A New Differential Configuration of Hybrid Electric Vehicle with Torque Regulationloop

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Abstract

The most significant weakness of hybrid electric vehicles (HEV) is the high construction cost and the complicated control strategies due to multiple power sources[1],[2] .In this paper a new developed configuration of hybrid vehicle is presented. The new configuration is simple, cost-effective and easy to implement .The differential unit, which acts as mechanical torque-overflow keeps engine torque within a predefined value . This is achieved by the aid of torque loop attached to one terminal of the differential.The new configuration proved to act continuously varying transmission (CVT) and also can perform efficient control strategies . Minimum emissions can be assured by running the IC-engine within best engine performance zone which is characterized by engine torque and engine speed.

KEYWORDS : Hybrid electric vehicle (HEV), torque loop, control strategy, continuously varying transmission (CVT).

بناء نموذج تفاضلي جديد من المركبات الكهربائية الهجينة مبني على أساس تنظيم العزوم الدوارة

المستخلص

أن من ابرز نقاط الضعف في المركبات الكهربائية الهجينة هي كلفة الإنشاء العالية والتعقيد في استراتيجيات السيطرة بسبب تعدد مصادر القدرة. تم في هذا البحث بناء نموذج جديد من المركبات الهجينة. يمتاز هذا النموذج بالبساطة وقلة الكلفة وسهولة التنفيذ. أن الوحدة الأساسية وهي الوحدة التفاضلية والتي تعتبر بمثابة الطوافة للسيطرة على العزوم الزائدة

للمحرك ولإبقاء عزم المحرك ضمن القيم المرغوبة والمعرفة سلفا للنموذج. يتم كل ذلك بمساعدة مسار التحكم بالعزم والمسيطر على احد أطراف الوحدة التفاضلية. لقد اثبت النموذج الجديد بأنه يوفر (مغير سرعة مستمر) ومسيطر جيد على المركبات الهجينة. ان النموذج الجديد يضمن كذلك تقليل الانبعاثات الملوثة عن طريق تشغيل محرك الاحتراق ضمن منطقة الأداء الأفضل ضمن مخطط السرعة والعزم للمحركات .

1. Introduction

A HEV is a hybrid electric vehicle in which propulsion energy is available from two or more kinds or types of energy stores, sources or converters, and at least one of them can deliver electrical energy[1] .

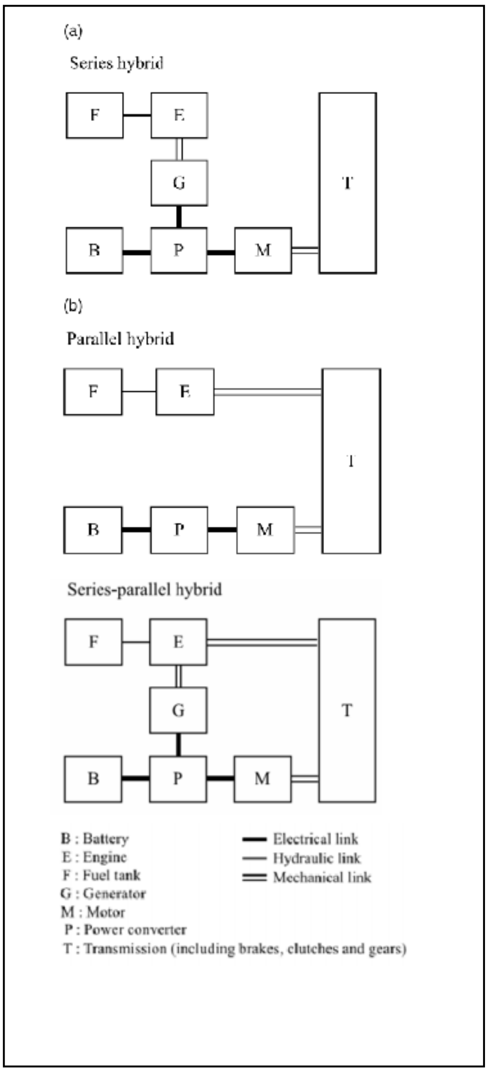


Figure (1). Classifications of HEV .

