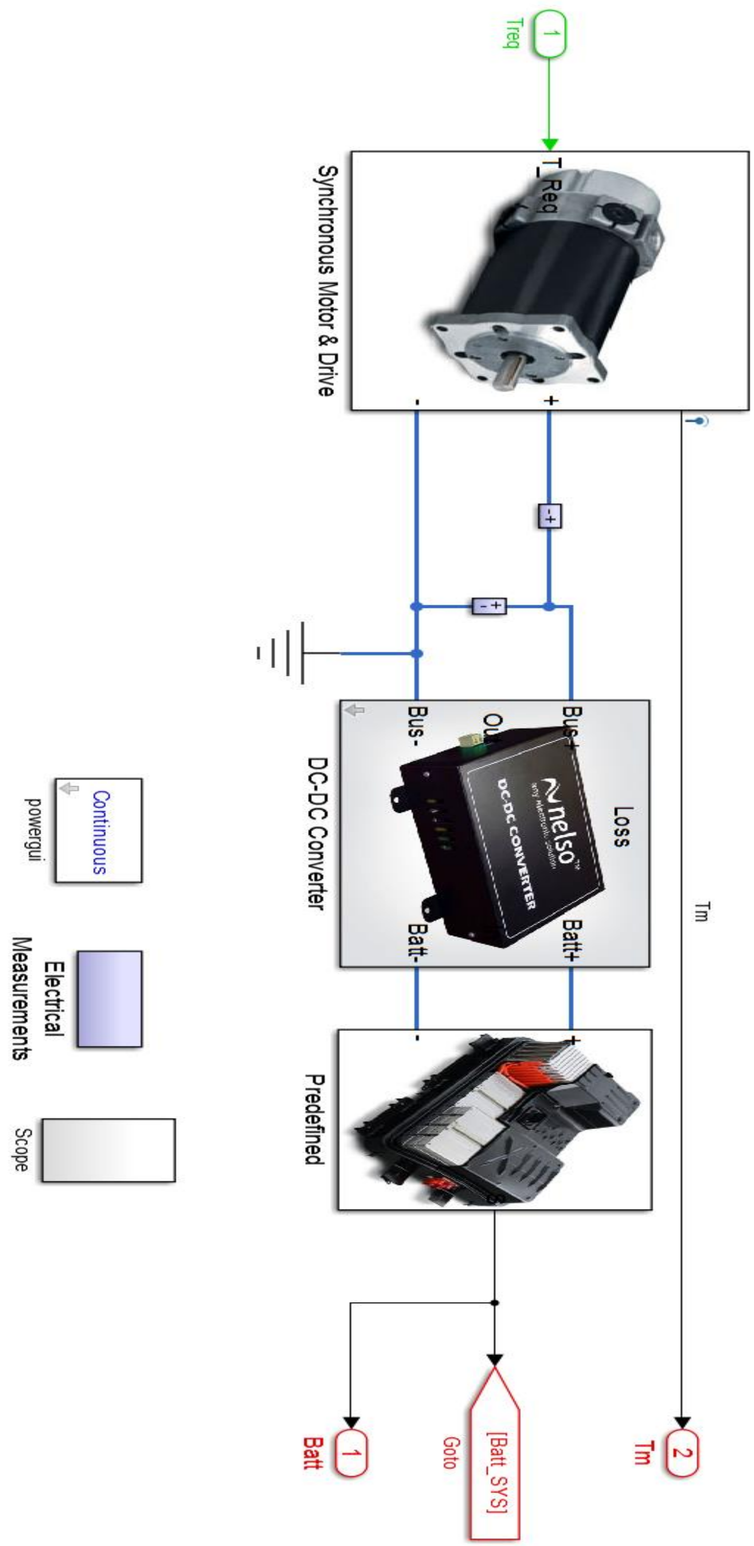

Figure 3.13. The electrical system of the tractor, which includes motor dynamics, DC – DC converter and battery.

3.2.1. Synchronous Motor:

The synchronous motor from Simscape libraries is used as a motor plant dynamics in this model. This block represents servomotor and drive electronics operating in torque control mode, or equivalently current-control mode. The motor's permissible range of torques and speeds is defined by a torque-speed envelope, and the output torque is assumed to track the torque reference demand Tr with time constant Tc.

The servomotor block should be connected to a DC supply. Electrical losses are considered to be the sum of a constant term plus two additional terms that are proportional to the square of the torque and the square of the speed respectively. Also, a resistor in series with the supply can be included to model transmission losses between the power supply and servo motor driver. “The block produces a positive torque acting from the mechanical C to R ports.” [10]

The toque – speed envelope is a look up table, which is developed as follows,

Motor Torque Speed LUT Speed (RPM) = [0 1200 2000 3000 4000 5000 6000 6500 10000];

Motor Torque Speed LUT Torque (Nm) = [400 400 225 150 100 80 70 0 0];

where maximum torque is limited to 400 Nm and top speed is limited to 10,000 rpm.

The other parameters of the synchronous motor are,

Motor Stator Resistance = 0.0065*14; (Ampere-hours)

Motor Damping = 1e-5; N*m/(rad/s)

Motor Torque Control Time Constant = 0.02*2/1.5;

Motor Shaft Inertia = 0.2; (kg. m^2)

Motor Series Resistance = 0.01; CHG

Motor Inductances = [0.001597972349731   0.002057052250467];

Motor Efficiency = 91;

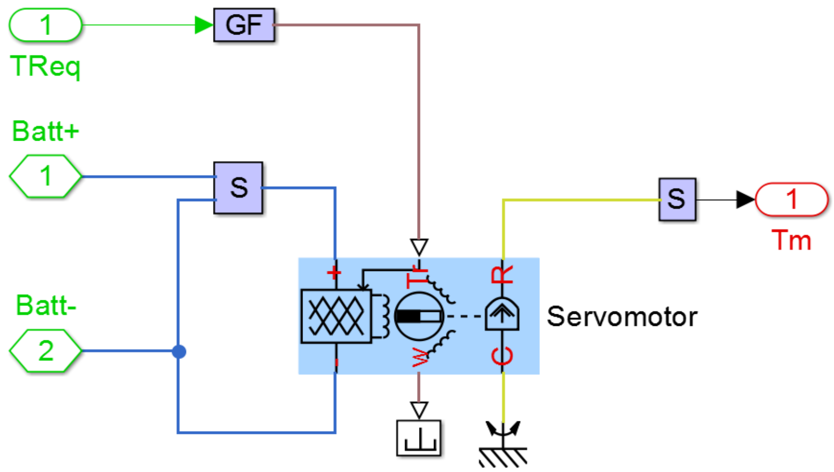

Figure 3.14. The Synchronous motor dynamics (model is taken from Simscape> sim electronics). The ports of this physical model as depicted in fig.3.14 are,

(+) Positive electrical DC supply

(-) Negative electrical DC supply

Tr Reference torque demand

W Mechanical speed output

C Mechanical rotational conserving port

R Mechanical rotational conserving port

3.2.2. DC – DC Converter:

"This power converter regulates voltage on the load side, and the required amount of power is drawn from the supply side to balance input power, output power, and losses. The converter can support regenerative power flow from load to supply".[11] As shown in the fig 3.15., this block has four electrical conserving ports. Polarity is indicated by the + and - signs.

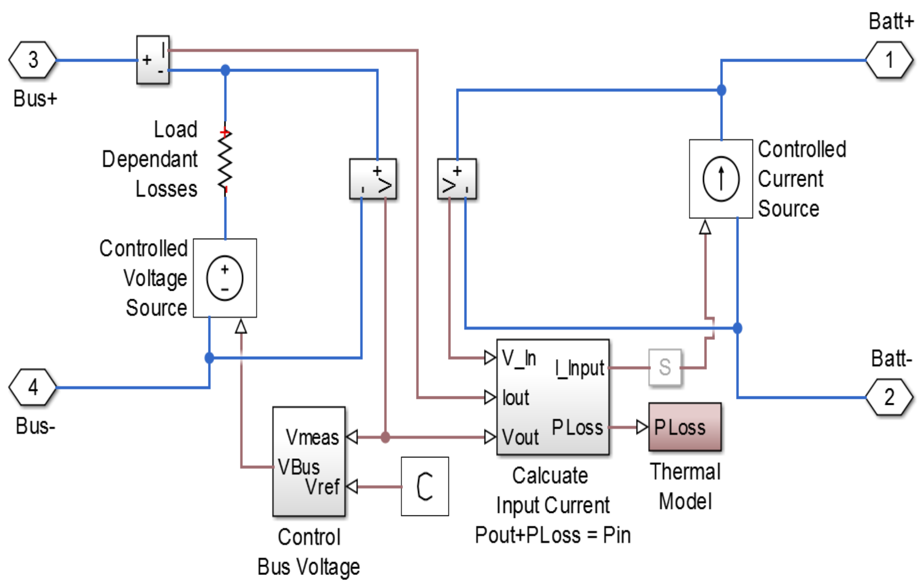

Figure 3.15. DC – DC converter physical model (taken from Simscape > sim power systems).

