A Study on a Developed Electro-Mechanical Epicyclic Power-Drive (EMEC) for Hybrid Electric Vehicles (HEV)

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Abstract:

Hybrid electric vehicles (HEV) draw much attention during the last years due to the need for alternative power resources with reduced emissions. The major disadvantages of HEV are the heavy weight, high cost and complicated control strategies. This paper focuses on a developed design for electro-mechanical differential unit. Most designer uses differential block as a mechanical linkage between two power sources. In this paper the differential unit is modified to do more than linkage. It acts as a continuously-varying-transmission (CVT), electric motivation unit and power regeneration unit. This of course leads to more compact and light weight vehicles. The developed model uses three main units: Synchronous block, Differential block, and Induction block the three blocks are combined in a compact design. Mechanical-electrical power transformation is carried out through the synchronous block which acts also as regeneration unit during braking. On the other hand electrical- mechanical transformation is carried out through the induction unit. The differential unit plays the role of smart linkage between the synchronous and the induction units. Simulation through Matlab-simulink is carried to show the validity of the model. The developed model proved to satisfy the properties of CVT and driving demands torques.

دراسة تطوير وحدة حركة كهروميكانيكية تعمل بشكل تفاضلي لنظام القدرة في السيارات الكهربائية الهجينة.

لقد جذبت السيارات الكهربائية الهجينة اهتماما متزايدا خلال السنوات الاخيرة بسبب الحاجة الى مصادرة طاقة بديلة اقل تلوثا . لكن من ابرز عيوبها هو ثقل وزنها وكلفتها العالية مع انظمة السيطرة المعقدة. استخدم بعض المصممون النموذج التفاضلي كوسيلة ربط بين الحمل من جهة وبين مصدرين للطاقة من جهة اخرى . في هذا البحث تم تطوير النموذج التفاضلي ليكون اكثر من وسيلة ربط . انه يعمل كمغير سرعة مستمر CVT ووحدة تحريك كهربائي ووحدة استرجاع للطاقة مما يؤدي الى سيارة اقل حجما ووزنا. يتكون النموذج المقترح من ثلاث وحدات هي الوحدة التزامنية والوحدة التفاضلية والوحدة الحثية. يتم التحويل الميكانيكي-الكهربائي من خلال الوحدة التزامنية والتي تؤدي ايضا دور استرجاع الطاقة اثناء الفرملة . بينما يتم التحويل الكهربائي-الميكانيكي من خلال الوحدة الحثية. تعمل الوحدة التفاضلية

كوحدة ربط بين الوحدتين التزامنية والحثية. لقد اجريت محاكاة للنظام باستخدام برنامج (Matlab-simulink) لاثبات فعالية النموذج .لقد لبى النموذج المقترح خواص مغير السرعة المستمر CVT مع عزوم التحريك المطلوبة.

Keywords

Hybrid electric vehicle (HEV), Power-Drive, Continuously Varying transmission (CVT), Powertrain, Control

1. Introduction

The studies for hybrid electrical vehicle (HEV) have attracted considerable attention because of the necessity of developing alternative methods to generate energy for vehicles due to limited fuel energy, global warming and exhaust emission limits in the last century [1]. HEV incorporates internal composition engine, electric machines and power electronic equipments. Many researchers classify HEV according to the power flow into serial, parallel and complex HEV's [2]. Recent papers focus on new configurations such as planetary [3] and differential [4] configurations. In planetary configuration (PC), the power-drive uses a planetary gear mechanism to connect an internal combustion engine, an electric motor and a generator. A highly efficient engine can simultaneously charge the battery through the generator and propel the vehicle (Fig.1). It is important to be able to set the engine operating point to the highest efficiency possible and at sufficiently low emission levels of undesirable exhaust gases such as hydrocarbons, nitrogen oxides and carbon monoxide. The motor is physically attached to the ring gear. It can move the vehicle through the fixed gear ratio and either assist the engine or propel the vehicle on its own for low speeds. The motor can also return some energy to the battery by working as another generator in the regenerative braking mode.

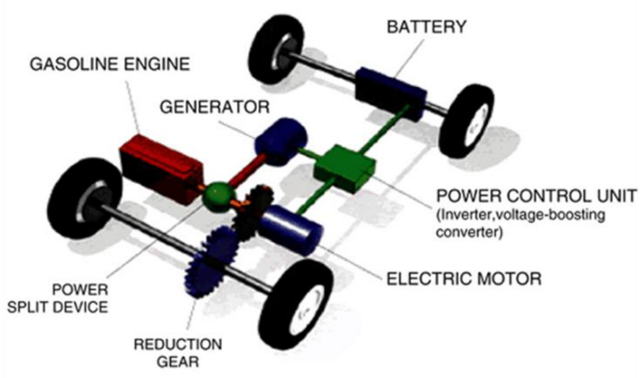

Fig.1 [3] the prius car PC

Another innovative configuration is called differential configuration (DIfC) [4]; The (DIfC) 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 (DIfC) configuration proved to act as a CVT (continuously varying transmission) 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. Fig.2 shows the main components of DIFC power-drive. IC engine is connected at shaft (B), DC generator connected to shaft (F1) and DC motor connected 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 [5]. 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 succeeds to run the engine at its rated torque.

