DESIGN OF TWO INPUT TRANSMISSION USING FUZZY LOGIC IN MATLAB

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ABSTRACT
This work presents proposed design of a parallel hybrid transmission with only one electric motor/generator (MG) and without any rotating clutches. The proposed motor/generator integrated hybrid transmission serves to regulate the engine's effective gear ratio (engine rotational velocity versus vehicle velocity) by mixing the engine and electric MG powers through a power controlling device. The proposed design provides some of the benefits and flexibility of a power-split design but using conventional available components in a simpler mechanical layout that makes the design compact, mechanically simple, and operationally flexible. With a control unit, four major modes of operation excluding a regenerative braking capability are shown to be feasible in the proposed hybrid transmission; electric motor mode, engine mode, engine/charge mode, and power modes. Continuously variable transmission (CVT) capability is provided with the engine/charge mode and with the power mode. The power mode can be further subdivided into three hybrid sub-modes that correspond to the direct drive, under-drive, and over-drive of a conventional automatic transmission.
The feasibility of the proposed hybrid transmission is demonstrated with a numerical example employing a simple gear train. In this work a controller is designed to vary the speed of the vehicle for different driving conditions. All basic driving conditions for a car are studied and identified. The new controller is implemented by using fuzzy logic and simulated in MATLAB/ Simulink.

KEYWORDS: Fuzzy Logic, MATLAB, Mechanisms, Nomograph, Planetary Gear trains, Simulink, Two Inputs, Transmission.

تصميم آلية نقل حركه ثنائية المدخل بأستخدام المنطق الغامض في برنامج الماتلاب

عصام العيبي إسماعيل / مدرس/جامعة القادسيه/كلية الهندسه

الخلاصه
يقدّم هذا البحث تصميم جديد لآلية نقل حركه هجينه بأستخدام محرك/مولد كهربائي واحد ودون أي قوابض دواره. يعمل التصميم الجديد على تنظيم النسبه السرعيه الفعاله للمحرك (السرعه الدورانيه للمحرك مقابل سرعه العربه) بخلط قدرتي ماكنة الاحتراق الداخلي والمحرك/المولد الكهربائي خلال وحدة تنظيم القدره. يقدم التصميم المقترح بعض فوائد ومرونة التصميم الشاطر للقدره ولكن بأستخدام مكونات تقليديه متاحه بتركيب ميكانيكي بسيط ، يجعل التصميم مدمجا ، بسيط ميكانيكيا، ومرن تشغيليا". بوجود وحدة سيطرة ، ولآليه نقل الحركه الهجينه المقترحه هناك أربعة أطوار رئيسيه ممكنه عمليا عدا طور الايقاف بتوليد الكهرباء وهي طور المحرك

الكهربائي فقط ، طور ماكنة الاحتراق الداخلي ، طور ماكنة الاحتراق الداخلي /المولد الكهربائي وطور القدرة (ماكنة الاحتراق الداخلي /المحرك الكهربائي). أن الحصول على آلية نقل حركه ذات أمكانيه لتغيير السرعه بصوره مستمره ممكن في طور ماكنة الاحتراق الداخلي /المولد الكهربائي الثاني وفي طور القدرة . ويمكن تقسيم طور القدره الثاني الى ثلاث أطوار ثانويه هي ما دون وما فوق القياده المباشره والقياده المباشره التي تناظر مثيلاتها في ألآليات الآليه التقليديه.

تم التحقق من أمكانية أستخدام الآليه الهجينه المقترحه بمثال عددي وبأستخدام مجموعة ترسيه كوكبيه بسيطه . وتم تصميم مسيطر لتغيير سرعة العجله في ظروف القياده المختلفه. وتم تشخيص جميع ظروف قيادة السياره الاساسيه والتصميم على ضوءها وقد تم تضمين المسيطر باستخدام المنطق الضبابي ومحاكاتها في (MATLAB/SIMULINK).

NOMENCLATURE

$B\omega_m$	The rotational loss torque of the system.
C	Clutch
EGM	Epicyclic gear mechanism
EGT	Epicyclic gear train
ESS	Energy Storage System
FLC	Fuzzy Logic Controller
HEV	Hybrid Electric Vehicle
$K_m = K_f . i_f$	e_a / e_m A constant, which is also the ratio
MG	Electric Motor/Generator
$N_{p,x}$	Gear ratio defined by a planet gear *p* with respect to a sun or ring gear *x*. $N_{p,x} = \pm Z_p / Z_x$, where Z_p and Z_x denote the numbers of teeth on the planet and the sun or ring gear, respectively, and the positive or negative signs depend on whether *x* is a ring or sun gear.
OWC	One way clutch
PGT	Planetary gear train
R_C	Reverse Clutch
SOC	State of Charge
THS	Toyota Hybrid System
Two-dof	Two-degree of freedom
Zi	Number of teeth on gear *i*
c	Carrier
s	Sun Gear
r	Ring Gear
p	Planet Gear
ω_i	Angular velocity of link *i*
$\tau_a = L_{aq} / R_a$	The electrical time constant of the armature.
$\tau_m = J / B$	The mechanical time constant of the system.

INTRODUCTION AND LITERATURE REVIEW

A Hybrid System combines two motive power sources, such as an internal combustion engine and an electric motor, to achieve efficient driving performance.

A hybrid electric vehicle (HEV) achieves fuel economy, and improved performance by combining a smaller than normal engine with electric motor(s) and an energy storage system (ESS). The engine is smaller in displacement, or downsized, so that the average loads that the vehicle has to meet during acceleration and highway driving are closer to the engine's higher efficiency operating zones, represented by the 30% efficiency in **Figure 1** [1].

A HEV uses the electric motors and ESS to average the load on the engine, to achieve an efficient use of fuel. One or two electric motors are used in a variety of ways, depending on how they are connected to the vehicle power train [2]. Motors can provide a positive torque to drive the vehicle alone in the forward or reverse direction, or assist the engine during acceleration. One way to increase the average load and decrease fuel use is to shut off the engine when the vehicle load is small. Commonly this is referred to as engine idle stop, but the engine can sometimes be kept off for light accelerations and low cruising velocities.

Peak power demands on the engine, such as a hard acceleration, can be lowered by using the motors to supply some of the additional power required, and discharge the batteries.

Under conditions in which motors demand negative torque, they operate as generators to recharge the batteries.

By acting as a generator, the electric motor increases the average load on the engine.

Numerous HEV configurations have been proposed. **John Miller's** book [1] is a good resource for more information about hybrid vehicles and hybrid systems. In the present work, only HEVs with epicyclic-type power trains will be considered.

Tsai and Schultz [3], proposed an improved design of the novel parallel hybrid transmission introduced earlier by **Tsai et al.** [4, 5]. The proposed design provides the transmission the functional appearance of a conventional 4-speed ratio change automatic transmission. The design needs a motor/generator unit with a conventional automatic transmission to function; therefore it requires more complicated controllers and extra electronics hardware than with other hybrids.