The model parameters of the DC – DC converter are,

DCDC Converter Output Voltage = 500;	Volts
DCDC Converter Resistance Losses = 1000/40^2;	Ohm
DCDC Converter Minimum Vin = 20;	
DCDC Converter Mean Boost Kp = 0.001;	
DCDC Converter Mean Boost Ki = 1;	
DCDC Converter EPower2Heat = 0.1;	Watts/Watts
DCDC Converter Thermal Mass = 0.1*10;	kg
DCDC Converter Specific Heat = 100;	J/kg/K

DCDC Converter Initial Temperature = 25;	C
DCDC Converter Air Temperature = 298;	K
DCDC Converter Convection Area = 20;	cm^2
DCDC Converter Convection.HT Coefficient = 100;	W/(m^2*K)

3.2.3. Li – Ion Battery:

The battery model is taken from the sim power systems library. The battery supplies power to the DC – DC converter when power is required at the load and stores the power developed by the generator.

The model parameters are,

Battery Nominal Voltage = 200;	
Battery Rated Capacity = 8.1;	% Ampere-hours
Battery Initial SOC = 50;	% Percent
Battery Series Resistance = 0.2/10;	% Ohm

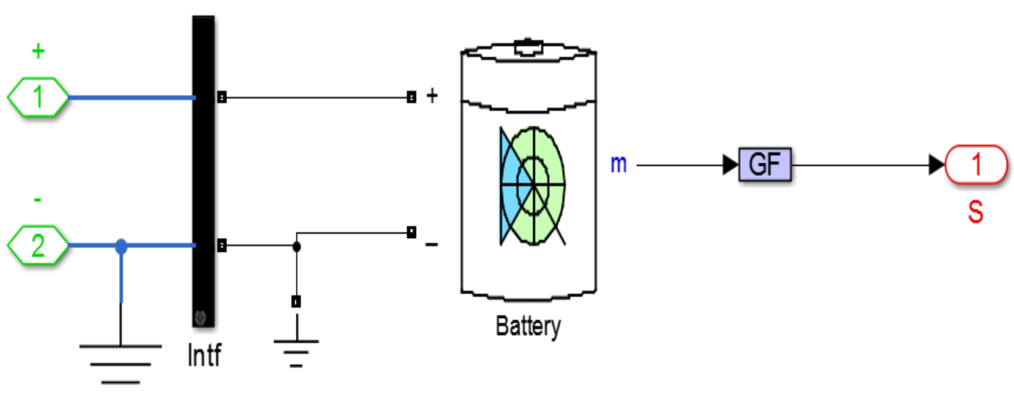

Figure 3.16. The Li – ion battery dynamics (taken from Simscape > sim power systems).

3.3. Engine Dynamics

ICE is modeled as a lug curve for different throttle values (without any transient dynamics), T_{eng} $(\theta_{throttle}, w_{eng})$,

$$J_{eng}*w_{eng}(t) = T_{eng}(\theta_{throttle}, w_{eng}) - T_{imp}(t) \qquad (3.1)$$

$T_{eng}(\theta_{throttle}, w_{eng})$, is known as engine map. The engine lug curve is developed for the John Deere PSS 9 L diesel engine from the engine performance curves as shown in the fig 3.17.,

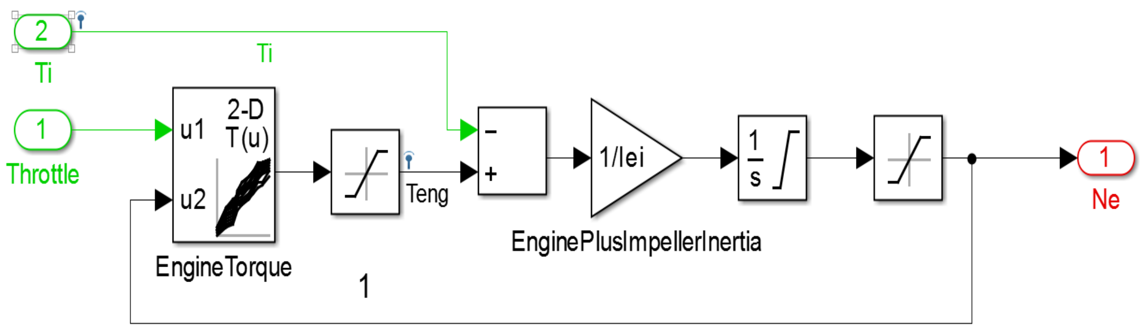

Figure 3.17. Engine Dynamics (includes engine lug curve of John Deere PSS 9 L diesel engine).

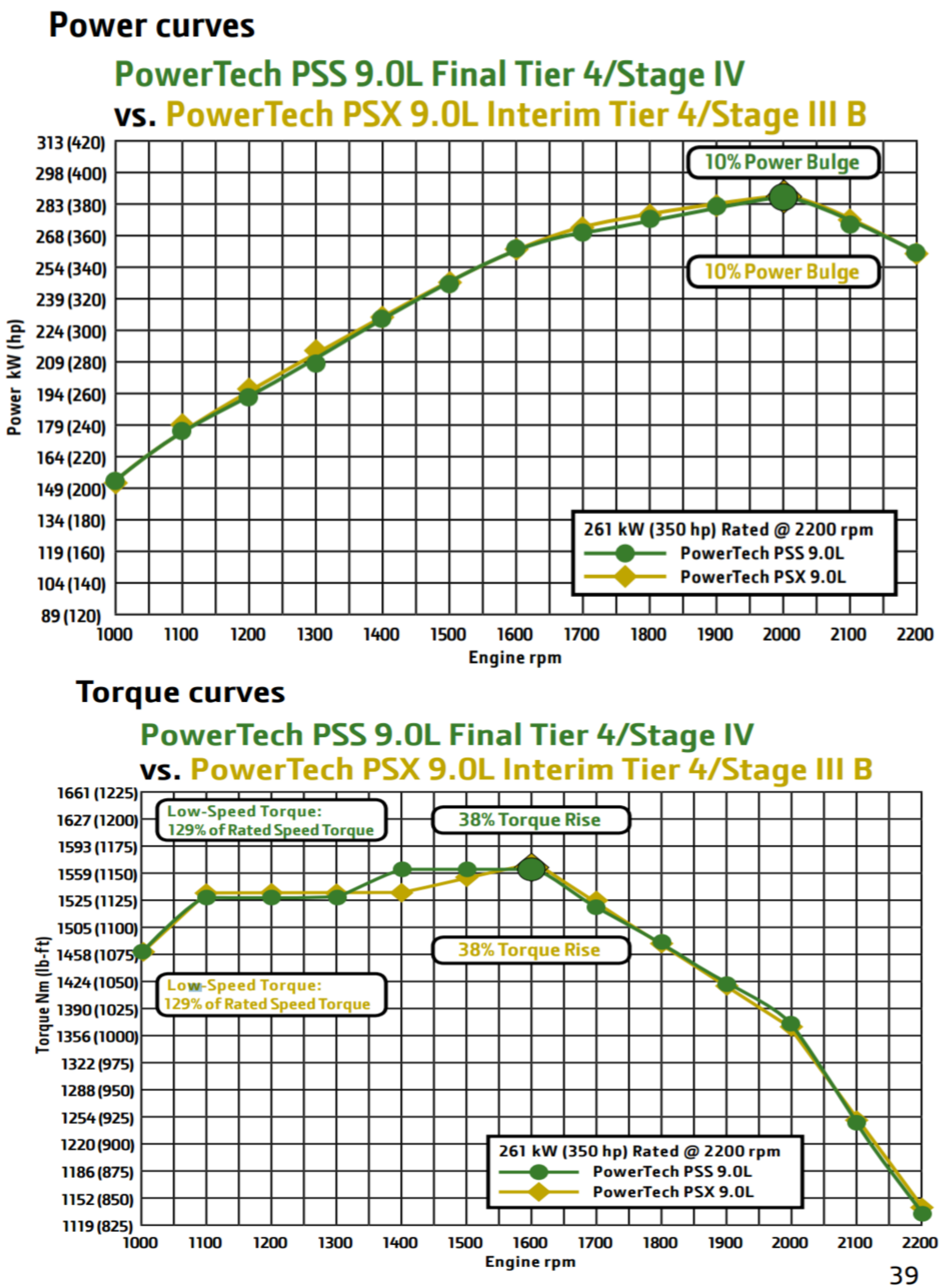

Figure 3.18. Engine lug curve for power and torque output as a function of an engine speed at full throttle. [12]

Table I John Deere PSS 9.0 L diesel engine details. [13]