Traditionally, HEVs were classified into two basic kinds—series and parallel. Recently, with the introduction of some HEVs offering the features of both the series and parallel hybrids, the classification has been extended to[1]:

• series hybrid,

• parallel hybrid,

• series–parallel hybrid, and

• complex hybrid.

The complex hybrid is a complicated mix of either type of hybrid models .

2. Series hybrid system (SHEV)

The series hybrid is the simplest kind of HEV .Its engine mechanical output is first converted into electricity using a generator .The converted electricity either charges the battery or can bypass the battery to propel the wheels via the same electric motor and mechanical transmission .Conceptually, it is an engine-assisted EV which aims to extend the driving range to be comparable with that of the ICEV .Because of the absence of clutches throughout the mechanical link, it has the definite advantage of flexibility for locating the engine-generator set .Although it has an added advantage of simplicity of its drive train, it needs three propulsion devices—the engine, the generator and the electric motor .Another disadvantage is that all these propulsion devices need to be sized for the maximum sustained power if the series HEV is designed to climb a long grade .On the other hand, when it is only needed to serve such short trips as commuting to work and shopping, the corresponding engine-generator set can adopt a lower rating[1].

3. Parallel hybrid electric vehicles (PHEV)

In PHEV, both the mechanical power output and the electrical power output are connected in parallel to drive the transmission as shown in Figure (1-a) .There are various control strategies used for parallel configuration .In the most common strategy, ICE is basically always in on mode and operates at almost constant power output at maximum efficiency point [2]Electric motor is tuned on when the power from the ICE is less than that required by the transmission .The electric motor can be used as a generator to charge the battery by regenerative braking or absorbing power from the engine when its output is greater than that required to drive the wheels.

4. Series-parallel hybrid system (SPHEV)

In the series-parallel hybrid, the configuration incorporates the features of both the series and parallel HEVs, but involves an additional mechanical link compared with the series hybrid and also an additional generator compared with the parallel hybrid .Although possessing the advantageous features of both the series and parallel HEVs, the series-parallel HEV is relatively more complicated and costly .Nevertheless, with the advances in control and manufacturing technologies, some modern HEVs prefer to adopt this system.

5. The complex hybrid system (CHEV)

As reflected by its name, this system involves a complex configuration which cannot be classified into the above three kinds . The complex hybrid seems to be similar to the series-parallel hybrid, since the generator and electric motor are both electric machinery .However, the key di□erence is due to the bidirectional power flow of the electric motor in the complex hybrid and the unidirectional power flow of the generator in the series-parallel hybrid.This bidirectional power flow can allow for versatile operating modes, especially the three propulsion power (due to the engine and two electric motors)operating mode, which cannot be o□ered by the series-parallel hybrid .Similar to the series-parallel HEV, the complex hybrid su□ers from higher complexity and costliness.Nevertheless, some newly introduced HEVs adopt this system for dual axle propulsion [1].

The new differential model with torque– loop

Figure (2) shows the new developed model .The differential

block, shown in hatched square represents the main linking unit .It links three power devices these are :IC engine-connected at shaft (B), DC generator connected to shaft (F1) and DC motor connected