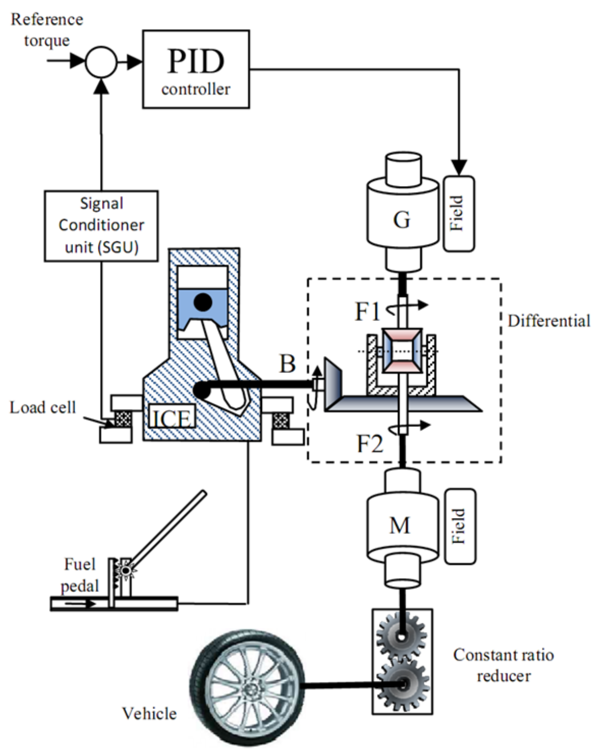

Fig.2 [4] DIFC power-drive

Developed Electro-Mechanical Epicyclic Power-Drive (EMEC)

The Differential configuration (DIFC) invented by Ali et al [4] has the advantage of mixed serial and parallel configuration. At vehicle speedup the (DIFC) acts serial from one side of view and parallel from another point. The mechanical power at one terminal of the differential unit is transformed to electrical power through the generator attached to this terminal; the generator passes this power to the motor. This type of power flow is a serial flow. On the other hand the other terminal of the differential receives the mechanical power from the ICE and passes it directly to the wheels. When the vehicle approaches the top-gear speed most of the power of the ICE flows mechanically to the wheels, while during the speedup period only a small mechanical power is passing directly to the wheels. The differential block allows for flexible mixing between mechanical and electrical power. In this paper a new modification is added to the configuration (DIFC). This modification implies a self gear shifting possibility without the need for torque loop regulation. Fig. 3 shows the new developed configuration (**EMEC).**

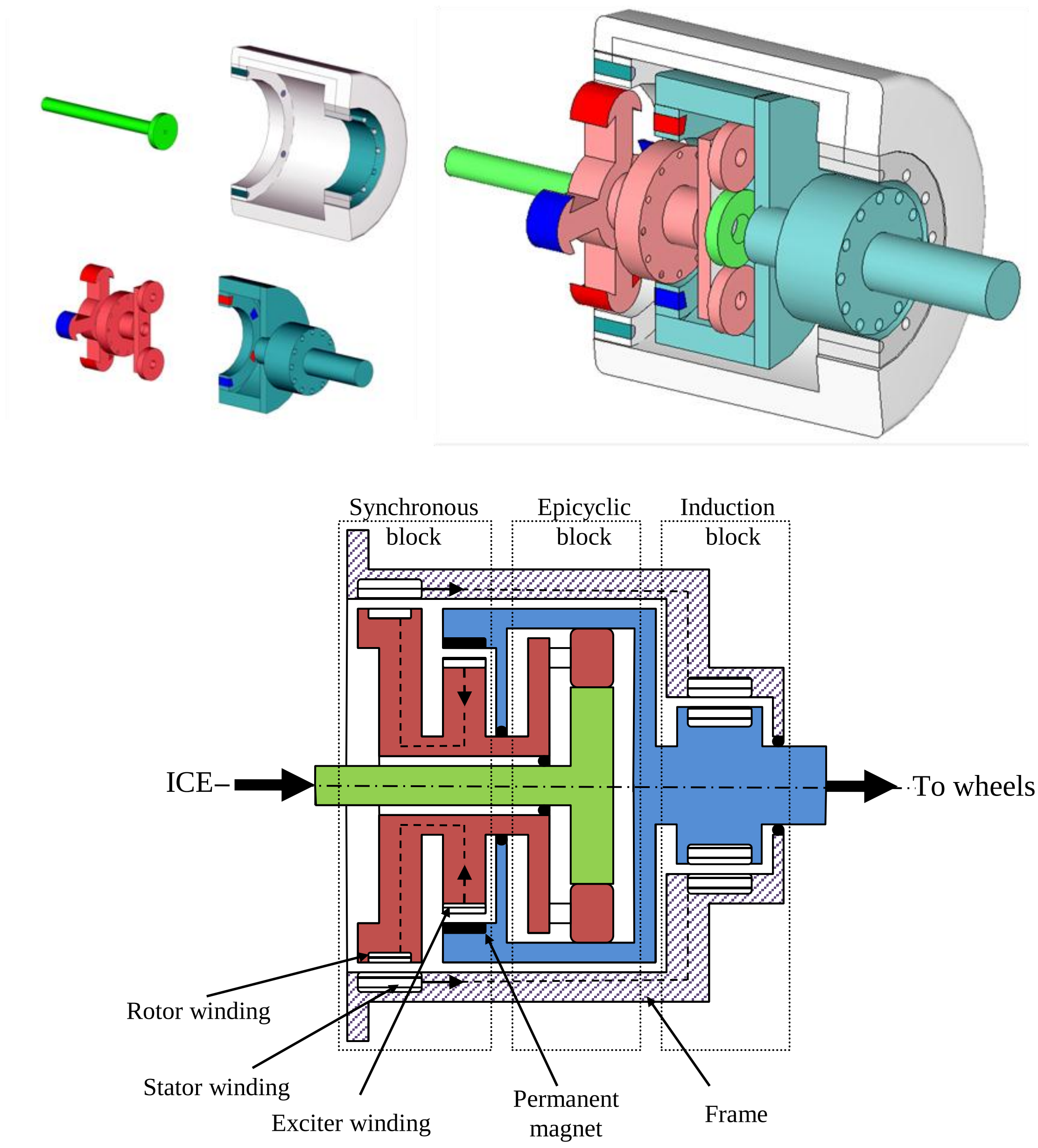

Fig.3 the EMEC power-drive

The (EMEC) power drive consists of three major blocks:

1.1 Epicyclic block: The epicyclic block is the mechanical part of the power-drive. It contain sun, planet and ring gears. The planet gear(s) are mounted on an arm which is attached to the rotor of the synchronous block, the second block in the drive. The sun gear is linked to the vehicle engine (ICE). It receives the power from the ICE and delivers it either to the arm or to the ring in a differential manner. The ring gear is attached to output shaft which transmits power for wheels. Sometimes, speed reducer is needed before wheels. The output shaft passes through the rotor of the induction block and keyed with it. The ring gear also carries the permanent magnets (PM) of the exciter. The ring gear assembly can be made of many parts to be assembled together. It also represents oil casing for all gears assembly. Seals are used when necessary as shown in Fig.3. The torque and speed relationship of the epicyclic block can be shown through Fig.4 :

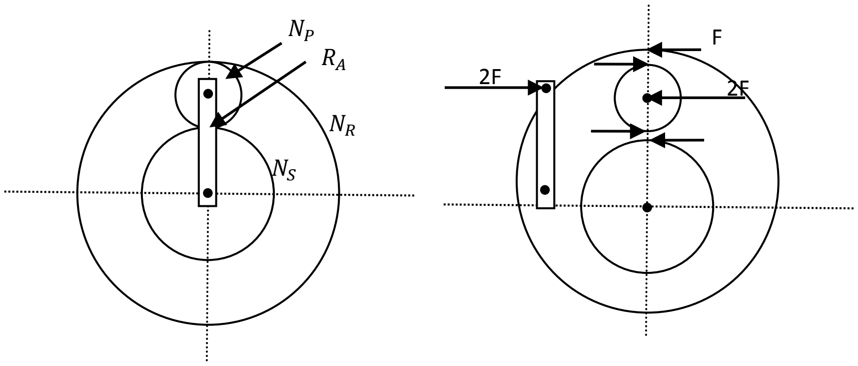

Fig.4 Speed and torque analysis of the epicyclic block

$$R_A = \frac{R_R + R_S}{2} \quad (1)$$

Speed relationships are [6]:

$$\frac{\omega_S - \omega_A}{\omega_R - \omega_A} = -\frac{R_R}{R_S} \quad (2)$$

Where: speed, R is radius.

Torque relationship:

$T_R = F * R_R$

$T_S = F * R_S$

$T_A = 2F * R_A = F * (R_R + R_S)$

One can write the torque relationship as:

$$T_S = \alpha T_R \ , \qquad \alpha = \frac{R_S}{R_R} \quad (3)$$

$$T_A = \beta T_R \ , \qquad \beta = \frac{R_R + R_S}{R_R} \quad (4)$$

1.2 Synchronous block

The synchronous block represents the impulsive hart of the power-drive. Permanent magnet synchronous machines are known as a good candidate for hybrid electric vehicles due to their unique merits [7]. Many researchers recommend using synchronous machines for HEV [8, 9, 10, and 11]. Fig.5 shows the synchronous block. It consist of rotor, which is the arm carrying the planet gear, and stator, which is procreator of electric power. The rotor itself consists of two parts exciter coil and salient pole rotor. The exciter coil cuts the magnetic field of the permanent magnet of the ring gear assembly. The cutting speed depends on the relative movement or relative speed between the ring and the arm assembly. The generated power rectified into DC power and passed to the salient poles of the Synchronous generator. The stator of the generator is attached firmly to the frame of the drive. The generated AC power has a frequency equal to the arm speed and a voltage proportion to the relative speed between the arm and the ring.