John Deere PSS	
	diesel
	6-cylinder
	liquid-cooled
	549.2 ci [9.0 L]
Bore/Stroke:	4.661x5.354 inches [118 x 136 mm]
Emissions:	Tier IV
Rated Power (EC 97/98):	370 hp [275.9 kW]
Maximum Power (EC 97/68):	407 hp [303.5 kW]
Fuel system:	electronic high-pressure common-rail
Compression:	16:1
Rated RPM:	2100
Starter:	Electric
Starter volts:	12
Oil capacity:	35.9 qts [34.0 L]
Coolant capacity:	44.4 qts [42.0 L]

3.4. Torque Converter

The torque converter is modeled as two steady – state functions, primary torque, and torque ratio, which are defined as a function of the speed ratio. The efficiency of the torque converter is assumed to be 100%. The two steady-state curves of the torque converter are defined as

$$T_{imp}\,(t) = T_p(w_{turb}/w_{eng}) * (w_{eng}/w_r)^2 \qquad (3.2)$$

$$T_{turb} = N_t\,(w_{turb}/w_{eng}) * T_{imp}(t) \qquad (3.3)$$

After simplification of above equations (3.2 and 3.3.), we will get following empirical relations,

$$T_p\,(w_{eng},\, w_{turb}) = 1000 - 4000 * ((w_{turb}/w_{eng}) - 0.5)^2 \tag{3.3}$$

$$N_r\,(w_{eng},\, w_{turb}) = 2.5 * (1 - w_{turb}/w_{eng}) \tag{3.4}$$

where wr is the rated speed where torque converter performance is given, $w_r = 2400$ rpm.

The turbine output of the torque converter is transmitted to the transmission through a lock-up clutch (where the input to output torque ratio of this clutch is 1:1) and a gear mechanism.

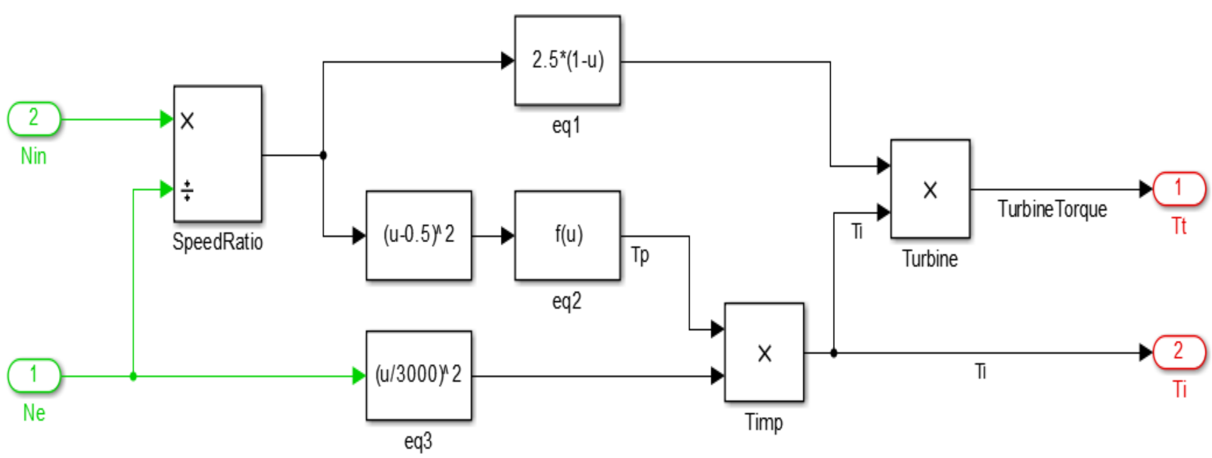

Figure 3.19. Torque Converter dynamics.

3.5. Clutch and Gear Mechanism

The torques from the ICE and motor are added by using two parallel shafts (for example, transaxle of the ford escape), which transfer torques to the transmission through gear mechanisms as shown in the fig 3.20. The gear C on the motor shaft and the gear H on the torque converter output shaft are connected to gear E and gear D respectively, where this mechanism adds the torques from the both shafts. The gear ratio from C to E and from H to D are maintained at 1:1, hence, transfer losses are neglected. Where gear D, E and F are mounted on a transfer gear, which acts as a counter shaft and the powers received from both engine and motor shafts are added here and then transferred to transmission input shaft through F and I gear mechanism. The motor power transfers to the transmission when the clutch 1 engages, and the synchronous cone and hub type mechanism (‘B’ as shown in the fig 3.20) attach the gear C to the motor output shaft while the power from the torque converter is transferred through a lock-up clutch (or torque converter). In the battery charging mode, the gear C disengages and gear A engages to the shaft by synchronizer B and the gear A takes power from the gear G at a gear ratio of 1:4. A maximum of 25 % power can be transferred from engine to generator through this mechanism.

Consider that Engine and Motor shafts are rotating in the clock – wise direction when you are looking from the rear end then the transfer shaft rotates in the anti-clockwise direction. The transmission input and output shaft rotate in the clockwise direction as the transfer shaft rotating in the anti – clockwise direction. In battery charging mode gear G rotates in the clockwise direction, which then turns gear A in an anti-clockwise direction. Hence, the motor acts as a generator. In the case of engine starting and when the state of charge of the battery is less than the 30 %, the motor runs in the anti-clockwise direction to run the torque converter shaft in a clockwise direction. Moreover, lockup clutch engages in this mode. Hence, the torque converter works as a direct drive to give enough kick to start the engine. This gear and clutch mechanism can be implemented in all types of wheel drives (for example, 4-wheel drive in John Deere 9370 R tractor).

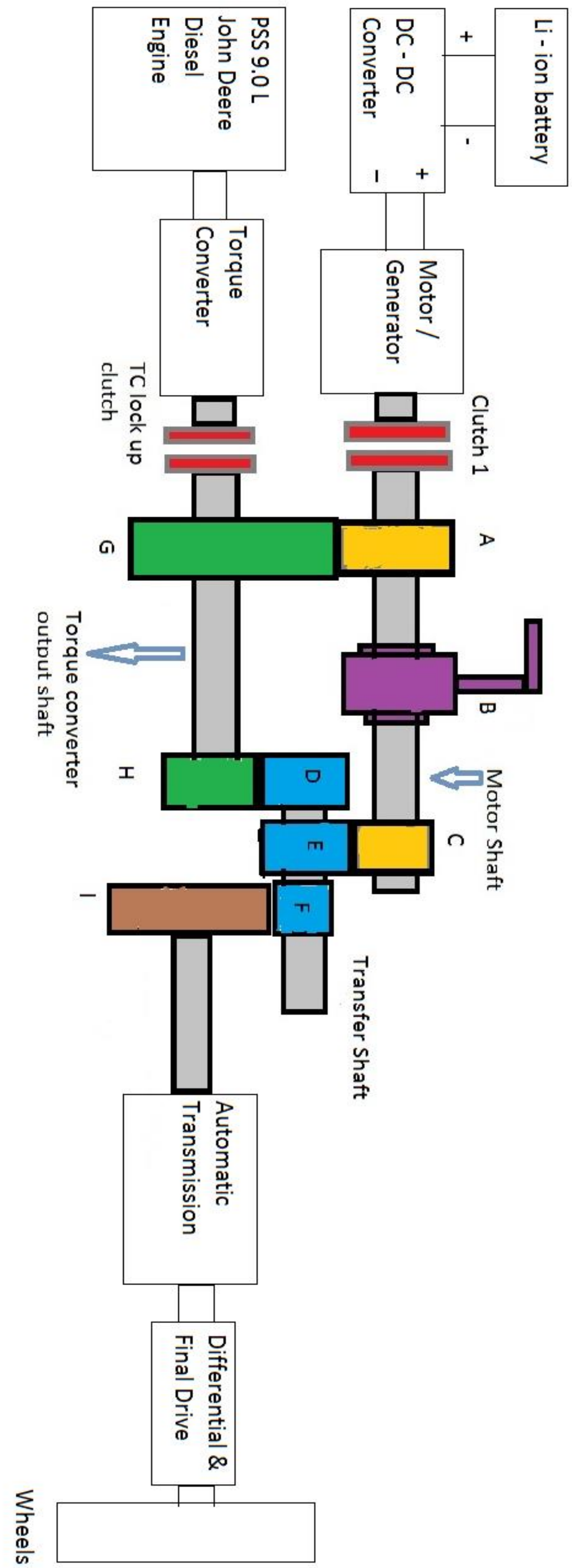

Figure 3.20. Block diagram of the powertrain with the clutch and gear Mechanism.