Tsai [6] proposed an innovative approach using just one internal combustion (IC) engine, one electric motor/generator, and a power regulating gearbox that can provide a vehicle with six different operating modes including a regenerative braking capability. Recently **Esmail** [7] proposed new designs of parallel hybrid transmissions with only one electric motor/generator (MG) and without any rotating clutches.

Toyota Hybrid System (THS) [2], which is a series/parallel hybrid, contains a power split devise that splits power into two paths. In one path, the power from the engine is directly transmitted to the vehicle's wheels. In the other path (electrical path), the power from the engine is converted into electricity by a generator to drive an electric motor or to charge the battery. Since the engine is the primary converter on the vehicle, the direct fuel to engine to wheels path is the most efficient energy path on the vehicle.

THS posses many favourable characteristics; however the potential disadvantages of THS design include the need for two electrical motors and a constant split of the engine power. Also, the simultaneous dual motor operation requires sophisticated control systems and intricate custom fabrication [8].

Electric machines are used to generate mechanical work in industries. The DC machine is considered to be basic electric machine. The aim of this work is to use computer simulation as a tool for conducting transient and control studies. Next to having an actual system to experiment on, simulation is often chosen by engineers to test conceptual designs [9].

SIMULINK is the program used to complete the modelling and simulation of a model; it is a subprogram of MATLAB. In SIMULINK, a model is a collection of blocks which, in general, represents a system. MATLAB/SIMULINK is used because of the short learning term that most students require to start using it, its wide distribution, and its general-purpose nature. This will

demonstrate the advantages of using MATLAB for analyzing system steady state behaviour and its capabilities for simulating transients in systems, including control system dynamic behaviour [10].
This work presents a new design of a hybrid transmission with only one electric motor/generator and without any clutches.
Any epicyclic gear set is considered adaptable to suit the new design of the hybrid transmission. For the kinematic analysis of epicyclic gear mechanisms (EGMs) various approaches have been proposed. In this work the new developed nomograph method [11] will be used.

NOMOGRAPHS

A nomograph is defined as three or more axes, or scales, arranged such that problems of three or more variables can be solved using a straightedge. In the particular case of EGTs, a nomograph can be constructed using three or more vertical parallel axes [11 and 12].
A basic EGT consists of sun gear, ring gear, planet, and carrier as shown in **Figure 2**. **Figure 3** shows the basic form of the graph to be created for a basic EGT. The term "gear ratio" is used in this paper to denote the ratio of a meshing gear pair. It is defined by a planet gear *p* with respect to a sun or ring gear *x*

$$N_{p,x} = \mp Z_p / Z_x \tag{1}$$

Where Z*p* and Z*x* denote the numbers of teeth on the planet and the sun or ring gear, respectively, and the positive or negative sign depends on whether *x* is a ring or sun gear.
Considering the kinematics of a fundamental circuit, the fundamental circuit equation can be written as Buchsbaum and Freudenstein [13]:

$$(\omega_x - \omega_c)/(\omega_p - \omega_c) = N_{p,x} \tag{2}$$

Equation (2) can be re-written for the links of the basic EGT to find $N_{p,r}, N_{p,s}, N_{p,p}$ *and* $N_{p,c}$. These values are used to place the axes of the nomograph shown in **Figure 3**. The ω_c axis passes at the origin, and the ω_p axis is one unit apart from it. The gear ratios for this train are

$$N_{p,r} = Z_p / Z_r \tag{3}$$

and

$$N_{p,s} = -Z_p / Z_s \tag{4}$$

From **Figure 3** the characteristic equation can be written as follows:

$$\frac{\omega_r - \omega_c}{\omega_r - \omega_s} = \frac{N_{p,r}}{N_{p,r} - N_{p,s}} \tag{5}$$

The number of teeth of ring gear is 71, the number of teeth of planet gear is 16 and the number of teeth of sun gear is 39.
By substituting these values in Equations3, 4 and 5 the following equation is obtained

$$\omega_c = 0.64566 \ \ \omega_r + 0.35427 \ \ \omega_s \tag{6}$$

CONCEPTAL DESIGN AND MODELLING OF THE HYBRID TRANSMISSION

The new hybrid transmission system consists of an engine and an electric motor/generator coupled together by a simple gear train in such a way that both of the engine and electric motor/generator

can simultaneously provide torque to the wheels. **Figure 4** shows the new hybrid transmission system.
The electric motor/generator can function as a motor to add torque to or as a generator to subtract torque from that produced by the engine. The electric generator regulates the speed of the vehicle by varying its loading so that the engine can be operated at a constant speed.
Figure 5 shows the block diagram of the new hybrid system. The engine serves as one power source and the battery as the second power source. The motor/generator can receive power from the battery to drive the vehicle or take power from the engine to charge the battery depending on the driving condition.
A power controlling epicyclic gear train (PC EGT) is used to control the power flow among the engine, the motor/generator and the vehicle, so that the vehicle can operate in several different modes. These modes are shown schematically in **Figures 6, 7, 8 and 9**.

OPERATION MODES

1. Electric Motor Mode

When first started, the vehicle begins to operate using the motor unless the battery state of charge (SOC) is low. The one-way clutch (OWC) is engaged and the electric motor alone drives the vehicle in the forward direction. To drive the vehicle in the reverse direction, the reverse clutch is engaged and the motor rotates in the opposite direction.
The electric motor alone drives the vehicle in the forward or reverse direction to avoid low load engine operation in which the engine experiences poor efficiency. The electric motor is used to lunch the vehicle from a standstill and for driving in city traffic.

2. Engine/Charge or First CVT Mode

Once the engine has started, MG begins generating electricity, or adding power depending on the power demand and the battery SOC.
When both of the demand for power and SOC are low with MG functioning as a generator part of the engine power is directed to the wheels and the other part goes to the electric MG for charging the batteries.
These conditions force the EGT to function as a power splitting; one-input and two-output device. Part of the engine power is directed to the wheels and the other part goes to the electric MG for charging the batteries. The ratio of these two powers is continuously variable. Therefore, it is possible to run the engine at optimal operating conditions while regulating the load of the output shaft by controlling the load of the generator. Also, for a given output power, it is possible to run the engine at an optimal operating efficiency point by controlling the load of the generator. **Figure 10** shows the nomograph for this mode with the upper and lower limits of the generator velocities for certain engine velocity.
From this Figure, we can easily visualize that the engine can operate at any desired velocity while the velocity of the vehicle is regulated by controlling the generator velocity. When all of the engine power is converted to electric power then the engine is idling and the vehicle is stationary. When MG is stationary the mode is the engine mode.

3. Engine Mode

During steady-state highway cruising and when the battery SOC is high to handle accessory loads, the transmission can operate in the engine mode.
The battery supplies MG with current to generate sufficient torque to lock it in place. The engine alone drives the vehicle in the forward direction, electricity generation is basically not necessary.