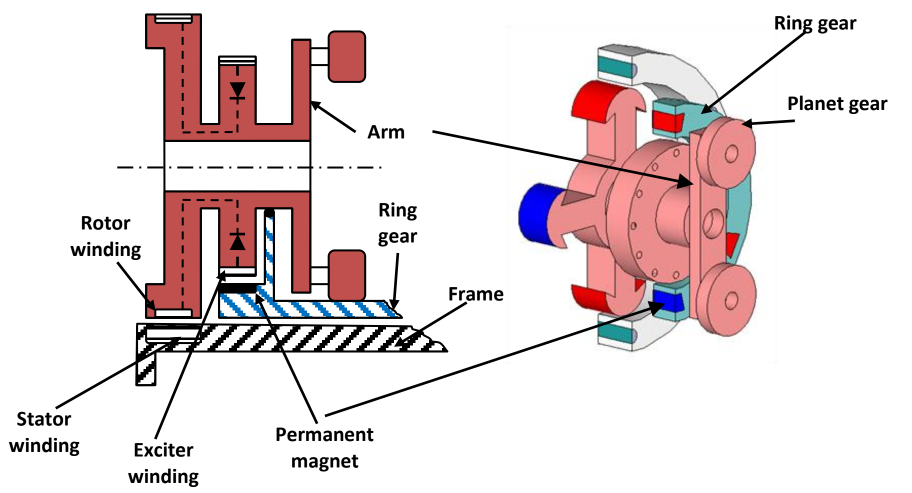

Fig.5 the Synchronous Block

The principle of operation can be explained as follows: When the vehicle is just start to move the ICE moves the sun gear which in turns moves the planet gear, the planet gear tries to move the ring gear which is attached finally to vehicle wheels. The starting torque need to be high at start-up, So when it is difficult to propel the ring gear, then the planet begins to roll inside the ring causing the arm to spin around its centre. The arm is attached to the synchronous block , so it moves exciter winding inside the magnetic flux of the permanent magnet of the ring gear, which is now either stationary or rotates slowly. The generated power is rectified with diodes before be fed to the salient poles rotor which is also attached to the arm assembly. The rotating flux of the salient poles generates AC power in the stator winding of the generator. According to the theory of synchronous generator [12], the generated frequency is equal to the speed of rotation of the rotor. On the other hand the voltage amplitude depends on two factors : 1-the excitation current which in turns depends on the rate of cutting the magnetic flux of the permanent magnet $(\omega_A - \omega_R)$, and :2-the rate of cutting the flux of the salient poles by the stator winding (ω_A). ring gear rotates at ω_R , the arm rotates at ω_A , so the generated voltage is :

$$E_1 = C_1\, \omega_A\, (\omega_A - \omega_R)\, sin(2\pi\omega_A t) \tag{5}$$

Where:

C_1 is a constant depends on magnetic properties of the synchronous block

1.3 The induction block

The induction block assembly is shown if Fig.6. It consists of a squirrel-cage induction motor attached to the ring gear. The stator of the induction motor is attached firmly to the frame of the drive. It receives AC power from the synchronous block. The torque generated from the induction motor, T_m , is added to the mechanical torque of the epicycli, T_R to form the total propulsion torque directed to the wheels, T_w. It is gained, and then by a constant depends on axel gears.

$$T_w = T_R + T_m \tag{6}$$

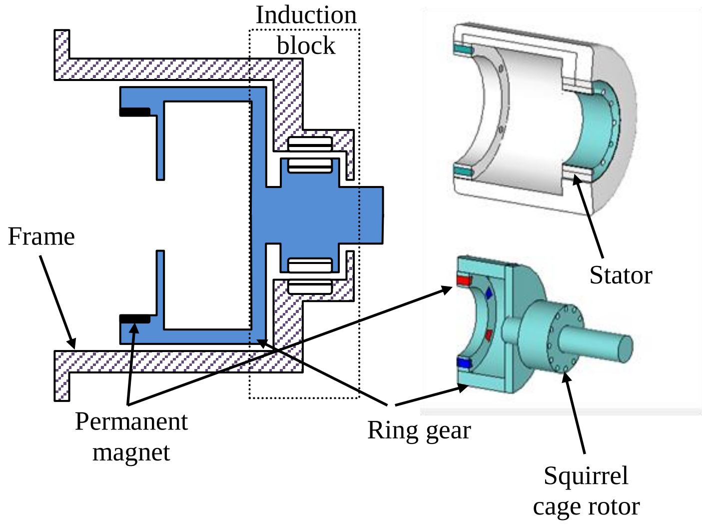

Fig.6 The induction block

2. Electrical analyses of the new (EMEC) power drive :

Electrical analysis of the drive assumes a two AC machines: synchronous generator and induction motor, connected end to end (or by using drive circuits). The generator generates AC power due to arm movement and flows it to the motor which is firmly attached to the ring gear. The simplified equivalent circuit of the two machines is shown in Fig. 7.

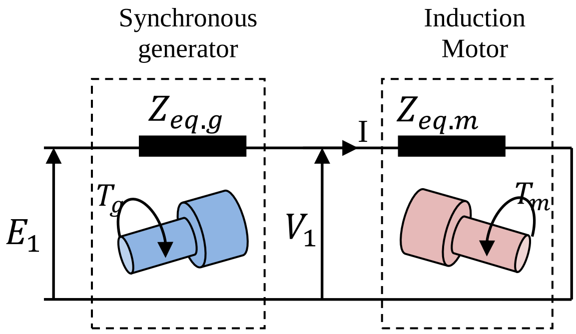

Fig.7 Equivalent circuit of the generator- motor set

For the generator:

The equivalent impedance $Z_{eq.g}$ is the vector sum of the stator resistance and reactance:

$$Z_{eq.g} = R_g + JX_g \quad (7)$$

Where: R_g and X_g are resistance and reactance of generator stator.

For motor block:

$$Z_{eq.m} = R_{eq.m} + JX_{eq.m} \quad (8)$$

Where $R_{equationm}$ and $X_{equationm}$ are the equivalent resistance and reactance of motor seen from stator.

The term $X_{equationm}$ is constant and depends on winding and magnetizing properties. The term $R_{equationm}$ is not constant but it can be divided into two parts [12]: continuous (R_o) and load equivalent resistance (R_L) which is equal to :

$$R_L = \acute{R}_2\left(\frac{1}{s} - 1\right) \quad (9)$$

Where $\acute{R}_2$ is the resistance of the rotor seen from the stator; S, is the slip and given by:

$$s = \frac{\omega_A - \omega_R}{\omega_A} \quad (10)$$

The synchronous speed here is n_A since it is the speed of the synchronous generator.

The circuit current, I, is:

$$I = \frac{E_1}{Z_1 + Z_2} = \frac{E_1}{\sqrt{R_{eq}^2 + X_{eq}^2}} \quad (11)$$

Where R_{eq}^2 and X_{eq}^2 are the equivalent resistance and reactance of the circuit seen from the terminals E1.