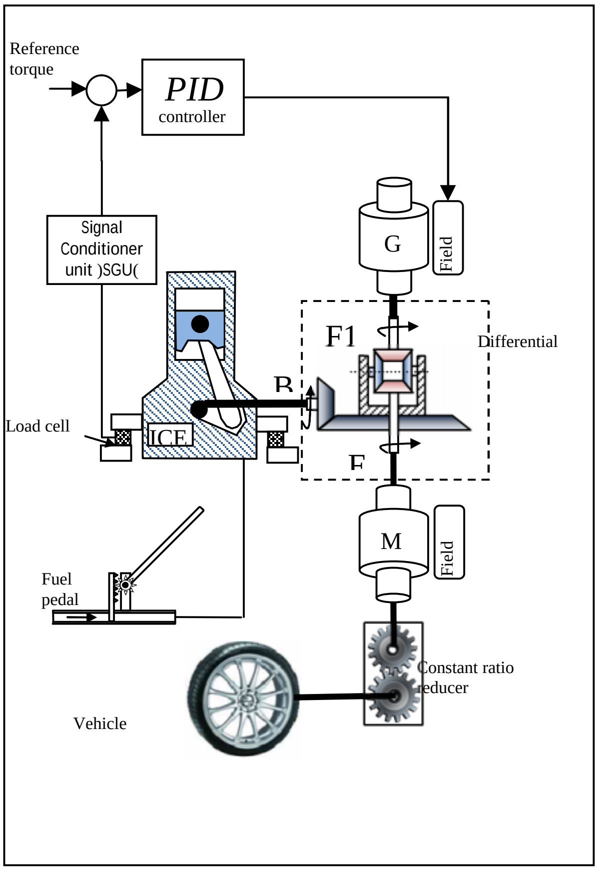


Figure (2). New differential model with torque– loop.

to shaft (F2). The DC motor is connected to the vehicle wheels either directly or by means of gear reducer . The other important thing to notice in this new configuration is the torque loop. Many researchers interested in torque control for hybrid electric vehicles [3]. The torque signal is generated by the load cell attached to the engine supports . The signal is conditioned then through an electronic circuit to be compared with a predefined value namely the reference torque. The result of comparison is fed to a well tuned PID controller to produce a suitable field voltage for the DC generator .The field voltage of the DC motor is considered to be fixed to the rated value. The driver has only one variable to control the vehicle with .It is the fuel pedal .As he pushes the pedal, engine speed increases . Generator speed is also increased the torque loop pushes an amount of field voltage to the generator .This amount is exactly the amount that produces a certain torque .Regulating the generator torque which is connected to on terminal of the differential leads to regulate the torque of IC-engine because all the terminal of the differential has constant torque relation . This model succeed to run the engine at its rated torque .The main blocks are described below:

The differential block

Figure (3) shown represents the differential block .The input shaft is to be shaft (B1)while the output shafts are (F1) and (F2).

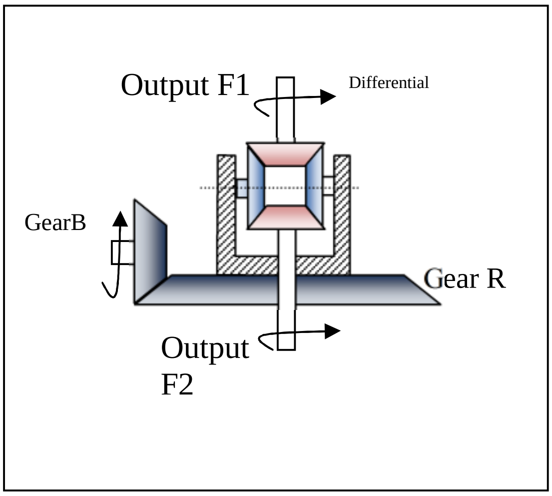


Figure (3) .The differential block.

The gear ratio between gear (R) and gear (B) is G_D . The speed relationship is [4]:

$$N_B = \frac{G_D}{2}(N_{F1} + N_{F2}) \tag{1}$$

This means that the speed is divided between (F1) and (F2) in a differential manner .

The torque relationship is given by:

$$T_{F1} = T_{F2} = G_D T_B \tag{2}$$

One can note that the torques of the three terminal of the differential block are linearly related . If any of the three terminals is released then the torque for all terminals will equal zero i.e. , that is, the lowest torque terminal will control the torque value of the block . Referring to Figure (2) :

$$T_G = G_D T_{IC} \tag{3}$$ Or

$$T_{IC} = \frac{1}{G_D} T_G \tag{4}$$

So regulating the value of generator torque (T_G) led to regulating the value of IC engine torque (T_{IC}).