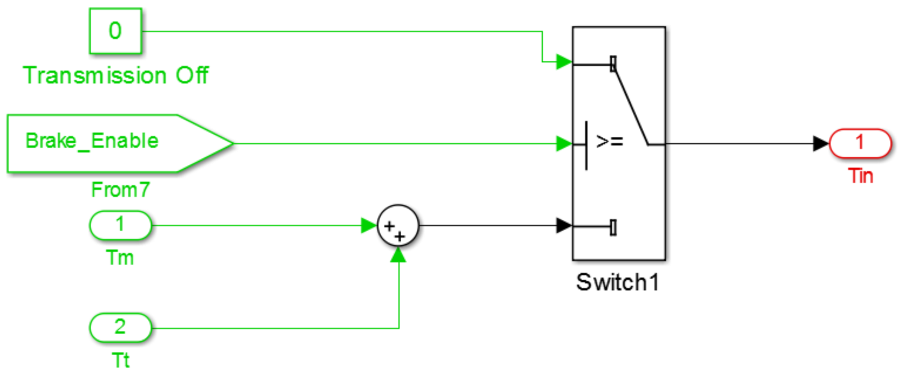

Figure 3.21. Inside clutch and gear mechanism block.

The transmission clutch disengages in two cases, such as brake mode and park – charge mode, where we can use engine power to charge the battery or else engine turns off.

3.6. Automatic Transmission

Transmission of the tractor is a 5 - speed automatic transmission type, where the planetary gear set is assumed to shift to the desired gear instantaneously. The transient time in the gear shifting is neglected, as well as the inertial and stiffness characteristics of the transmission. Simply modeled as an ideal gear ratio device.

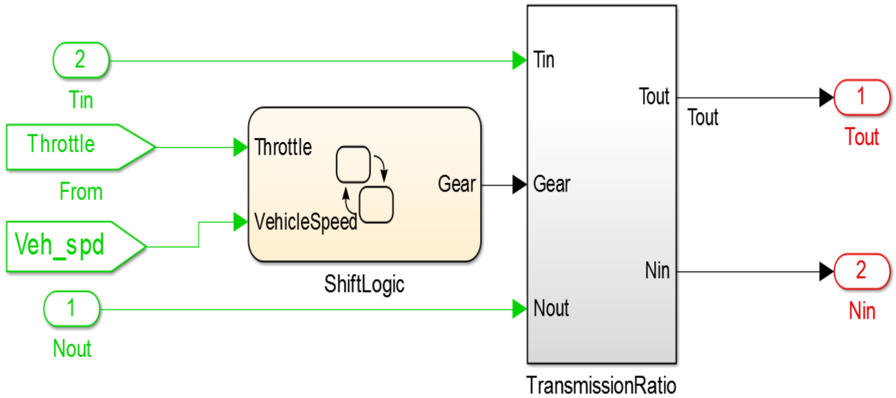

Figure 3.22. The 6 – speed Automatic Transmission including Shift Logic.

3.6.1. Transmission Controller:

The gears are selected by using shift logic as shown in the fig. 3.22., the gear shift is estimated based on the vehicle speed and throttle angle demand. The threshold is computed using two look-up tables as shown in the fig 3.23.

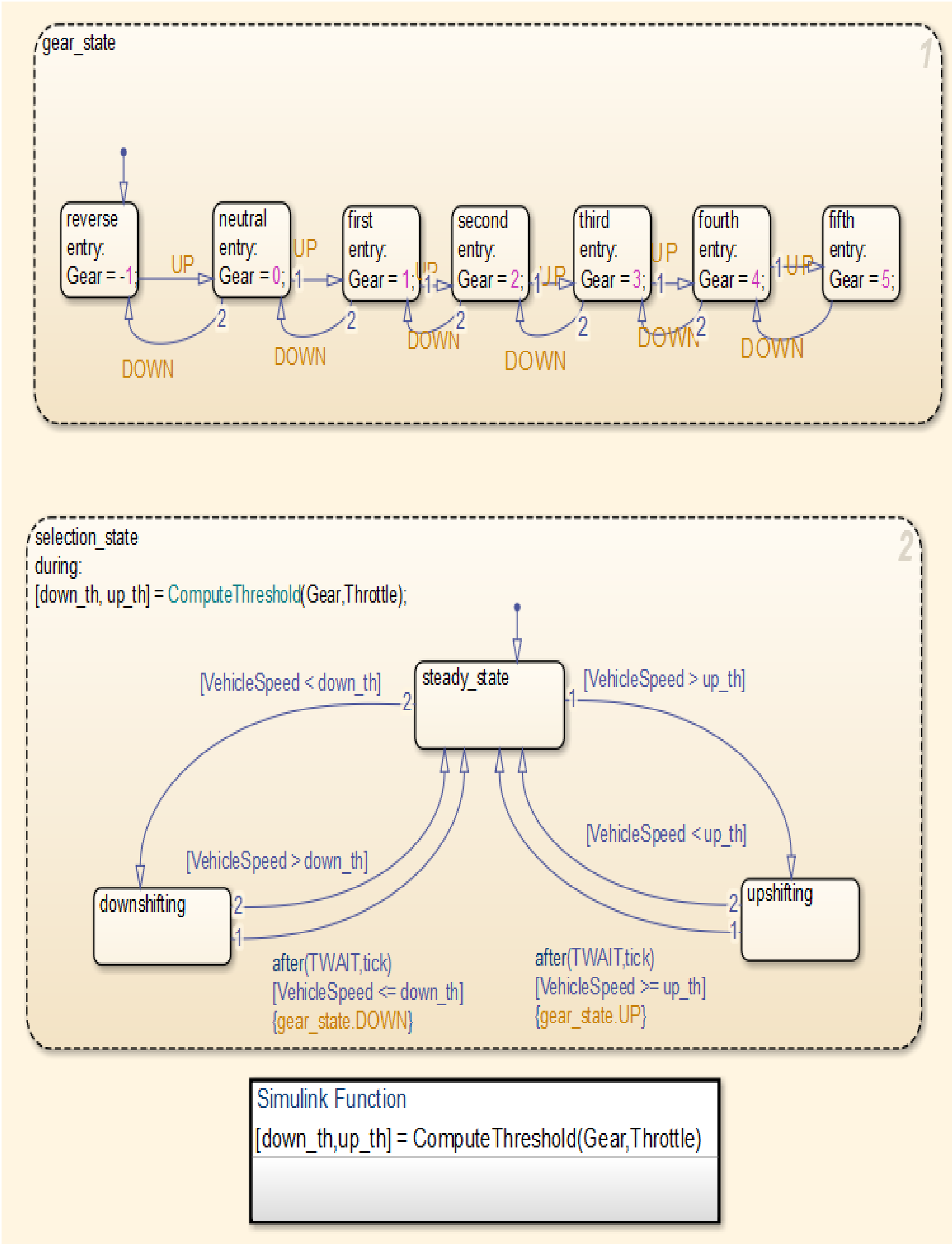

Figure 3.23. Gear Shift Logic.

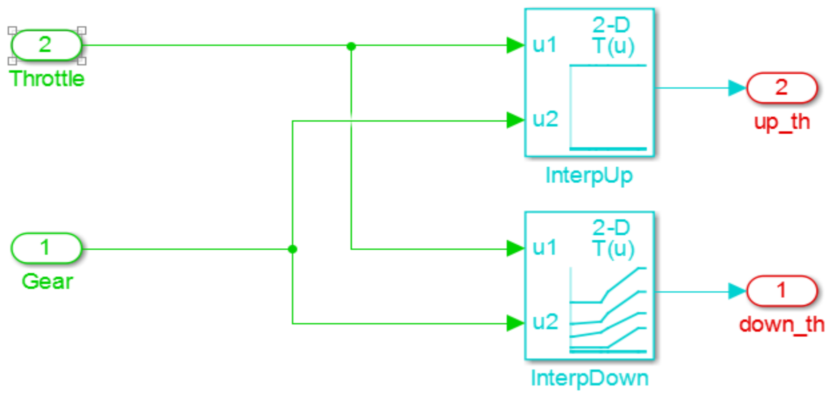

Figure 3.24. Threshold calculation (left).

3.6.2. Transmission Dynamics:

The transmission is modeled by using two simple relations such as,

$$T_{out}(t) = Np * T_{turb}(t) \quad (3.5)$$

$$w_{out}(t) = (1/Np) * w_{turb}(t) \quad (3.6)$$

And customized to John Deere DF 250 Transmission, [14]

Gear number vs gear ratio:

$$Np\ (-1, 0, 1, 2, 3, 4, 5) = \{5,0,5,2.5,1.5,1.0,0.5\} \quad (3.7)$$

Gear number vs. maximum vehicle speed (KPH):

1. Up threshold

   $Np\ (-1, 0, 1, 2, 3, 4, 5) = \{-30, 0, 10,25,35, 45, 75\}$

2. Down threshold

$$Np\ (-1, 0, 1, 2, 3, 4, 5) = \{0,0,0,10, 25, 40,55\} \quad (3.8)$$

Note: negative sign indicates reverse direction.