The total circuit power delivered by the generator is given by:

$$P_g = 3E_1 I \cos \emptyset \quad (12)$$

Where $\emptyset$ is the power factor of the circuit:

$$\emptyset = tan^{-1}(\frac{X_{eq}}{R_{eq}}) \quad (13)$$

If one neglect windage and frictional losses then the generator torque is:

$$T_g = \frac{3E_1 I \cos \emptyset}{\omega_A} \quad (14)$$

On the other hand, the mechanical power of the induction motor is given by [12]:

$$P_m = 3I^2 \acute{R}_2 \left(\frac{1-s}{s}\right) = T_m \omega_R \quad (15)$$

But, $\omega_R = (1-s)\omega_A$

$$T_m = 3I^2 \frac{\acute{R}_2/s}{\omega_A} \quad (16)$$

Substituting the value of the current (I) in equation (16) yields to:

$$T_m = 3\frac{E_1^2 \acute{R}_2/s}{(R_{eq}^2 + X_{eq}^2)\omega_A} \quad (17)$$

Substituting the value of E_1 (equation 5) and s (equation10): in equation (17) gives:

$$T_m = 3C_1^2 \frac{\omega_A^2(\omega_A - \omega_R)\acute{R}_2}{(R_{eq}^2 + X_{eq}^2)} \quad (18)$$

$$T_m = 3C^2 \frac{\omega_A^2(\omega_A - \omega_R)R_2}{(R_{eq}^2 + X_{eq}^2)} \quad (19)$$

Where the ratio $\acute{R}_2/R_2$ is included in the new constant, C.

If we let m to be the ratio:

$$m = \frac{Number\ of\ motor\ poles}{number\ of\ generator\ poles} \quad (20)$$

Then

$$T_m = 3mC^2 \frac{\omega_A^2(\omega_A - \omega_R)R_2}{(R_{eq}^2 + X_{eq}^2)} \quad (21)$$

3. The Simulink model :

The Simulink model of the new proposed power-drive (EMEC) is shown in Fig.8. The model is constructed in two subsystems: electrical and mechanical. Connections between these systems are shown in Fig.8. The type of analysis is continuous and a powergui block is necessary for power drive system analysis.

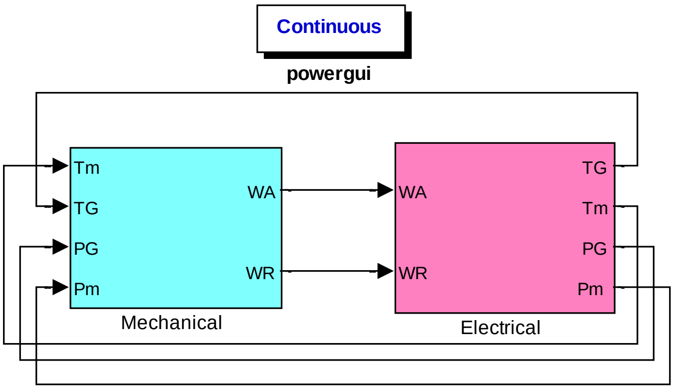

Fig.8 Simulink model

3.1 The Electrical Subsystem

The electrical subsystem implies the mathematical modelling of the electrical part of the power-drive. It contains the synchronous generator block connected directly to the induction motor block. Torque and speed relation derived in sec.3 are implemented in this block. The inputs are speed of arm (W_A) and speed of ring (W_R) (the letter W used instead of the symbol ω).W_A input is connected to the synchronous generator and hence it determines the electrical synchronous speed of the system. W_R input is connected to the rotor of induction motor and hence it represents the shaft speed of the motor. Electrical slip (s) is calculated according to the two inputs (W_A and W_R) as in equation (10) . The electrical subsystem exports two signals: motor torque, Tm and generator torque, T_G. It contain also all the necessary measuring scopes and devices.

3.2 The Mechanical Subsystem

The mechanical subsystem is shown in Fig. 9. This unit contain mechanical parts of the power-drive, Tyre block, vehicle block, ICE block and driving cycle block. The epicyclic unit is connected to the ICE engine as the primary source of power in one terminal. It delivers power to the arm (=generator) through the second terminal and receives power through third terminal, the ring (=motor). Inertia blocks are used at each terminal of the differential block. Motion sensor block senses the motion of a driveline axis. The block can output the motions angular velocity (ω), in radians/second. The Torque Actuator block actuates the connected driveline axis with a torque. You specify this torque as a Simulink input signal in Newton-meters. The generator torque represents a load on the mechanical unit so it multiplied with (-1) while motor torque is multiplied with (+1) because it encourages movement. The two inputs Tm and Tg are Simulink signals, so a conversion block is needed to convert them to power-drive signals, the block is the torque actuator. Inertia blocks are necessary to make the model simulate real systems. Other blocks such as vehicle and tyre blocks are standard blocks in Simulink program and can be customised according to real systems. Shaft sensors are necessary to convert power drive signal into Simulink type. . Vehicle model used in this simulation assumes a mass of 1200kg. Tyre block receives mechanical signal and coverts it to driving forces.