The DC machines

The general form for the torque on any Dc machine is given by[5]:

$$T = K_1 \phi I_a \tag{5}$$

$$T = K_2 I_f I_a \tag{6}$$

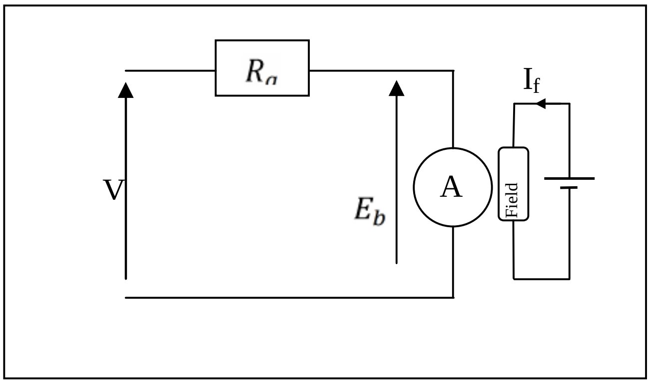
Where I_a is armature current and ϕ is the magnetic flux.

The generated back emf (E_b) is given by:

$$E_b = K_3 \phi N \tag{7}$$

$$E_b = K_4 I_f N \tag{8}$$

Where N is the speed of the machine.



Figure(4). DC machine.

For the set of generator-motor

The current passing through both armatures as shown in Figure (5) is given by :

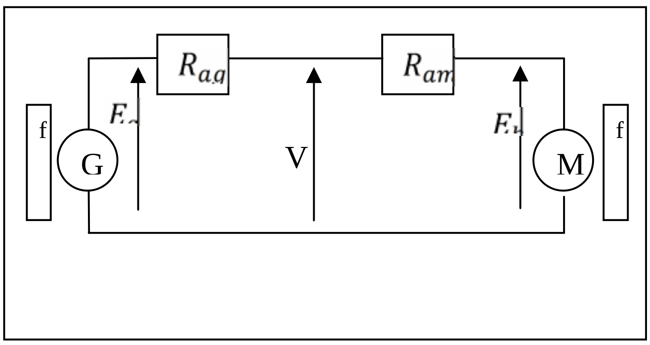


Figure (5). Generator-motor set.

$$I_a = \frac{E_a - E_b}{R_{ag} + R_{am}} \tag{9}$$

$$I_a = \frac{K_4 I_{fg} N_g - K_4 I_{fm} N_m}{R_{ag} + R_{am}} \quad (10)$$

Where : I_{fg}, I_{fm} is the field currents of generator and motor respectively.

N_g, N_m are the speeds of generator and motor respectively.

R_{ag}, R_{am} are the armature resistance of generator and motor respectively.

$$T_m = K_2 I_{fm} I_a = K_2 I_{fm} \frac{K_4 I_{fg} N_g - K_4 I_{fm} N_m}{R_{ag} + R_{am}}$$

All K_2, K_4, R_{ag}, and R_{am} are constants

$$T_m = K_6 I_{fm}(I_{fg} N_g - I_{fm} N_m) \quad (11)$$

Similarly for generator :

$$T_g = K_2 I_{fg} I_a$$

$$T_g = K_6 I_{fg}(I_{fg} N_g - I_{fm} N_m) \quad (12)$$

For the hybrid configuration of Figure (2),

$$T_g = K_6 I_{fg}(I_{fg} N_g - I_{fm} N_m) = T_{ref}$$

$$(I_{fg} N_g - I_{fm} N_m) = \frac{T_{ref}}{K_6 I_{fg}}$$

$$T_m = \frac{I_{fm}}{I_{fg}} T_{ref} \quad (13)$$

For similar machines (similar field impedance)

$$T_m = \frac{V_{fm}}{V_{fg}} T_{ref} \quad (14)$$

Where V_{fm}, V_{fg} are field voltages of generator and motor respectively.