4. Power or Second CVT Mode

At moderate and high vehicle velocities with MG functioning as a motor, both the electric motor and the engine drive the vehicle simultaneously in a power mode [14].

There are three cases:

- When both of the motor and engine rotate at the same velocity, the gear set locks up as a rigid body. A hybrid mode that corresponds to the direct drive of a conventional automatic transmission except for the fact that both of the electric motor and engine transmit their power to the output shaft with a one-to-one gear ratio.
- At moderate vehicle velocities, the motor rotates slower than the engine; both of them drive the vehicle in an under-drive.
- At high vehicle velocities, the motor rotates faster than the engine; both of them drive the vehicle in an over-drive.

From **Figure 11** by regulating the amount of the motor power (by varying its rotational velocity), the motor allows the engine to operate at an optimal condition. In this regard the EGT functions as a CVT.

In another words, the engine can be operated at any desired velocity while the velocity of the vehicle is regulated by the electric motor.

MOTOR MODELLING AND SIMULATION

To perform the simulation of a system, an appropriate model needs to be established. For this work, the system contains a DC motor. Therefore, a model based on the motor specifications needs to be obtained.

DC machines are one of the most commonly used machines for electromechanical energy conversion. Converters are used continuously to convert electrical input to mechanical output or vice versa. They are called electric machines. An electric machine is therefore a link between an electrical system and a mechanical system. In these machines, the conversion is reversible. If the conversion is from mechanical to electrical, the machine is said to act as a generator. If the conversion is from electrical to mechanical, the machine is said to act as a motor.

Therefore, the same electric machine can be made to operate as a generator as well as a motor [9]. DC machines may also work as brakes. The brake mode is a generator action but with the electrical power either regenerated or dissipated within the machine system, thus developing a mechanical braking effect. It also converts some electrical or mechanical energy to heat, but this is undesired.

The major advantages of DC machines are easy speed and torque regulation. The major parts of any machine are the stationary component, the stator, and the rotating component, the rotor. Assuming magnetic linearity [9], the basic motor equations are

$$T = K_f . i_f . i_a = K_m . i_a \tag{7}$$

$$e = K_f . i_f . \omega_m = K_m . \omega_m \tag{8}$$

The Laplace transforms of Equations (7) and (8) are

$$T_{(s)} = K_m . i_{a(s)} \tag{9}$$

$$E_a = K_m . \omega_{m(s)} \tag{10}$$

Let the switch SW be closed at t = 0. After the switch is closed,

$$V_t = e_a + R_a i_a + L_{aq} \frac{di_a}{dt} \tag{11}$$

From Equation (8) and (11)

$$V_t = K_m.\omega_m + R_a i_a + L_{aq}\frac{di_a}{dt} \tag{12}$$

The Laplace transform of Equation (12) for zero initial conditions is

$$V_{t(s)} = K_m.\omega_{m(s)} + R_a.I_{a(s)} + L_{aq}s.I_{a(s)} \tag{13}$$

Or

$$V_{t(s)} = K_m.\omega_{m(s)} + R_a.I_{a(s)}.(1+s\tau_a) \tag{14}$$

The dynamic equation for the mechanical system is represents the rotational loss torque of the system

$$T = K_m.i_a = J.\frac{d\omega_m}{dt} + B\omega_m + T_L \tag{15}$$

The Laplace transform of Equation (15) is

$$T_{(s)} = K_m.i_{a(s)} = J.s.\omega_{m(s)} + B\omega_{m(s)} + T_{L(s)} \tag{16}$$

From Equation (15) and (16)

$$\omega_{m(s)} = \frac{T_{(S)} - T_{L(s)}}{B(1+s.J/B)} = \frac{K_m I_{a(s)} - T_{L(s)}}{B(1+s\tau_m)} \tag{17}$$

From Equation (16) and (17),

$$I_{a(s)} = \frac{V_{t(s)} - E_{a(s)}}{R_a(1+s.\tau_a)} = \frac{V_{t(s)} - K_m\omega_{m(s)}}{R_a(1+s.\tau_a)} \tag{18}$$

A block diagram representation of Equation (17) and (18) is shown in **Figure 13**. This block diagram can be simplified and implemented in SIMULINK and the model window shown in **Figure 14** should appear**;** where $L = R_a.\tau_a$ and $J = B.\tau_m$ **.**

For DC motor and as given by reference [15], the following parameters are used:
J=0.01 N.m.s^2/rad
B=0.1
km=10 N.m/A (Engine-motor constant)
km=8 N.m/A (DC-motor constant)
R=1 ohm
L=0.5 F
Load =0.001 N.m
The engine is simulated as a motor in the operational block diagram of the speed control system.

INTELLIGENT CONTROLLER DESIGN

The intelligent speed control system should be designed to provide smooth ride and robustness of the system to varying operating conditions [15 and 16]. In this work a controller has been designed to vary the speed of the vehicle for different driving conditions. The block diagram identifying all necessary functional relations between the controller and other subsystems of the mobile is shown in **Figure 15.** The controller is used as an interface between the vehicle driver and two power sources, IC engine and DC motor. Driver controls the vehicle by pressing accelerator/decelerator pedal. The controller responds to the driver commands and selects an optimal driving condition for the car vehicle mixing intelligently the energies from the two power sources by means of epicyclic

gear train. The feedback loop is used additionally to monitor the actual speed of the DC motor. All basic driving conditions for the car have been identified as follows:
i) Vehicle idling -engine runs, car is still stationary, pedal is untouched.
ii) Vehicle accelerates – accelerator pedal is being pressed to some extent.
iii) Vehicle runs with constant speed – no change in position of the accelerator pedal.
iv)Vehicle decelerates –pedal is being pressed to less extent.
v) Vehicle stops – pedal has been released.
vi) Vehicle reverses – reverse switch is on, accelerator is being pressed.
The new controller is implemented by using fuzzy logic and simulated in MATLAB/SIMULINK. The operational block diagram of the speed control system is shown in **Figure 16**. The default settings are used when running fuzzy logic.
The apparent success of fuzzy logic controller (FLC) can be attributed to its ability to incorporate expert information and generate control surfaces whose shapes can be individually manipulated for different regions of the spaces with virtually no effects on neighbouring regions. FLC is ideal for the velocity control problems, since there is no complete mathematical model of the engine and other components of the car [17]. However, some human driving experience and visual feedback can be used in the design of control system as well [18–23]. Human operators control the velocity of the car by pressing the accelerator pedal. From these human actions, fuzzy rules were formulated using the amount and the rate at which the accelerator and decelerator pedal is pressed [24–26].
The membership functions to represent the inputs and the outputs of FLC are symmetric triangles with equal distribution over the entire range or the universe of discourse. For example, the input values to the controller from the accelerator/decelerator pedal are divided into ten membership functions to describe pedal position in terms of generation or taking electricity, the negative sign refers to the generation of electricity and the positive sign refers to absorbing electricity from batteries. They are ‘very high generation’, ‘high generation’, ‘medium generation’, ‘low generation’, ‘very low generation’ ‘very low motor’, ‘low motor’, ‘medium motor’, ‘high motor’, ‘very high motor’. Similar functions are developed for the feedback velocity.
In the design of the controller the output is presented in the form of voltage signal. Therefore, the output membership functions are named as ‘very high negative voltage’, ‘high negative voltage’, ‘medium negative voltage’, ‘low negative voltage’ , ‘very low negative voltage’, ‘very low positive voltage’, ‘low positive voltage’, ‘medium positive voltage’, ‘high positive voltage’ , ‘very high positive voltage’. There are total of 100 rules formulated for the controller design using Mamdani implications.