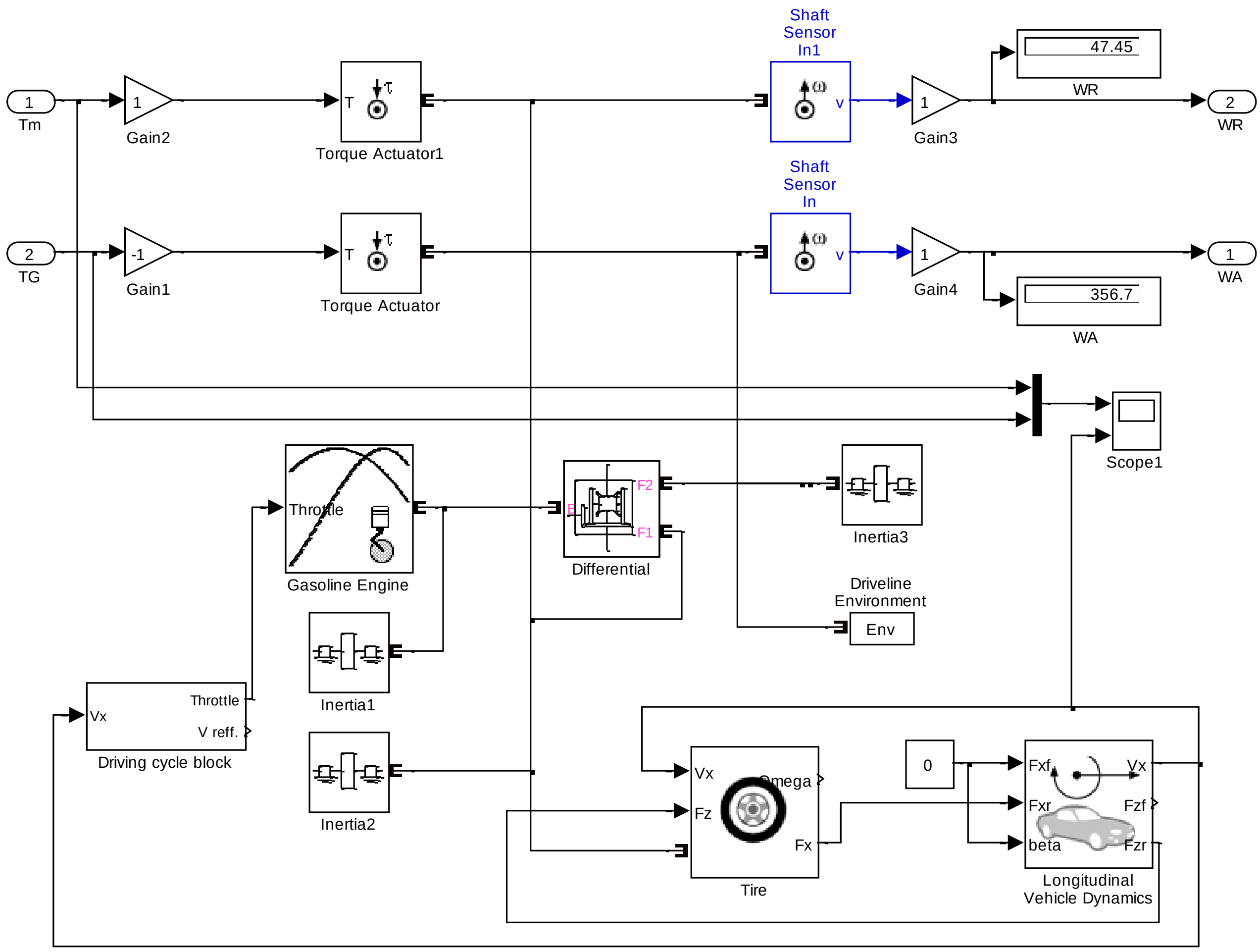

Fig.9 Mechanical subsystem

4. Tests and Results :

Many tests were carried on the model (EMEC) to show model validity. All tests are performed in the environment of Matlab-simulink .The first test was to show the response to reference speed. Fig.10 shows the references speed, throttle and vehicle speed. In driving cycle block, a virtual reference speed is considered. The profile assumed to be a ramp signal. The throttle opening seems to response well to the reference speed demand. It is saturated at a value of unity (full throttle). The developed power drive show accepted response. The vehicle moves smoothly from stationary to the desired speed. The time needed to pick the desired speed depends on the initial design parameters such as engine horsepower, motor size and vehicle properties.