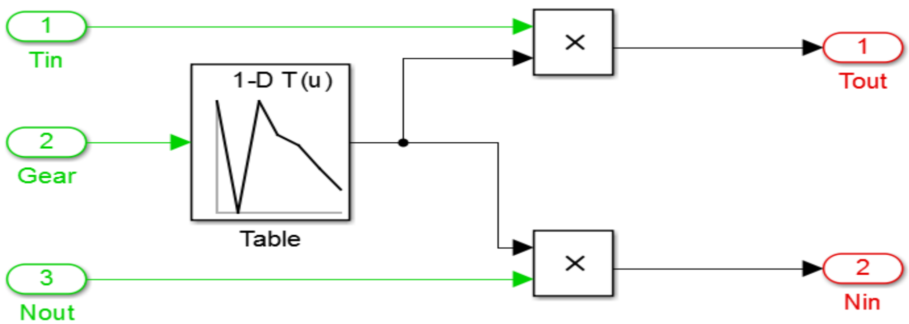

Figure 3.25. Transmission Dynamics.

3.7. Vehicle Dynamics

The vehicle dynamics are modeled by assuming the friction coefficient at each tire–ground contact is constant, and the same for all tires and the vehicle weight is equally distributed in all tires.

$$m_{vehicle} \cdot \ddot{x}(t) = F_{traction}(t) - F_{load}(t) \quad (3.9)$$

where

$$F_{traction} = \mu r * 1/ R_{wheel} * T_{out}(t) \quad (3.10)$$

The F_{load} is given by [15]

$$F_{load} = F_{roadload} + F_{gravity} \quad (3.11)$$

$$F_{roadload} = F_{roll} + F_{drag} + F_{damp} \quad (3.12)$$

$$F_{rollfriction}(t) = \mu f * mg * \cos(\beta\pi/180^{o}) \quad (3.13)$$

$$F_{drag}(t) = \alpha V^{2} * sgn(V) \quad (3.14)$$

$$F_{gravity}(t) = m_{vehicle} * g * \sin(\beta\pi/180^{o}) \quad (3.15)$$

$$F_{damp} = b_{w} * V / R_{wheel} \quad (3.16)$$

Table II Numerical values for the tractor in this simulation.

Description	Symbols	Nominal value	Units
Vehicle mass	m	2200	Kg
Drag coefficient	α	6	N/(m/s)2
Bearing damping coefficient	bw	0.035	N ms/rad
Radius of tire	Rwheel	0.5	m
Friction coefficient	μf	0.015	
Gravity acceleration Road slope/grade Traction coefficient	G B μr	9.81 0-25 0.9	m/s2 deg

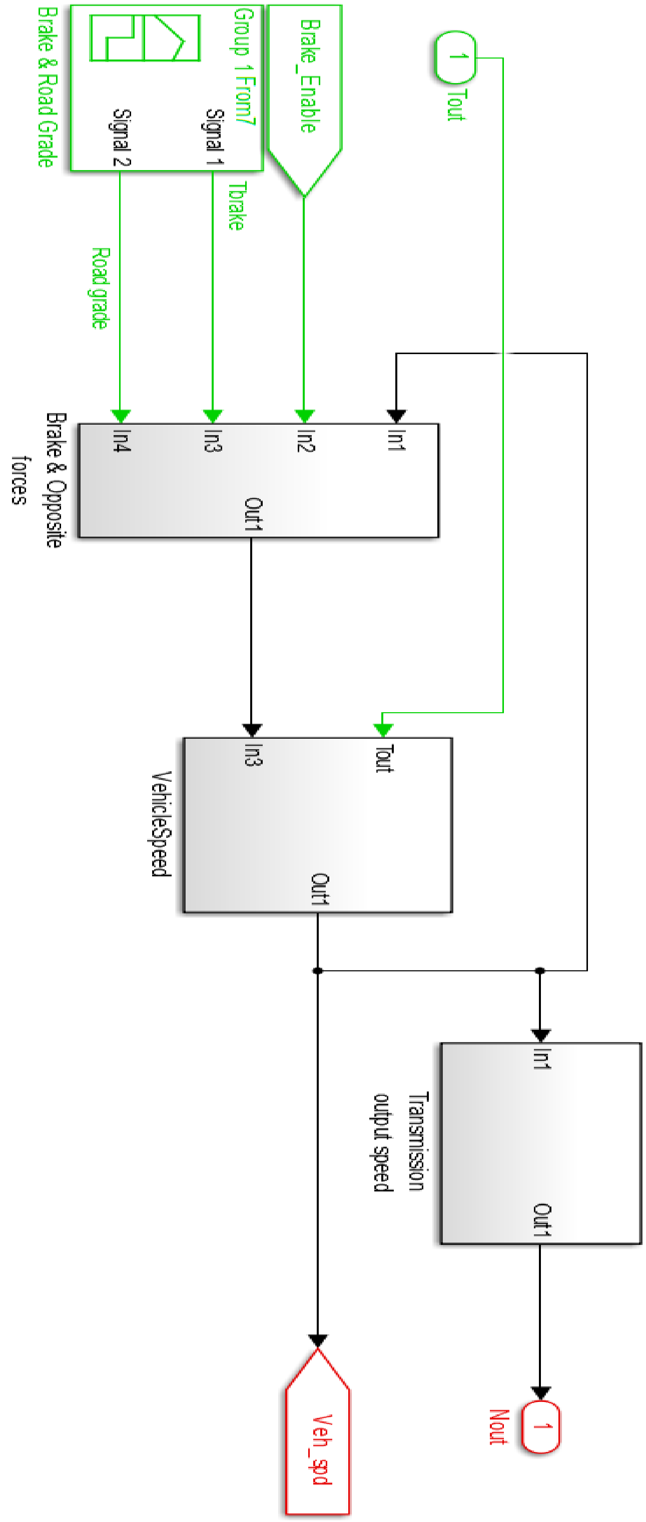

Figure 3.26. Vehicle Dynamics.

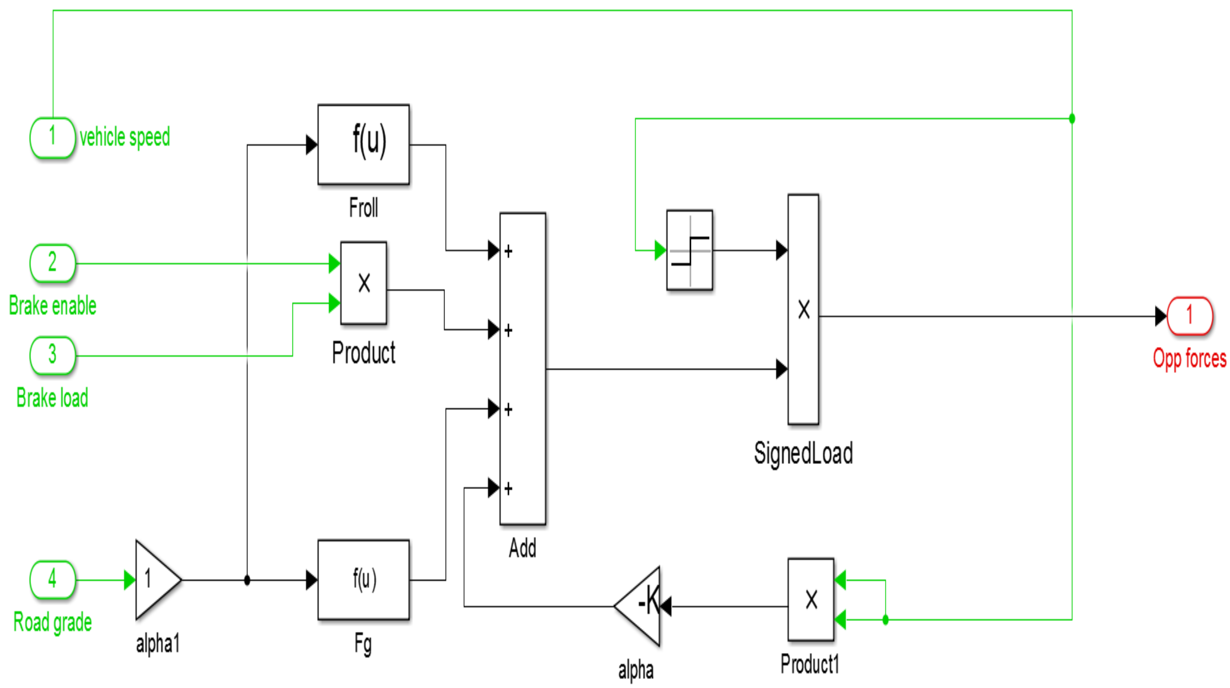

Figure 3.27. Brake and Other Forces.