SIMULATION RESULTS

In order to test the performance of the designed controller, the MATLAB software and its Fuzzy Logic Toolbox (V7.6.0.320) is used. The toolbox provides a friendly Graphical User Interface (GUI), which makes the testing faster and more efficient.

1. Power Mode

The first step in testing the controller is to generate an operator signal for testing. **Figure 17** shows a motor/generator signal that begins to work at second two as a motor till the eight second. The response of the motor is shown in blue and that for the engine is shown in yellow. The total speed of the vehicle is shown in purple colour in **Figure 18**. The engine is energized and picking up the speed until it begins to rotate in a constant velocity. The DC motor is still off till the time when it begins to pick up speed. The results of simulation are shown in **Figure 18** and **Figure19**, for power mode in which the vehicle accelerate, run with constant velocity or decelerate.

2. Engine/Charge Mode and Power Mode

Figure 20 shows another motor/generator signal that begins to work as generator, then after second two it begins to work as a motor till the eight second. The response of the motor is shown in blue and that for the engine is shown in yellow. The total speed of the vehicle is shown in purple colour in **Figure 21**. The engine is energized and picking up the speed until it begins to rotate in a constant velocity. The DC motor is still off till second two when it begins to pick up speed. The results of simulation are shown in **Figure 21** and **Figure 22** for a power mode in which the vehicle accelerate, run with constant velocity or decelerate.

CONCLUSION

This work successfully introduces a new hybrid transmission design for hybrid vehicles recently immerged in automotive industry. The system does not require a physical braking subsystem which will reduce the overall cost of a car.

The paper presents a new control approach in driving a vehicle. The controller is built on the speed mixing capability of a two degree of freedom epicyclic gear train. Signals from the accelerator/decelerator pedal and reverse button are intelligently treated in FLC to generate input signals for two driving actuators – car engine and additional DC motor. They, in turn, jointly control the speed of vehicle wheels according to the characteristic equation of the selected epicyclic gear train.

This work illustrates the simulation results of basic driving conditions of a car, such as engine idling, car acceleration, deceleration, stop, and reverse.

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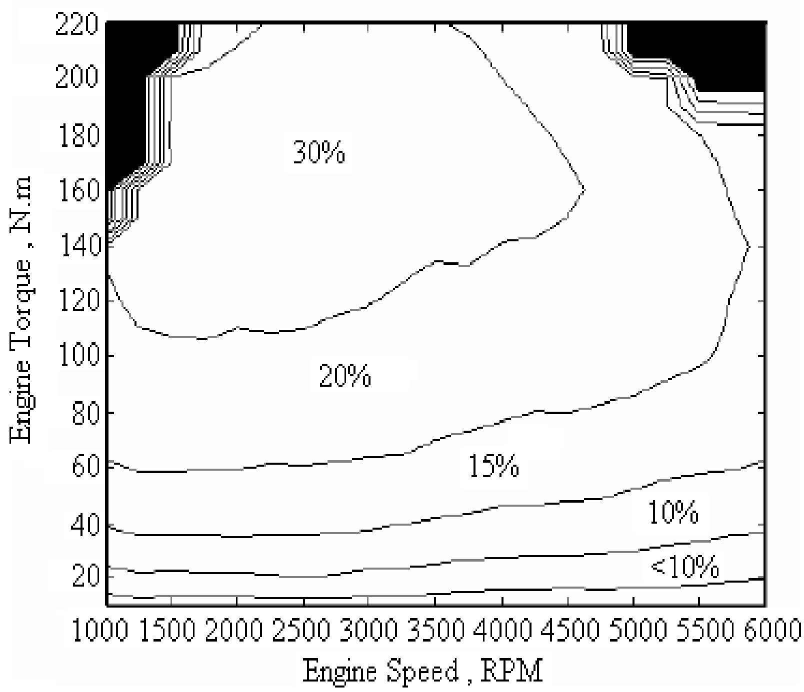

Figure 1 Typical engine efficiency map [1].

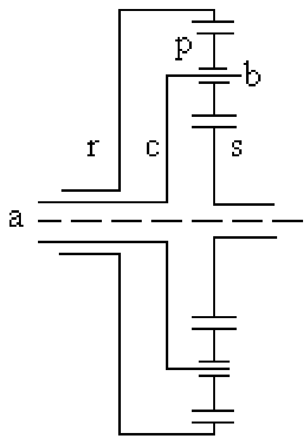

Figure 2 A basic epicyclic gear train.

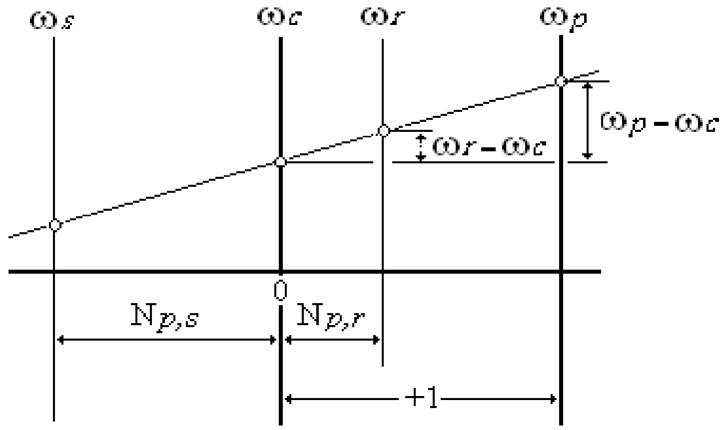

Figure 3 Nomograph for the basic epicyclic gear train [8].