To solve for I_{fg}, let the electrical torque gain (γ) equal :

$$\gamma = \frac{T_m}{T_g} = \frac{I_{fm}}{I_{fg}} = \frac{V_{fm}}{V_{fg}} \quad (15)$$

or

$$I_{fm} = \gamma I_{fg}$$

Substitute in Eq. (12) gives:

$$T_g = K_6 I_{fg}(I_{fg} N_g - I_{fm} N_m) = T_{ref}$$

$$T_g = K_6 I_{fg}(I_{fg} N_g - \gamma I_{fg} N_m) = T_{ref}$$

$$T_g = K_6 I_{fg}^2 (N_g - \gamma N_m) = T_{ref}$$

$$I_{fg} = \sqrt{\frac{T_{ref}}{K_6(N_g - \gamma N_m)}} \tag{16}$$

The speed of top gear is to start at (V_t)

The top gear means that $\gamma = 1$ and :

$$\gamma = \frac{V_t}{V_x} \tag{17}$$

where V_x is vehicle velocity. The motor speed is linearly related to vehicle speed and one can write:

$N_m = C_2 \, V_x$ so:

$$V_{fg} = C1\sqrt{\frac{T_{ref}}{(N_g - \gamma C_2 V_x)}} \tag{18}$$

The above formula derived for a differential gain of $G_D = 1$ for values other than 1, it must be included and hence:

$$V_{fg} = C1\sqrt{\frac{G_{D*}T_{ref}}{(N_g - \gamma C_2 V_x)}} \tag{19}$$

Where T_{ref} is the reference torque of the IC engine. Its value depends on the performance map of the engine . At any speed of the IC-engine there is an optimum value for the torque to give highest power and minimum emissions.

Equation (19) is a straightforward relation that gives always a unique value for field voltage of the generator corresponding to the desired reference torque of the IC-engine and the current speed of the generator.

Referring to Figure (2) , the total driving torque T_D is the sum of T_{F2} and T_m , so:

$$T_D = T_{F2} + T_m \tag{20}$$

but

$T_{F2} = G_D T_{IC}$ (Eq.2) and $T_m = \gamma T_g$(Eq.15)

$T_D = G_D T_{IC} + \gamma T_g$

The generator is connected to the terminal F1 of the differential so $T_g = G_D T_{IC}$,

$T_D = G_D T_{IC} + \gamma G_D T_{IC}$

The torque loop tries to regulate the engine torque to its reference value ,$T_{IC} = T_{ref}$ this means:

$$T_D = (G_D + \gamma)T_{ref} \tag{21}$$

Equation (21) summaries all the current work .It shows that the total torque gain is compound of two components :mechanical, G_D , which is constant and electrical , γ, which is variable with vehicle speed . This work shows that there is no further need to change the mechanical gain G_D manually or automatically since it is possible to easily change the value of electrical gain γ .Also it is important to notice that the torque loop which is acting as the watchdog for the torque of the engine , keeps the torque always near its reference value .

The question arises now, will γ be changed automatically or there is a need for manual shifting?

When the vehicle just start to move it needs for large torque gain , the engine tries to move the terminal F1 of the differential but it is heavy to move so the differential flows power to the other easy terminal , F2, which is attached to the generator .The generator starts to speed up and according to Eq.(19), there is always a unique value for V_{fg} that combine all the variable (T_{ref}, N_g, V_x and γ) .This means also that the field voltage of the generator plays this magic role for satisfying vehicle torque and engine torque, and acts together with the torque loop as CVT(continuously varying transmission).

The simulink model

Figure (6) represents the simulink structure of the proposed model.The differential blocks links the gasoline engine with the generator and the motor . The two DC machines are runnig in the speed mode .Shaft sensor block is needed to transform the mechanical link to simulink signal .The torque actuator block is used to transform the simulink torque signal of the motor to mechanical link to be coupled then with the port (F1) of the differential.