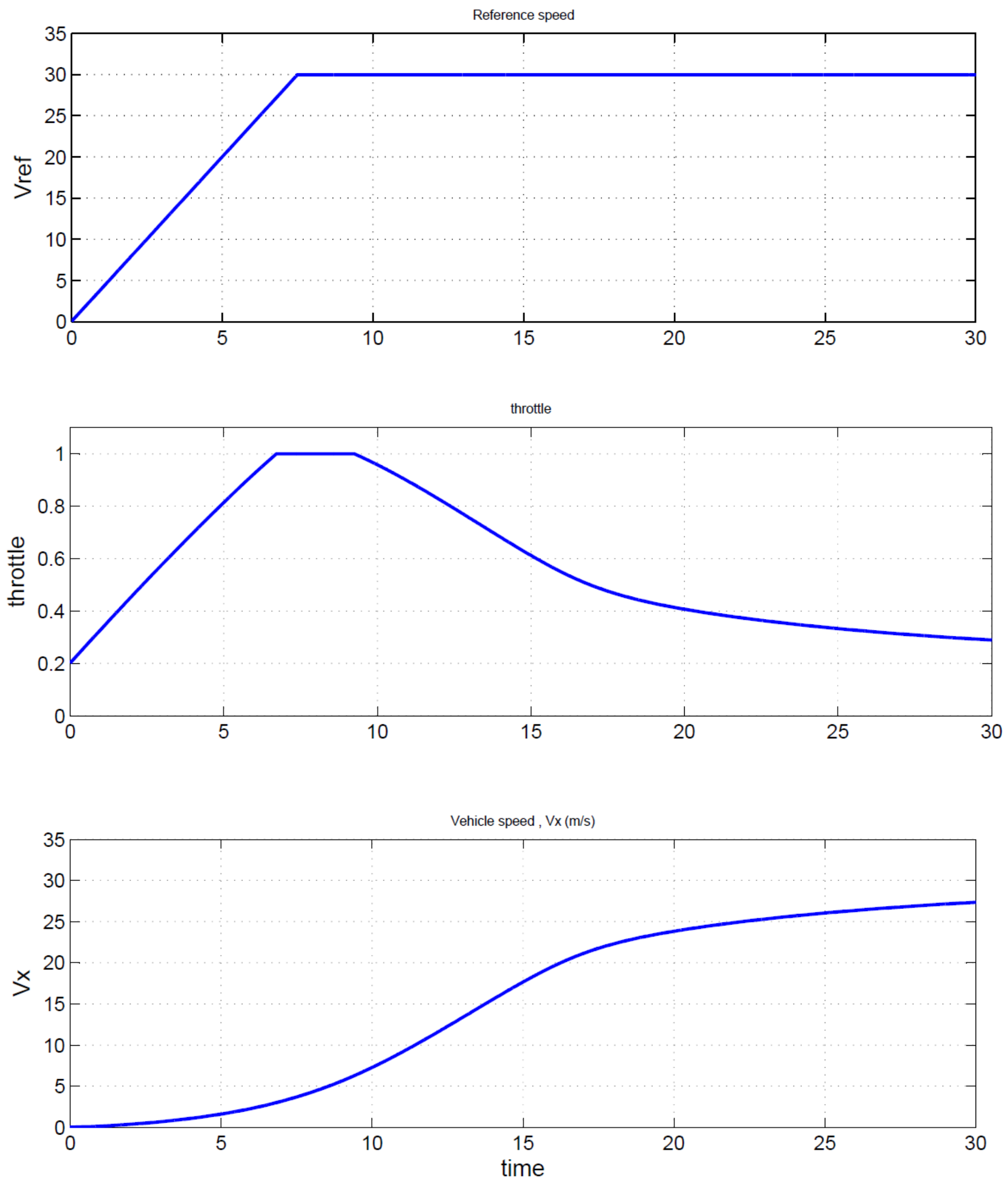

Fig.10 Response to reference speed

The other test was to show the automatic gear shifting capability. Fig.11 shows the motor and generator torque verses vehicle speed (Vx). Motor poles number is 4 times that of the generator, this led to the electrical torque gain shown. The automatic gear shifting is clear from the descending value of the torque against the vehicle speed which is exactly the situation in automatic transmition. This tests show the (CVT) capability of the EMEC power drive. For a vehicle speed of 9 m/s for example, the value of T_m is about 700 N.m while the value of T_G is 220 N.m. The ratio is about 3.2. When the vehicle speed increased it is no further need for high torques and one can see that the values of T_m and T_G begin to decrease. It is the desired behavior in real Vehicles, where high torqueses are needed for speedup and less torques are needed for steady high- speeds. At a speed of 24 m/s the values of T_m and T_G are 300 and 75 Nm respectively. The ratio is about 4 which is the pole ratio (m). It is clear also from the figure that although the torques T_m and T_G are decrease with vehicle speedup, the ratio T_m/T_G is seemed to be fixed.

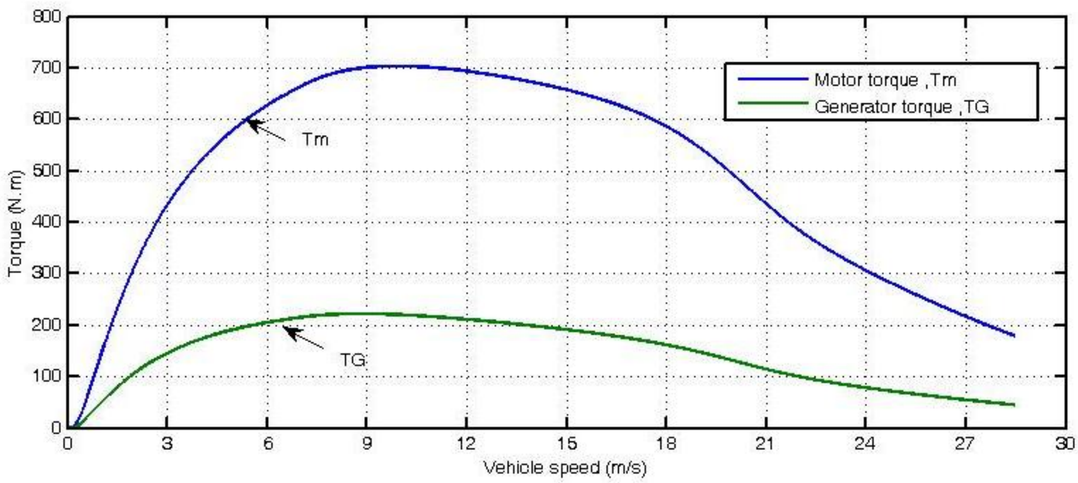

Fig.11 Automatic gear shifting test

The second test was to show the in/out efficiency of the power-drive. Fig.12 shows the drive efficiency against vehicle speed. The efficiency is inversely related to copper losses of the electrical machines. At start up, where low rotating speeds and hence low terminal voltage the losses are small and hence the efficiency appears to be near 100%, as the vehicle grew faster, the electrical machines are also faster and hence high terminal voltage and high power losses. When the vehicle about to pick its top-gear speed , the need for electrical torque became less and hence less electrical power is needed , this means that the power drive behave electro-mechanic at low speeds and became approximately 100% mechanically at near top-gear speed. This is the major advantage of the EMEC power drive. The estimated efficiency represents the power drive efficiency. It is calculated by dividing the motion power (force x speed) by the total mechanical and electrical powers.