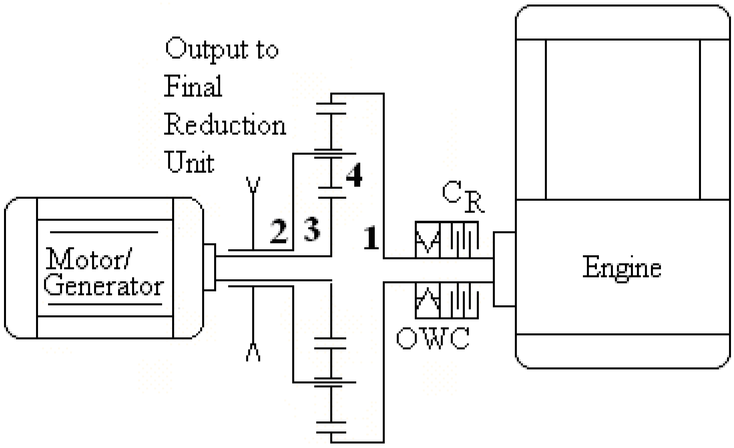

Figure 4 The new hybrid transmission system.

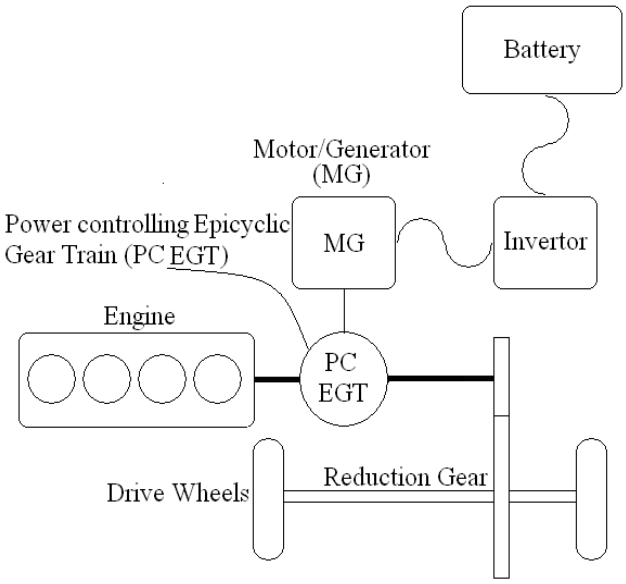

Figure 5 Block diagram of the new hybrid system.

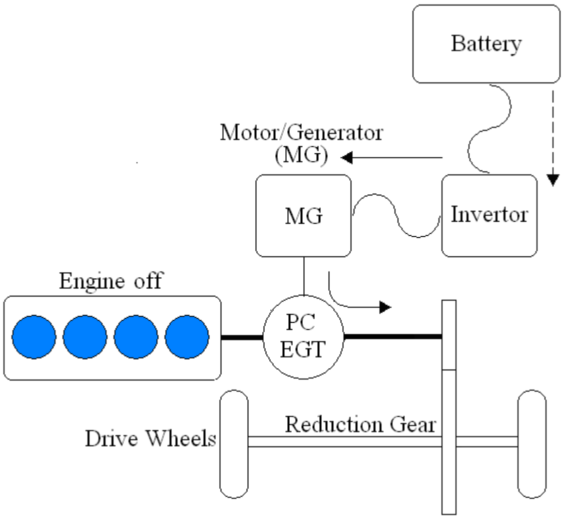

Figure 6 Electric motor mode.

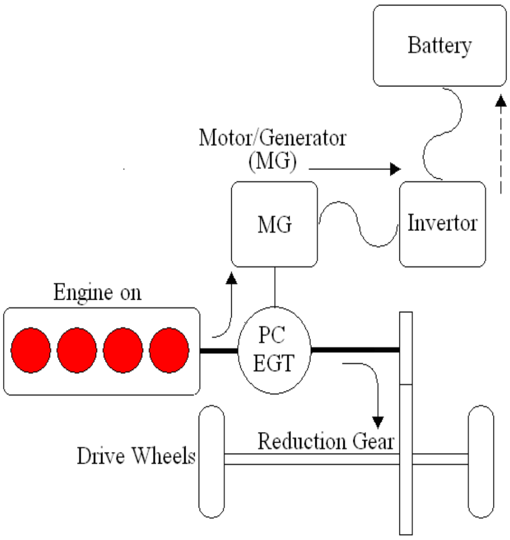

Figure 7 Engine/charge mode.

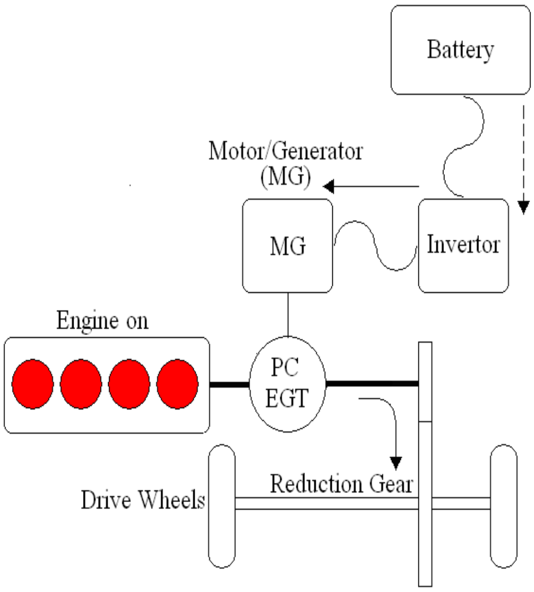

Figure 8 Engine mode.

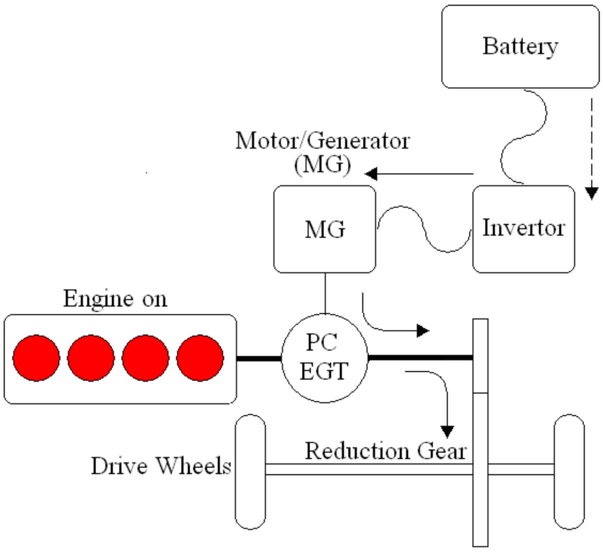

Figure 9 Power mode.

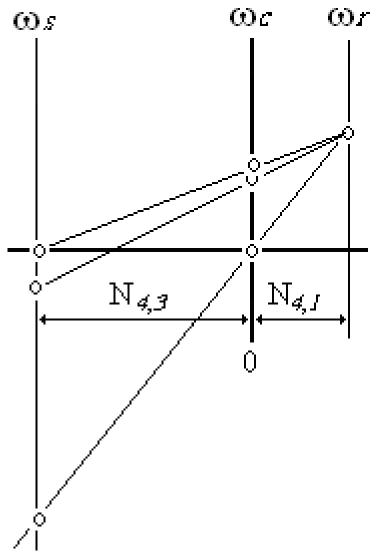

Figure 10 Nomograph for the engine and engine-charge modes of the new hybrid transmission.