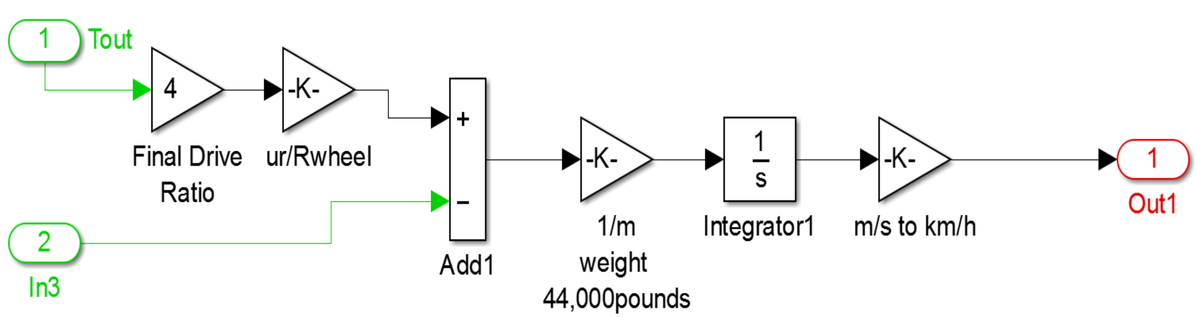

Figure 3.28. Vehicle Speed Model.

4. SIMULATIONS AND RESULTS

Model Parameters:

% PREDEFINED LI-ION BATTERY PARAMS

Battery Nominal Voltage = 200;

Battery Rated Capacity = 8.1; % Ampere-hours

Battery Initial SOC = 50; % Percent

Battery Series Resistance = 0.2/10; % Ohm

% MOTOR PARAMETERS

Motor Stator Resistance = 0.0065*14; % Ampere-hours

Motor Torque Speed LUT Speed (RPM) = [0 1200 2000 3000 4000 5000 6000 6500 10000];

Motor Torque Speed LUT Torque (Nm) = [400 400 225 150 100 80 70 0 0];

Motor Damping = 1e-5; %N*m/(rad/s)

Motor Torque Control Time Constant = 0.02*2/1.5;

Motor Shaft Inertia = 0.2;

Motor Series Resistance = 0.01; %CHG

Motor Inductances = [0.001597972349731 0.002057052250467];

Motor Efficiency = 91;

% DC-DC CONVERTER PARAMETERS

DCDC Converter Output Voltage = 500; % Volts

DCDC Converter Resistance Losses = 1000/40^2; % Ohm

DCDC Converter Kp = 0.01;

DCDC Converter Ki = 10;

DCDC Converter Minimum Vin = 20;

DCDC Converter Mean Boost Kp = 0.001;

DCDC Converter Mean Boost Ki = 1;

DCDC Converter EPower2Heat = 0.1; % Watts/Watts

DCDC Converter Thermal Mass = 0.1*10; % kg

DCDC Converter Specific Heat = 100; % J/kg/K

DCDC Converter Initial Temperature = 25; % C

DCDC Converter Air Temperature = 298; % K

DCDC Converter Convection Area = 20; % cm^2

DCDC Converter Convection HT Coefficient = 100; % W/(m^2*K)

% CONTROLLER PARAMETERS

Control Engine Start RPM = 600; % RPM

Control Engine Stop RPM = 590; % RPM

Control Mode Logic TS = 0.1;

Control ICE Kp = 0.02;

Control ICE Ki = 0.01;

Control Gen Kp = 10;

Control Gen Ki = 3;

Control Mot Kp = 500;

Control Mot Ki = 300;

Control Vehicle Speed Kp = 0.008;

Control Vehicle Speed Ki = 0.4;

Sample time (Ts) =0.01:

Solver settings: ode 23 t – variable step.

Results:

a. Vehicle speed (V) vs. Vehicle Speed Demand (Vd):

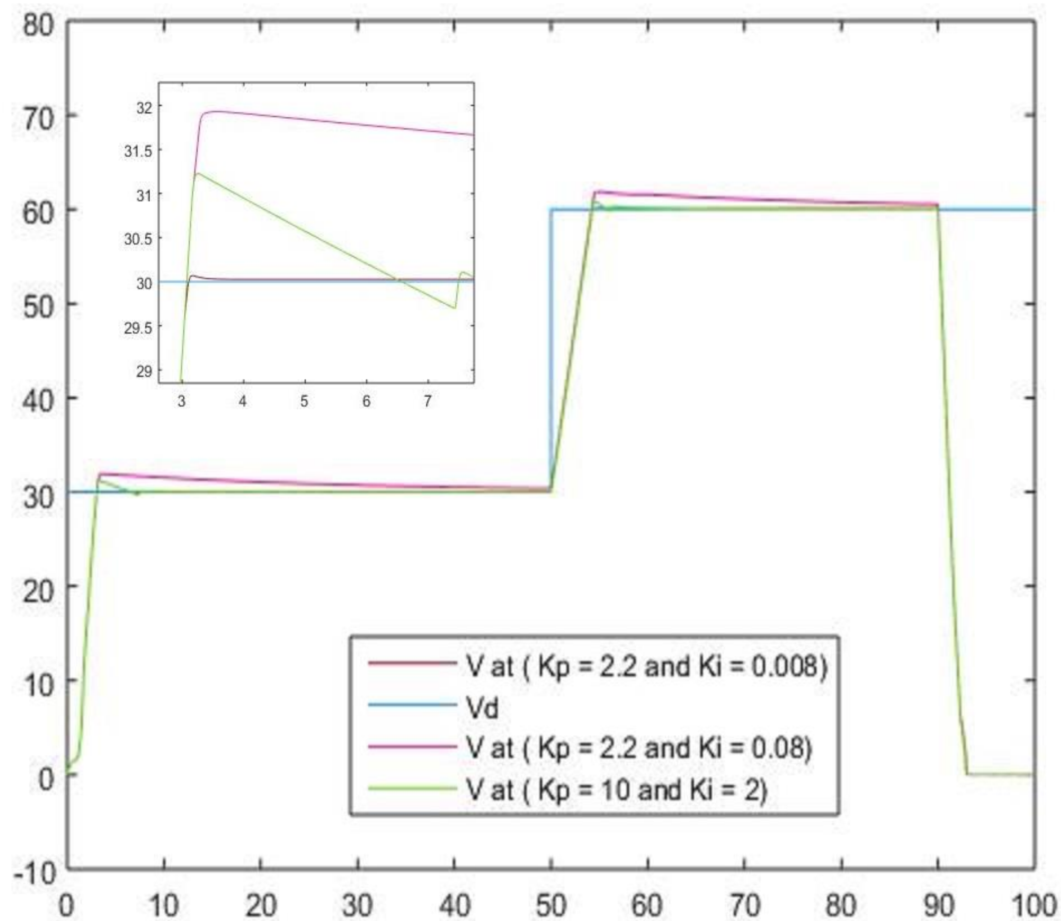

Figure 4.1. Vehicle speed (V) vs. Vehicle Speed Demand (Vd).

The gains of the PI – controllers are estimated using trial and error method and found out Kp = 2.2, and Ki = 0.08 are feasible values for this model. By increasing the Kp value, there is an increase in the overshoot. By decreasing the Kp value, there is an increase in the rising time. Ki value also has a significant effect on the response of the system; the steady state error is growing by increasing or decreasing the integral gain. The rise time of the output signal at Kp = 2.2 and Ki = 0.008 is noted as 3.12 secs, and the steady state error of the output signal is 0.022, where the settling time of the signal is 3.6 secs.

b. Engine Output Torque (Teng) and Motor Torque (Tm) vs. Motor Torque Demand (Tmd):