The torque loop is started with (T_{ref}). It is important to note that the value of T_{ref} used here is equal to ($G_D \times T_{ref}$)of the engine , this is because we measure the torque of the generator not the IC engine .In physical or practical system where it is possible to measure T_{ref} of the engine by attaching load cells to engine base and hence no need to modify by G_D.
A well tuned PID controller is used in this loop together with saturation block to limit the output field voltage to its upper limit.

The gasoline engine used in this structure has 80 kw max power at 2000 rpm and has maximum speed limit of 3000 rpm.

6. Discussions

To show the vehicle capabilities of acceleration and smooth gear shifting during driving scheme, a block of suitable parameters is built . It is the reference speed block . The block assumes that the vehicle accelerates from 0 to 100 km/h (30m/s) at 10 seconds . It watches the vehicle speed and checks if it is coincide with the reference velocity profile . Any error between the reference speed and the actual speed pushes the block to open extra throttle.

This exactly what a human driver do when he want to drive a vehicle. Any drive has its own driving profile .Some have fast profile and other have slow profiles .This block is needed just for simulation to add real time throttle control .In practical case it is not needed since human driver is doing the job.

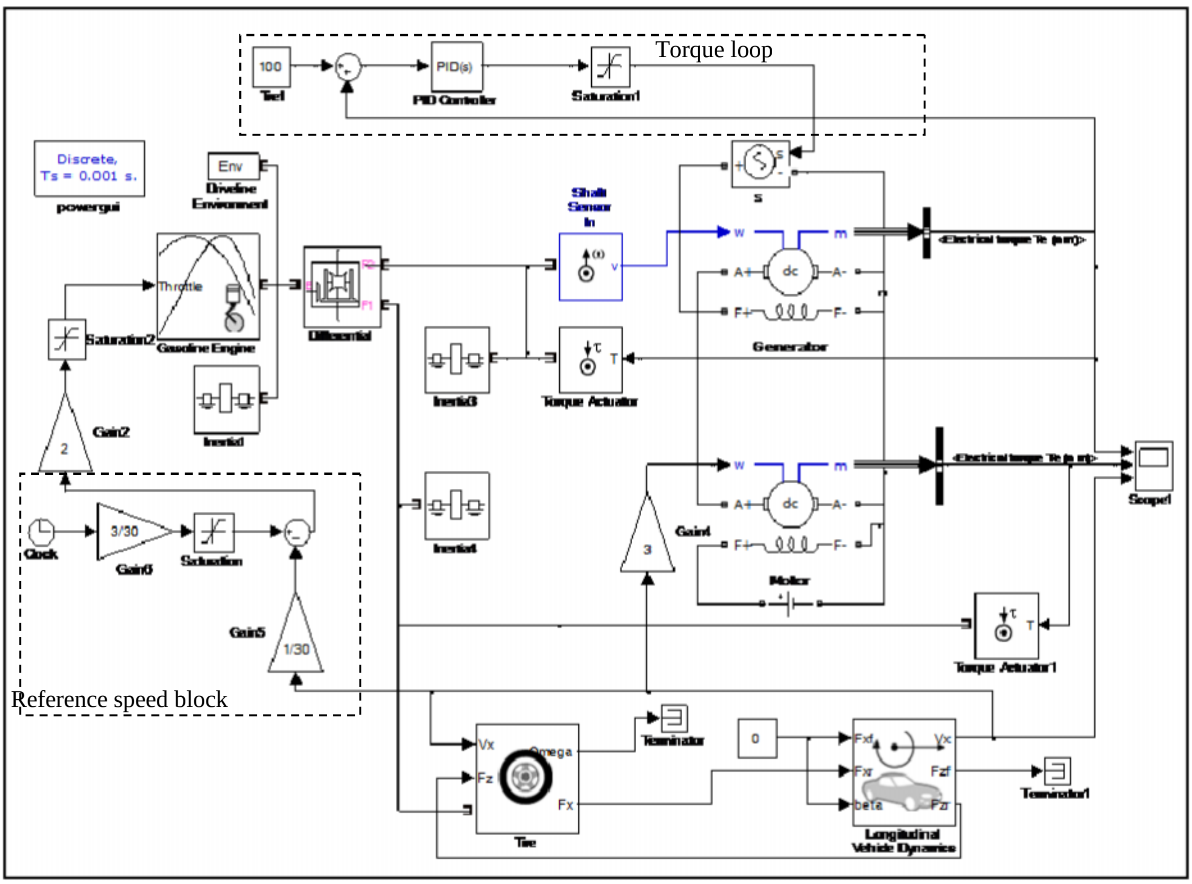


Figure (6). Simulink model .