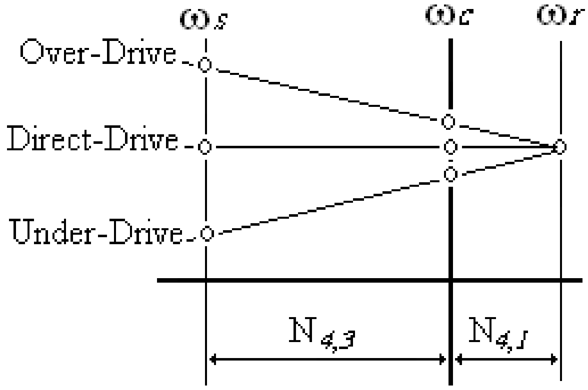

Figure 11 Nomograph for the power mode of the new hybrid transmission.

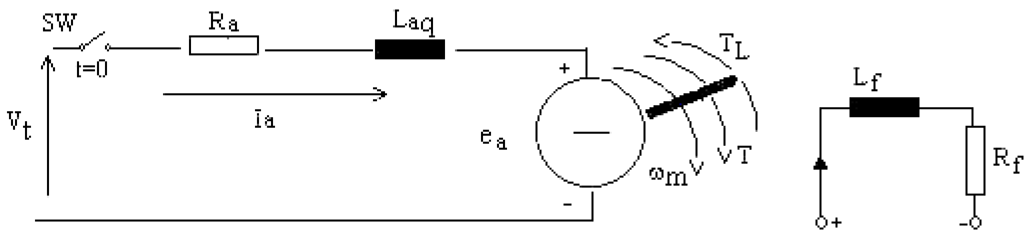

Figure 12: Schematic diagram of a DC motor

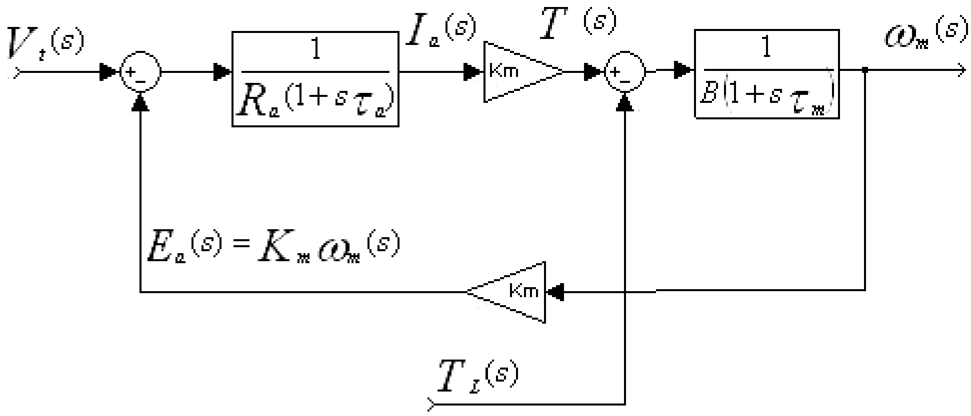

Figure 13 Block diagram representation of a DC motor.

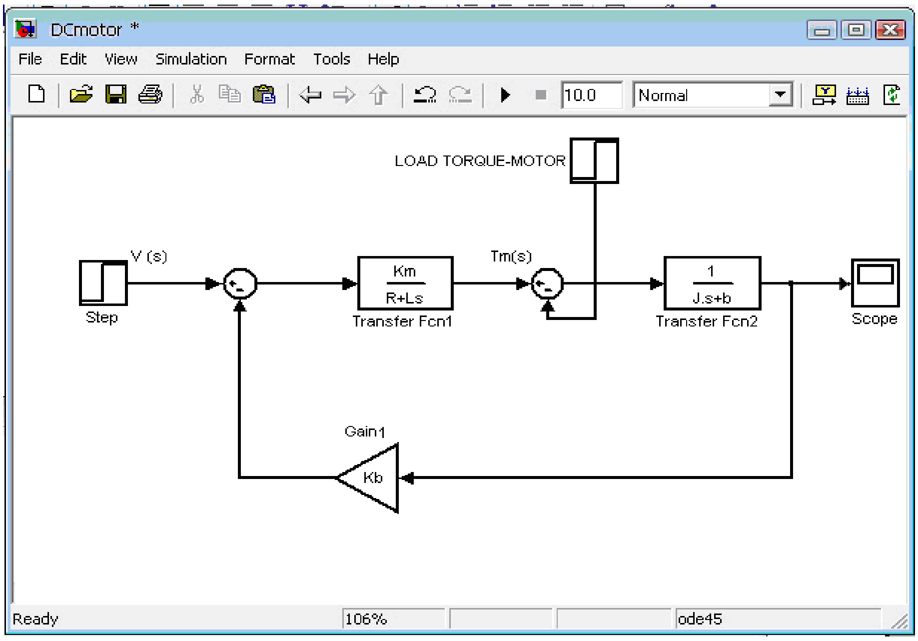

Figure 14 Block diagram representation of a DC motor in SIMULINK.

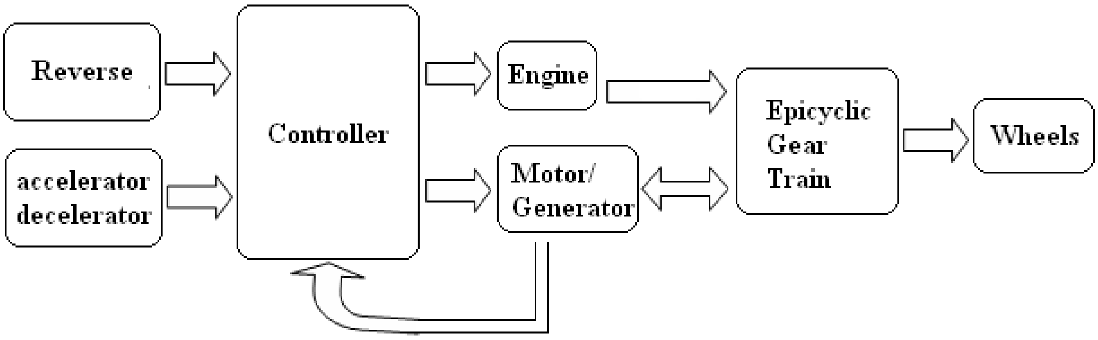

Figure 15 Functional interrelations between subsystems.