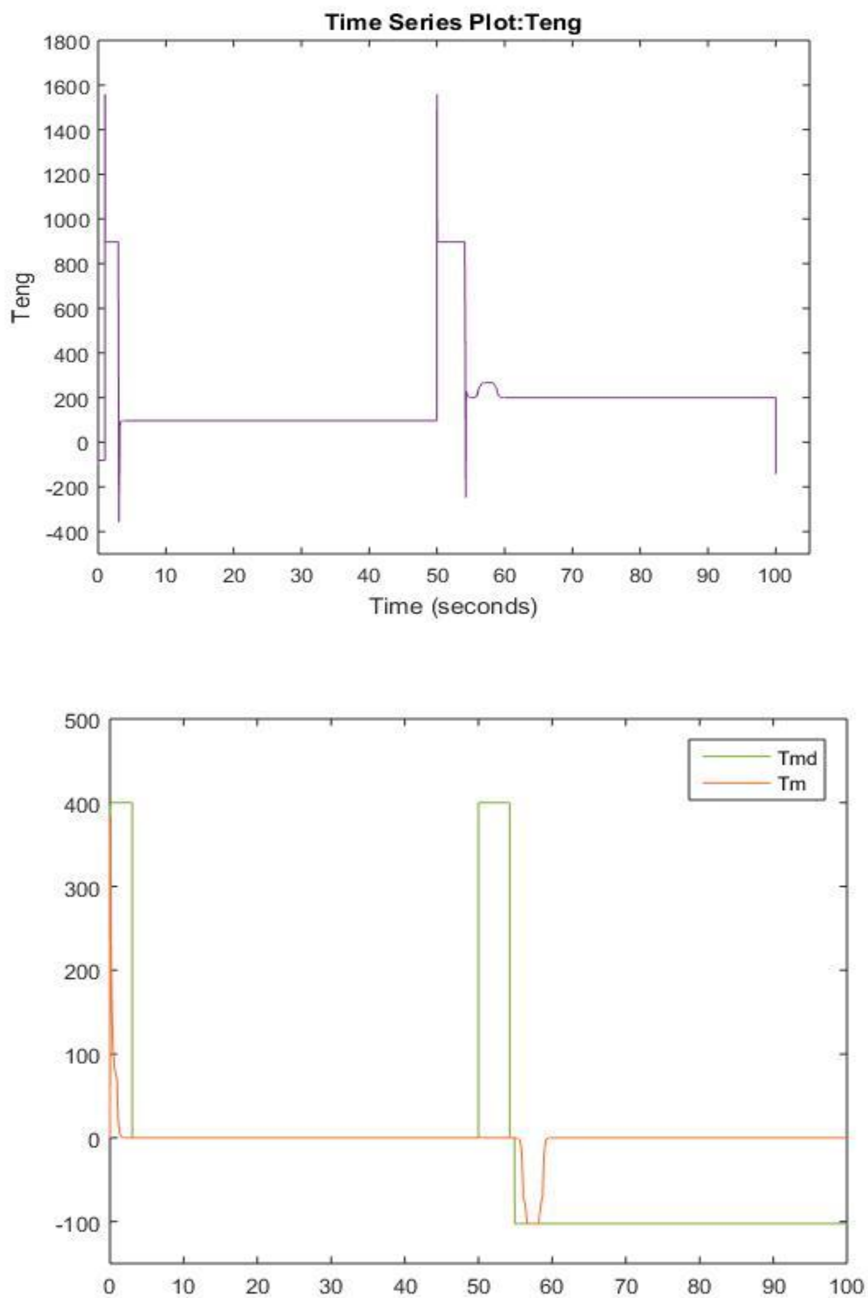

Figure 4.2. The output torque of the engine (Teng) and motor torque (Tm) vs. motor torque demand (Tmd) in Nm

As the engine torque is reaching its maximum torque value at 1525 Nm, which is comparable to the PSS 9L diesel engine maximum torque as shown in the fig 3.17 and the rated rpm is 2200 rpm. Where the engine is producing approximately 80% of the overall torque and remaining torque is produced by the motor as shown in above figure.

c. Engine Speed in RPM (Ne) and Motor Speed in RPM:

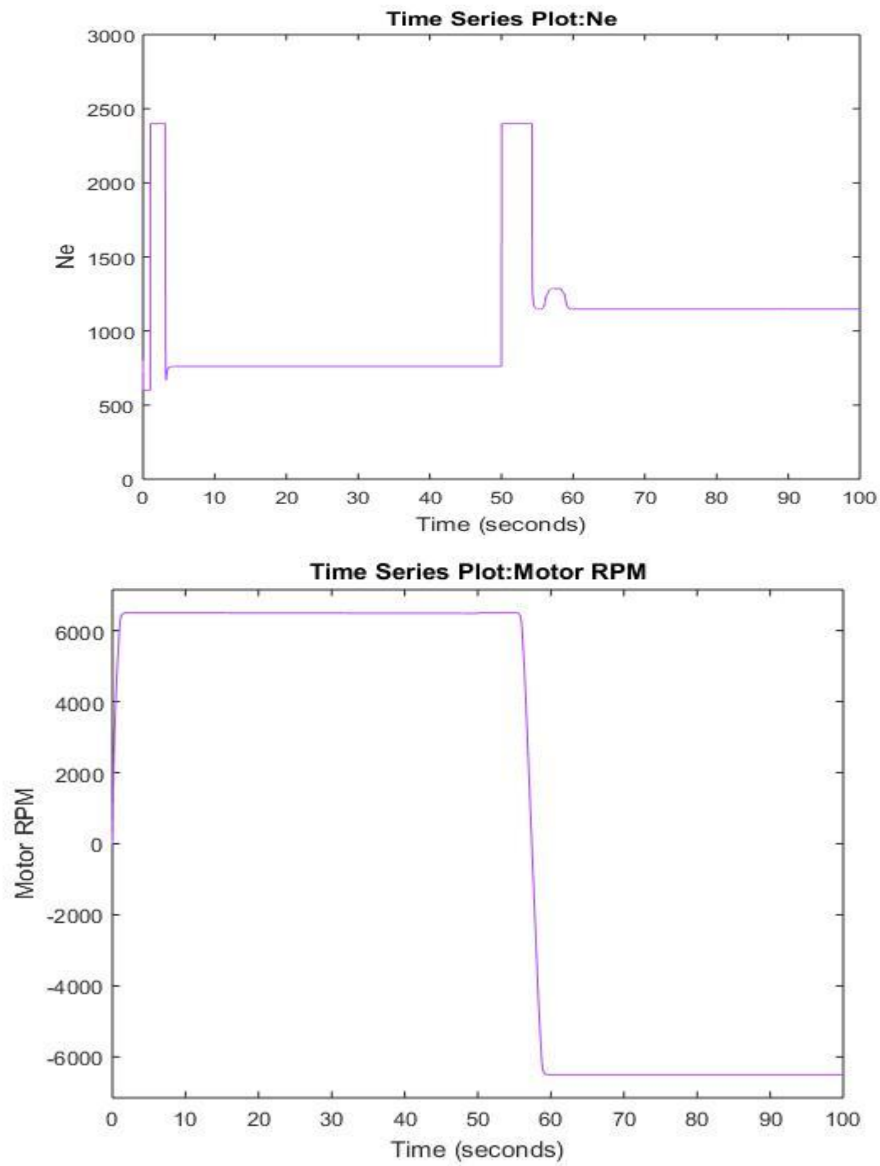

Figure 4.3. Engine speed in RPM (Ne) and motor RPM.

d. State of Charge (SOC %):

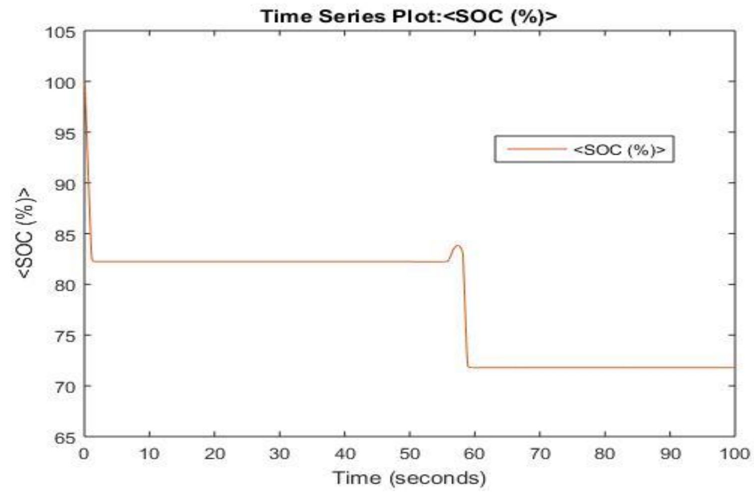

Figure 4.4. The battery state of charge (SOC%).

The motor model is unable to generate the demanded torque due to which the battery is draining. In the case of recharging mode, the motor model is unable to produce the desired torque as shown in the fig. 4.3. Therefore, the SOC% values are not feasible.

e. The output torque to the final drive (Tout):

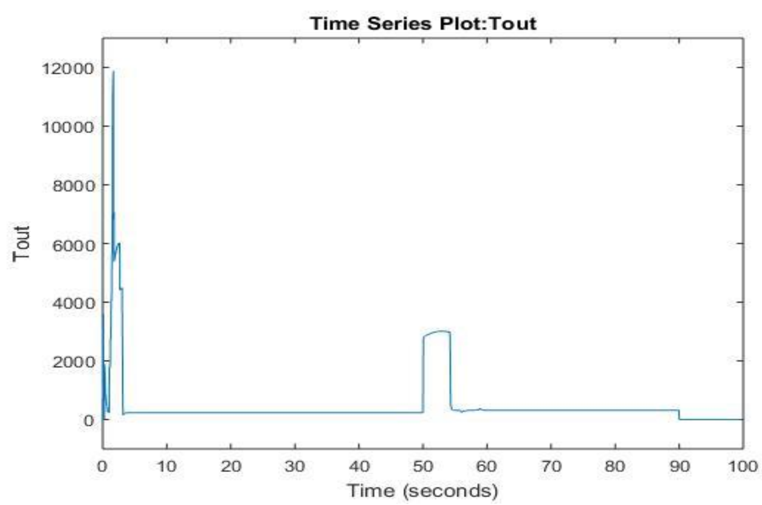

Figure 4.5. The output torque of the Transmission (torque available to the final drive).