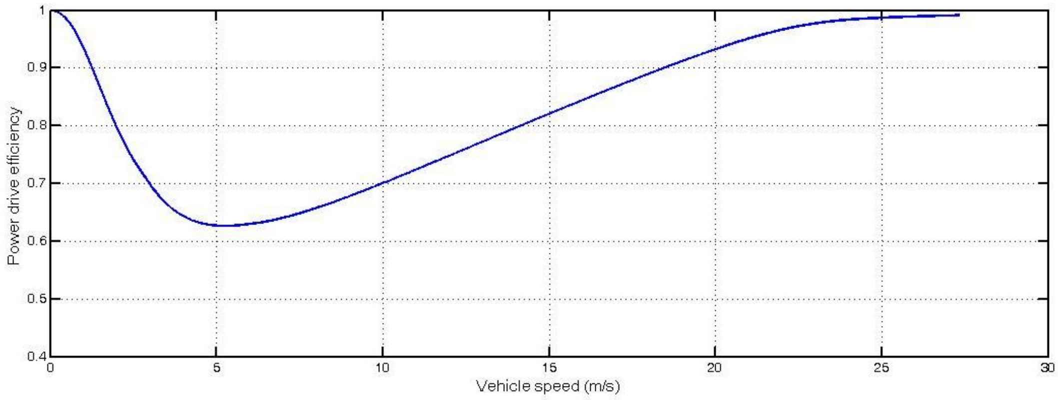

Fig.12 Power-drive efficiency against vehicle speed

The automatic mixing behaviour of the proposed power drive between mechanical and electrical behaviour has a major role in governing power losses in conductor's resistance. The electrical behaviour is activated at low speeds and high torques and it is eliminated at high speeds.

Fig.13 shows the effect of selecting a certain pole ratio (m), equation (20), on torque gain (T_m/T_G). The result is expected according to equation (21). This can also eliminate the use of post gear reducer to adjust the propulsion torque. It is important to note that the selection of m can be carried on the phase of design. High values are suggested for heavy vehicles and light values can be used for light vehicles. Now days, some electric machine can shade some poles and hence variable pole numbers can be assumed. This can add extra flexibility for speed ratios during operation as well as during initial design.

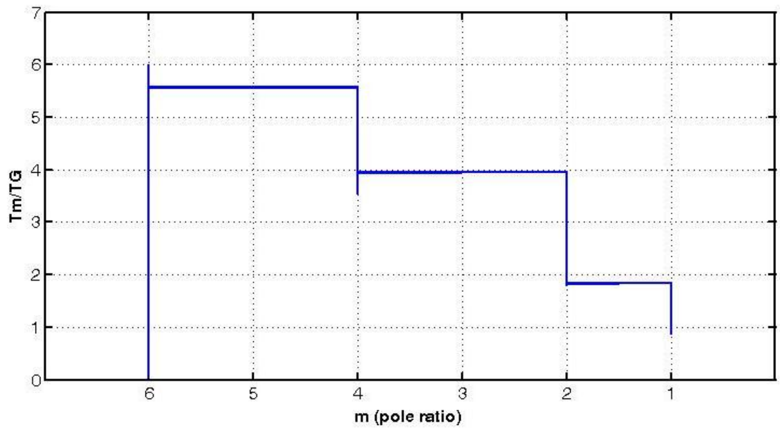

Fig.13 Electrical torque gain (T_m/T_G) verses pole ratio (m)

5. Conclusions

The developed model (EMEC) proved to drive the vehicle according the driving cycle demand, It gives high electrical torque at start up and reduces that torque when vehicle begin to pick its speed. The Generator-motor set is connected directly and hence no complicated control circuits are needed. This also allows for simple control strategies for Hybrid electric vehicle which is the main goal of this paper.

The EMEC power-drive behaves electro-mechanically at low speeds, where high torques is needed by electrical torque gain between generator and motor. At speeds near the Top-Gear speed it behaves approximately 100% mechanically; this will eliminate the electrical losses. This behaviour gave the model advantages over the serial hybrid configuration where the electrical losses still acts even near high vehicle speeds.

Properly selecting the motor/generator pole ratio results in more flexibility in power-drive design. It allows for properly selecting electrical torque-gain.

6. Recommendations

Adding driving circuits (inverters) between Generator and motor could affect the torque ratio of the two machines and allow for battery power to be delivered to the motor. The regeneration process could be tested and validated in the future works.

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8- Nomenclature

Symbol	Description	Symbol	Description (m)
α,β	Constants	R_G	Generator resistance (Ohm)
AC	Alternative current	R_M	Motor resistance (Ohm)
CVT	Continuously varying transmition	R_R	Ring radius (m)
DC	Direct current	R_S	Sun radius (m)
DIFC	Differential configuration	S	Slip
E1	Endued voltage (V)	T_A	Arm torque (N.m)
EMEC	Electro-mechanical epicyclic configuration	T_R	Ring torque (N.m)
F	Force (N)	T_S	Sun torque (N.m)
HEV	Hybrid electric vehicle	T_w	Wheel torque (N.m)
IC	Internal combustion	W_A , ω_A	Arm speed (rad/sec)
ICE	Internal combustion engine	W_R, ω_R	Ring speed (rad/sec)
J	Imaginary component	W_s, ω_s	Sun speed (rad/sec)
Pg	Generator power	X_{eq}	Equivalent reactance (Ohm)
PID	Proportional-integral-derivative	X_G	Generator reactance (Ohm)
P_M	Permanent magnet	X_M	Motor reactance (Ohm)
P_m	Motor power	$Z_{eq.m}$	Equivalent impedance/motor
R_A	Arm radius (m)	$Z_{eq.g}$	Equivalent impedance/generator
R_{eq}	Equivalent resistance (Ohm)		