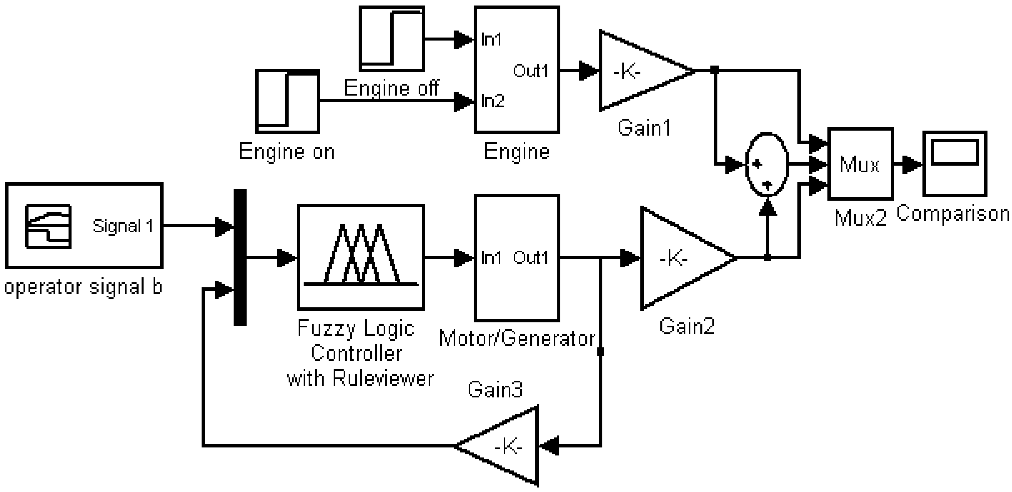

Figure 16 Operational block diagram of the speed control system.

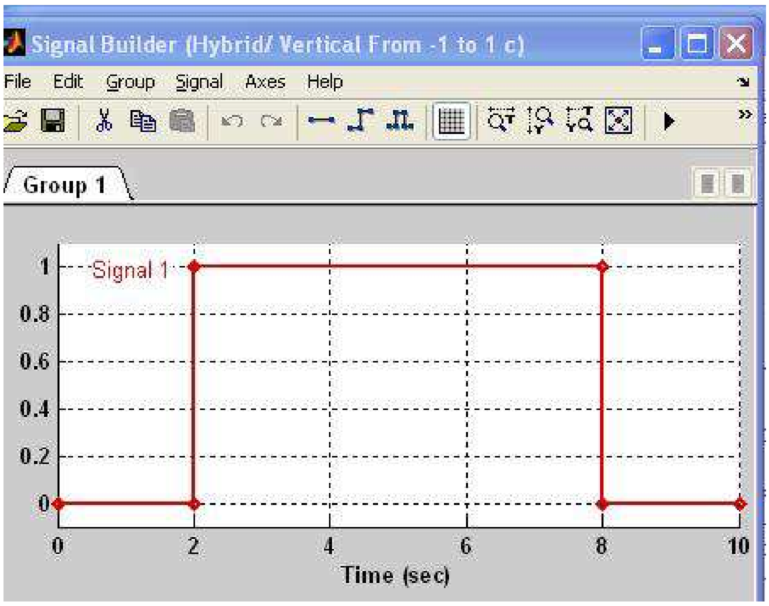

Figure 17 a motor/generator signal.

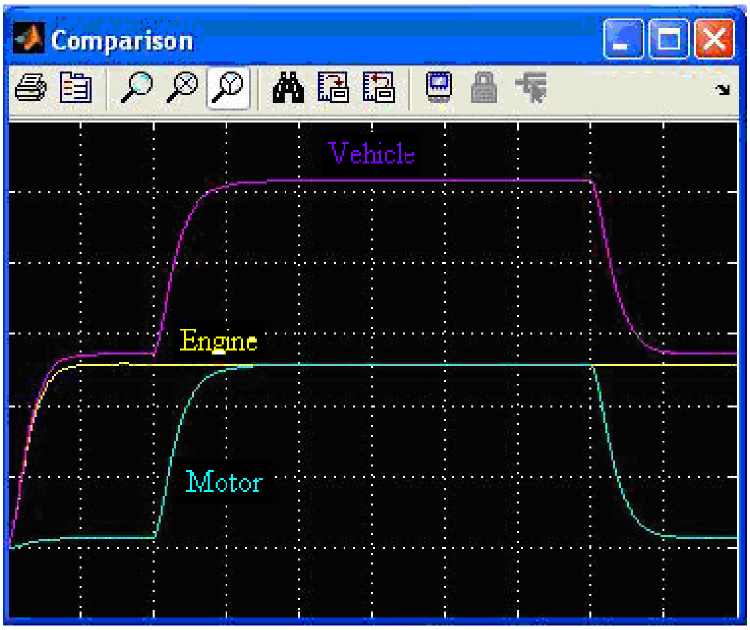

Figure 18 Response of the motor, engine and vehicle.