The longitudinal vehicle dynamics block represents the vehicle . The mass used here is 1400 kg which is a midsized vehicle . Scopes are used whenever needed to monitor a variable.The generator torque is seemed to be regulated at the reference value (which is 100N.m). It is negative because the generator torque is a load against engine torque . The PID controller tries to keep the torque within its reference value . The second graph ,which is the motor torque graph is the most important graph . During the first period of time the torque starts to increase until it become enough to move the vehicle .It reaches its maximum value and then begins to fall as the vehicle speed builds up .At top gear speed the motor torque approximates the generator torque as seen it became asymptote to (100 N.m). The third graph shown in Figure (7) represents the vehicle speed in (m/s) . The top gear speed in this model is 30m/s (around 100km/h). It is also clear that when the vehicle speed reaches the top gear speed the motor torque became equal approximately to generator torque and consequently the electrical torque gain (γ) becomes equal to 1 . The velocity profile of the vehicle coincides with the reference velocity profile, where the vehicle is assumed to accelerate from 0 to top gear speed in approximately linear ramp.It is important to note that as the generator torque is locked to the value of 100 N.m which is (G_D $\square$ T_{ref}), the engine torque is locked to the value of T_{ref} . This means that it is possible to run the IC engine within the recommended perform.

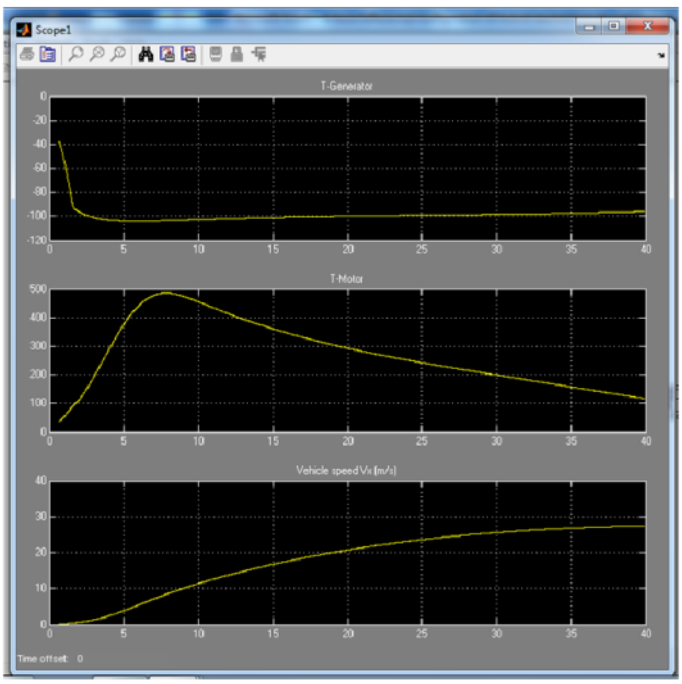


Figure (7). Simulation graphs of generator torque, motor torque and vehicle speed.

performance. Driving an IC engine within its reference torque through the use of torque loop is a new control strategy developed by many researchers [7].