1. Effect of the road grade angle on the vehicle speed:

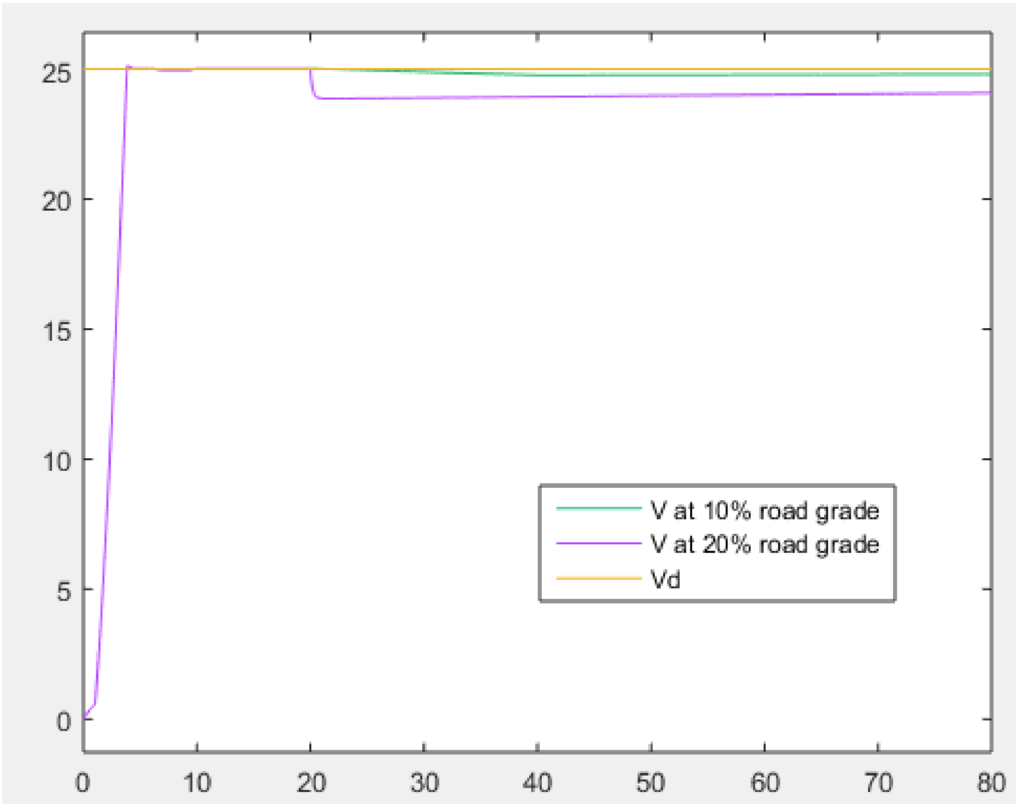

Figure 4.6. The effect of the road grade of 10% and 20% of the vehicle speed (at the vehicle weight of 44,000 pounds).

At the vehicle weight of 44,000 pounds, the powertrain model is capable of maintaining the desired constant speed of 25 kmph after a slight decrease in the vehicle speed upto the road grade of 10%. There is a reduction in the vehicle speed before attaining constant speed at the 20 % of the road grade. By increasing the weight of the vehicle to 60,000 pounds by adding external load, we can observe a significant decrease in the vehicle speed at 20% road grade.

2. Drive cycle:

To study the performance of the PI – controllers, the standard drive cycle is taken as an input velocity signal to the system. This simulation is carried out to study the performance of the tractor powertrain model on the roads. The results in the fig 4.10 indicate that the PI – controller is capable enough to control the vehicle speed of the tractor.

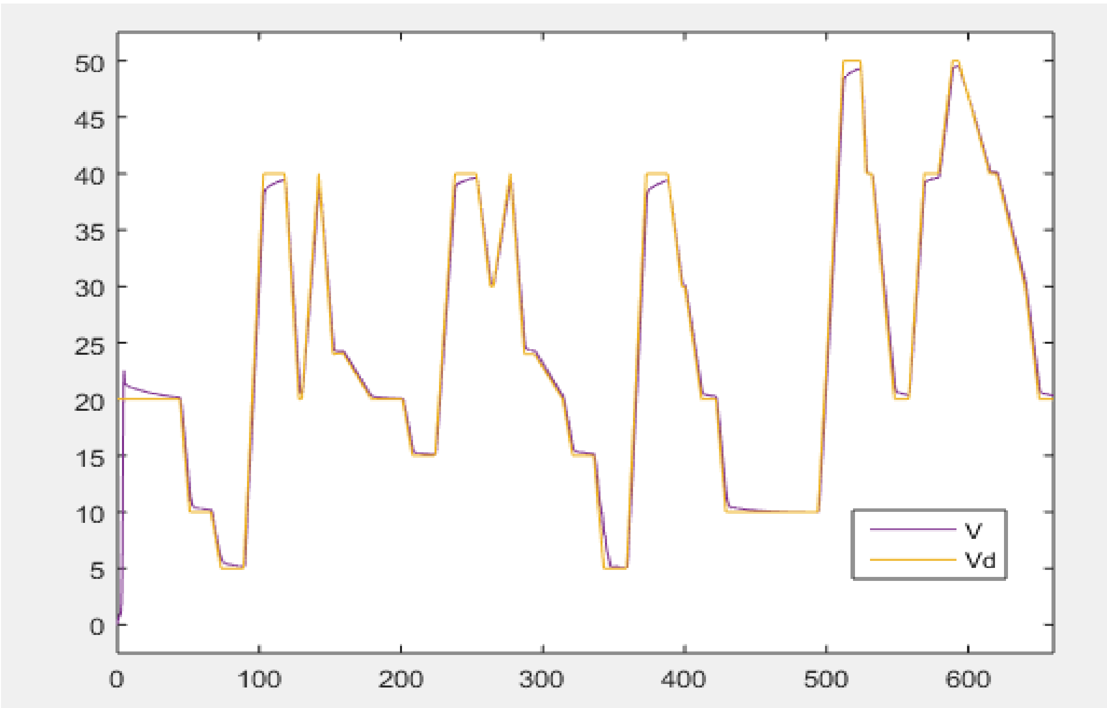

Figure 4.7. The system response to the drive cycle.

5. DISCUSSIONS

The performance of the developed powertrain model is compared with the John Deere 9370 R tractor performance to validate this model. The experimental drawbar pull force results from the NEBRASKA OECD tractor test 2107 – summary 970 John Deere 9370 R are considered, and drawbar pull forces of the developed model are calculated from the torque output after the final drive.

The drawbar pull force is calculated as follows [16]

DP = T x R ÷ r – RR

DP = drawbar pull force.

T = torque output from the power sources.

R = gear reduction including transmission and final drive.

r = radius of the drive wheel.

(T x R ÷ r) = tractive force.

RR = rolling resistance force, which is given by

RR = GVW * C / 1000. (the constant will be 100 in the case of SI units)

Where GVW = Gross vehicle weight.

C = rolling resistance coefficient = 20 (pounds per thousand pounds of rolling resistance on good concrete)

The drawbar full is calculated at three different speeds at the vehicle weight of 44,000 pounds, and rolling resistance of a good concrete surface is considered for calculations.

Table III The drawbar pull calculations.

Vehicle speed (km/h)	Drawbar pull force (KN) of the John Deere 9370 R	Drawbar pull (KN) of the developed powertrain model
7.81	100.60	93.3
9.54	82.33	91.6
13.13	59.46	79.5

6. CONCLUSION

- By introducing another power source such as the motor, the maximum speed of the vehicle is increased to 60 km/h from 45km/h, and the vehicle can achieve the top speed within 9 seconds.
- The drawbar pull force of this model is comparable to the drawbar pull of the John Deere 9370 R model. Despite the contradiction at the speed of 7.81 km/h, the drawbar pull force of this model is greater than the original model, which is due to the consideration of 100% efficiency for torque converter, transmission and lower powertrain in this developed model.
- The developed powertrain model can climb at the desired constant speed of 25 km/h up to the road grade of 10 %. After that, we can notice a velocity drop before achieving a constant speed.

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VITA

NAME:	Bharath Raj Reddy Dere
EDUCATION:	B.E., Mechanical Engineering, Osmania University, Hyderabad, India, 2014
	M.S., Mechanical Engineering, University of Illinois at Chicago, Chicago, Illinois, 2017
PUBLICATIONS:	Bharath, Rajiv, Srinath. “Stability analysis of vertical takeoff and landing aircraft using ANSYS FLUENT tools.” IJERT (ISSN: 2278-0181), volume. 3, issue 9, September 2014.
	Bharath, Divya Sree, Mahesh. “Design and Analysis of ‘Cyclone Separator’ by varying its geometrical parameters using CAD & CFD.” IJERT (ISSN:22780181), volume. 3, Issue 8, August 2014.