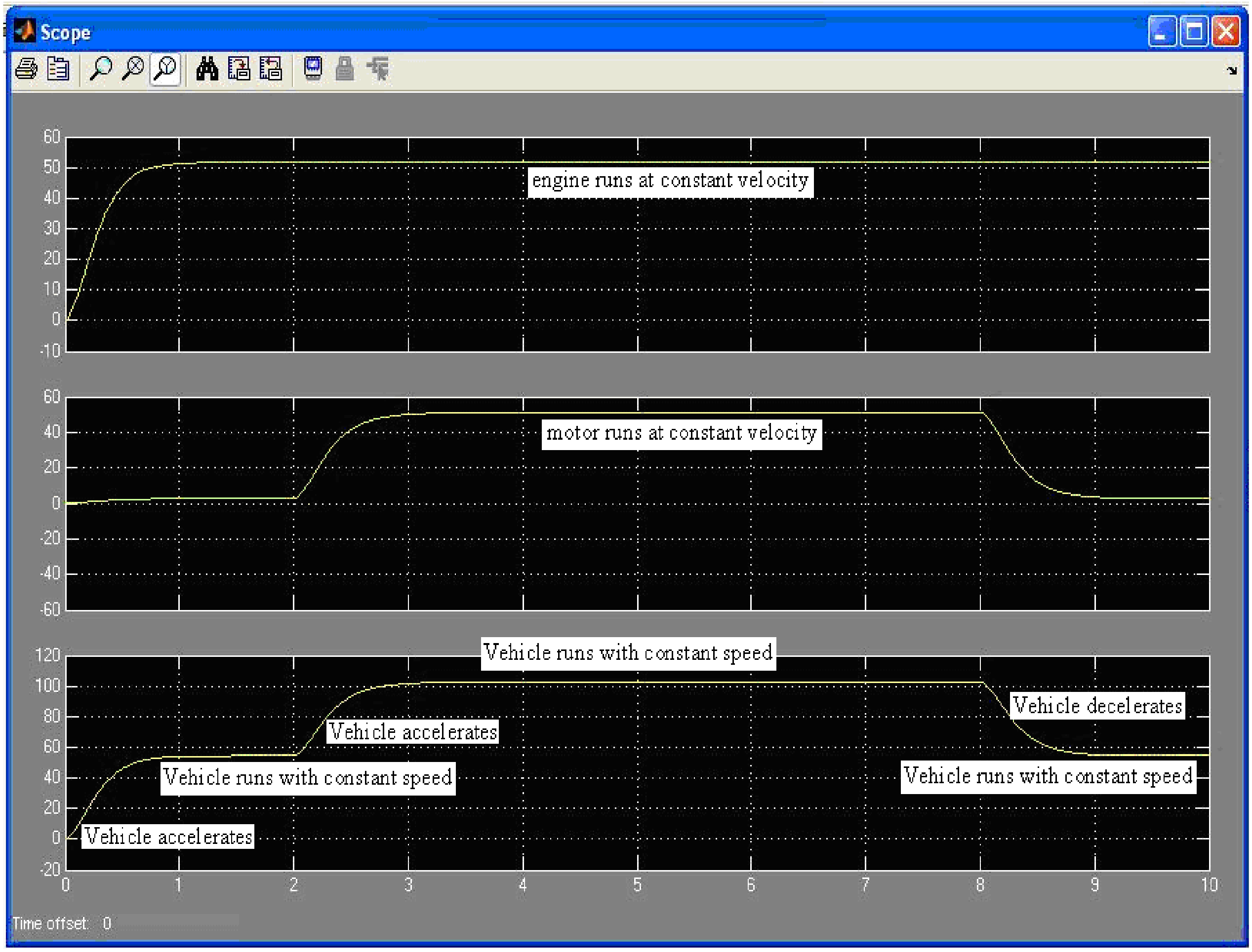

Figure 19 Simulation results for acceleration, deceleration or cruising of the car.

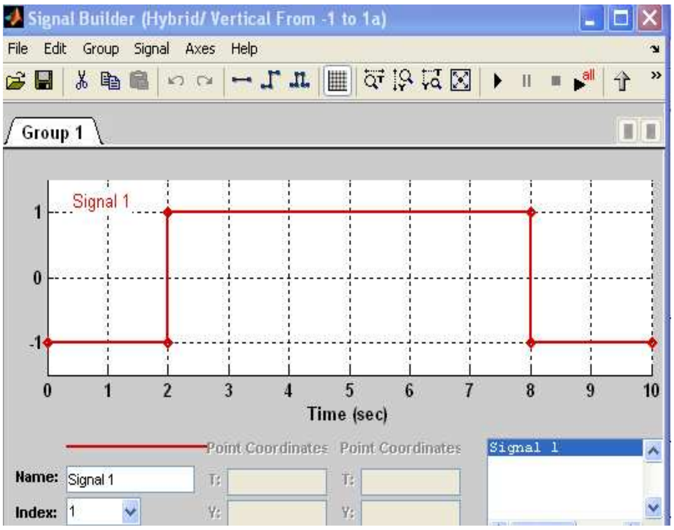

Figure 20 a motor/generator signal.

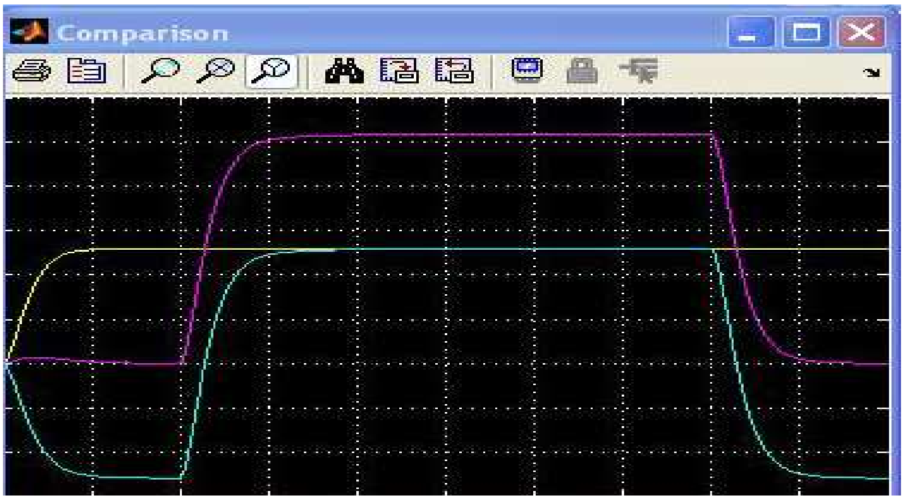

Figure 21 Response of motor, engine and vehicle.

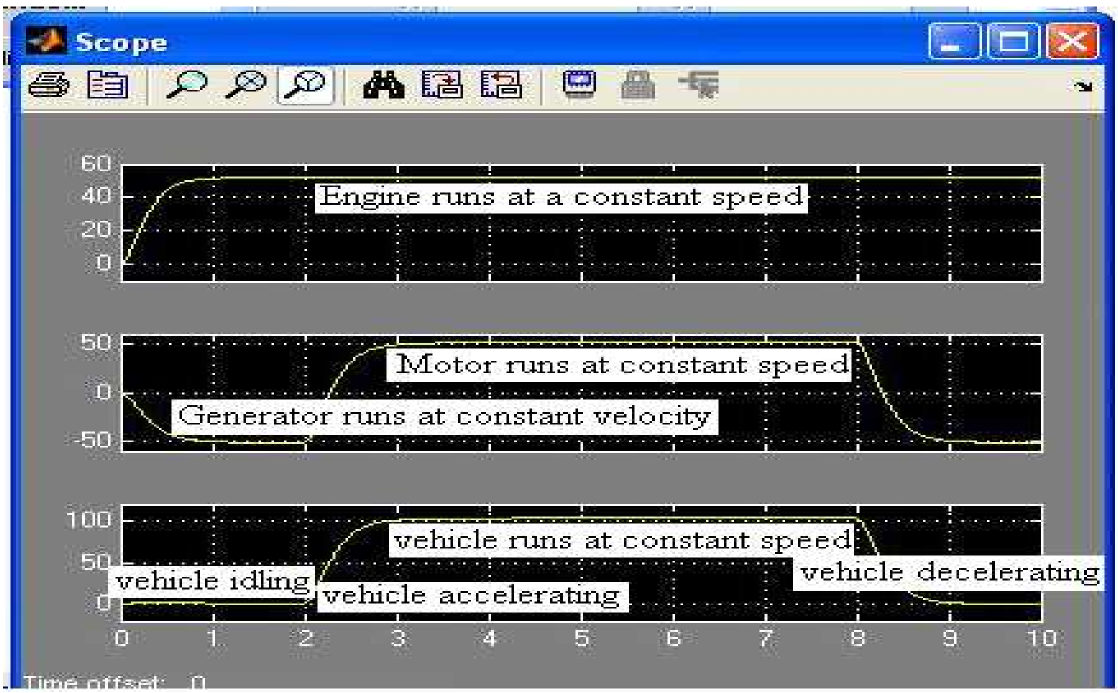

Figure 22 Simulation results for idling, acceleration, deceleration or cruising of the car.