7. Conclusions

The electrical torque gain (γ) which is the ratio of motor torque to the generator torque is drawn in Figure (8) against the relative velocity of the vehicle . The relative velocity of the vehicle at any time is the division of the current velocity (V_x) by the top gear velocity (V_T). From Figure (8) it is clear that the electrical torque gain γ is acting as a five-speed gear box with automatic shifting .As the relative speed reaches 1 the ratio approximates 1 . This means that the differential configuration acts together with the torque loop as a virtual (CVT).
Many researchers proved the validity of their new model by showing its robustness against load uncertainties[6]. Here , the new developed model is subjected to a step load.
Figure (9) shows the shift down capabilities of the

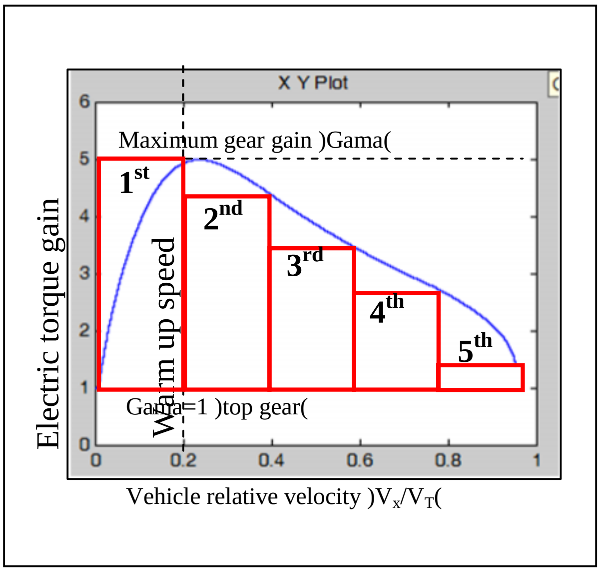


Figure (8). Gama verses relative speed.

current virtual Gear box .The Vehicle is subjected to a step force of 2000N at (T=10 sec and for 5 sec period).

During the first 10 seconds the torque gain starts to shift down automatically until it reaches about 3.2 at T=10sec . At this moment the step load is applied against the vehicle . The Value of Gama starts to increase again (this mean a shift down gear in a mechanical gear box).It is exactly the desired behaviour of standard automatic gear box . It automatically shifts down when load is increased and automatically shifts up when load decreases .

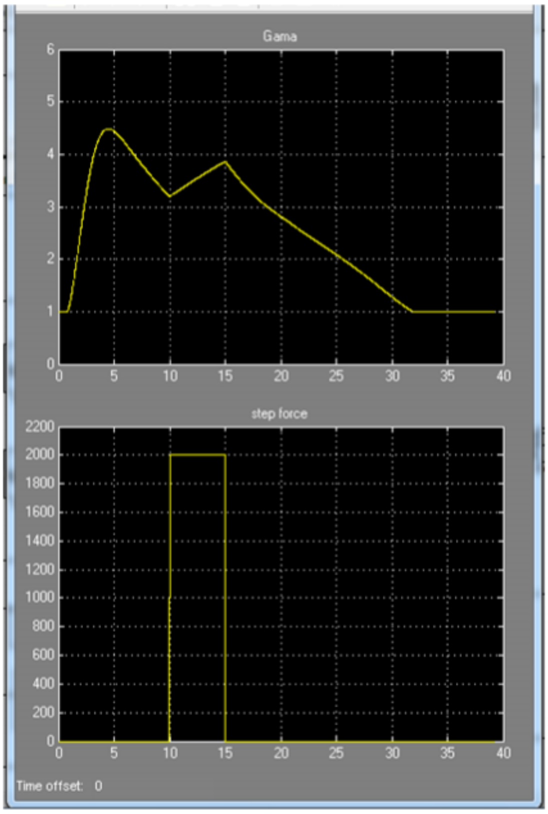


Figure (9). Robustness against step load.

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