A new series-parallel hybrid electric vehicle configuration based on an induction motor coupled to a DC machine

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With emphasis on a cleaner environment and efficient operation, vehicles today rely more and more heavily on electrical power generation for success. In this paper, to improve the speed performance of the drive against uncertainties caused by load disturbances, an integral switching surface couple mode speed controller was proposed. As such, mathematical modeling of the HEV components as the three phase induction motor coupled to the DC motor in hybrid electric vehicle was introduced. The controller of the ‘induction motor’ (IM) was designed based on input-output feedback linearization technique. It allowed greater electrical generation capacity and the fuel economy and emissions benefits of hybrid electric automotive propulsion. Hybrids transient torque allows the use of start/stop operation as well as brake energy regeneration. Thus, the results of Matlab-Simulink simulations and a comparison between the control schemes are presented.

Key words: Hybrid electrical vehicle, induction motor control, D.C motor.

INTRODUCTION

The current development process of automobiles is shaped by the different demands of the legislator, the manufacturer and the customer. Nowadays, such efficient schemes have been implemented in electric vehicles. The trend within EV technology today is to develop AC motor drive systems for the next generation of such vehicles due to reduced size, weight, volume and maintenance (Takahashi and Noguchi, 1986). EVs and HEVs have been studied by numerous authors in the past, and one of such comprehensive studies is that of Chan (2002). First, the full-scale hybrid vehicle work in Turkey is the Doblo/Tofas example realized at the Marmara Research Centre (Chan, 2002). University theses and an industry project constitute the basis of this study (Chen et al., 2008; Gao et al., 2007; Yimin et al., 2003; Singh and Ravi, 2006; Yuan and Xu, 2006). One of the main contributions is that of Gao et al. (2007), where energy conservation and energy balance method was adopted. The input-output feedback linearization technique combined with an adaptive backstopping observer in the stator reference frame of the induction motor (Yimin et al., 2003), used in the series hybrid electric vehicle, is controlled (Kuo et al., 2004).

A suitable closed loop torque controller is required to enable this new three-level inverter to be used in the electric vehicle. Torque control is preferred for electric vehicle applications instead of precise closed loop speed control, because it mimics the operation of an internal combustion engine. It is important to make an electric vehicle drive like a standard vehicle, in that an ideal electric vehicle motor drive system would have high efficiency and produce low torque ripple. By reducing the current distortion, losses in the motor are reduced. Increasing the inverter switching frequency could reduce current distortion, but this would result in increased switching losses in the inverter. Therefore, it is important for the control scheme to produce minimal current distortion for a given switching frequency. The ‘transient direct torque control’ (TTC) method is characterized by its simple implementation and a fast dynamic response.

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Furthermore, the inverter is directly controlled by the algorithm, that is, a modulation technique for the inverter is not needed. However, if the control is implemented on a digital system, which can be considered as a standard system nowadays, the actual values of flux and torque could cross their boundaries too far (Barsali et al., 2002; Depenbrock, 1988).

As such, this is based on an independent hysteresis control of flux and torque. The main advantages of the TTC are absence of coordinate transformation and the current regulator absence of the separate voltage modulation block. Common disadvantages of the conventional TTC are a sluggish response (slow response) in both start-ups and changes in either flux or torque, and also large and small errors in flux and torque which are not distinguished. In other words, the same vectors are used during start up and step changes and during the steady state. In order to overcome the mentioned drawbacks, there are different solutions, which can be classified as follows: modification of the switching table, modified TTC (M-TTC) and twelve sectors of TTC (12-TTC). Its comparison of various direct torque control methodologies (Conventional TC, M-TTC and 12-TTC) have been presented with evaluation of the influence on the transient performances of induction motor (Casadei et al., 2002).

This paper focuses on a new HEV modeling to make a couple-two electric motor, IM and DCM close loop sinusoidal PWM inverter, to control the speed of a three phase induction motor. This compact inverter had its hardware reduced to a minimum, through the use of a programmable integrated circuit (PIC) micro-controller (PIC16C73A). In this sense, a microcomputer interface was avoided. Four different control schemes are investigated to determine their suitability for this application. A brief overview of the operation of each scheme is presented followed by the results from Matlab-Simulink simulations. It was found that the transient torque control (TTC) using space vector modulation scheme is best for this application. At the end, a typical HEV is modeled and investigated. The simulation results obtained show the IM and other component performances for a typical city drive cycle.

Theoretical background

Basic HEV architecture of series-parallel 2x2

To blend the features of controlling the ICE operating point seen in a series architecture and excellent performance seen in a parallel architecture, a unique architecture named series-parallel 2x2 was introduced (Singh and Ravi, 2006). The series-parallel 2x2 architecture gives an additional degree of freedom in operating the ICE. A correctly sized electric machine operating as a generator coupled to the ICE improves fuel economy ratings over the parallel 2x2 by operating the ICE in an optimal efficiency zone. A schematic layout of the series-parallel 2x2 architecture used in the Akron Challenge X HEV is given in Figure 1. This architecture is relatively more complicated, involving an additional mechanical link when compared to a series hybrid HEV, and also an additional generator coupled to the ICE shaft when compared to a parallel 2x2 HEV. More information on the various HEV architectures can be obtained from
vehicle’s body moving through the air. Consequently, the formula for this component is seen in the dynamic modeling and simulation of an induction motor realized as:

\[ f_{AD} = \frac{1}{2} \xi CD AV^2 \]  

(2)

The gravity force due to the slope of the road can be expressed by:

\[ f_{grade} = Mg \cdot \sin \alpha \]  

(3)

where \( \alpha \) is the grade angle.

In addition to the forces shown in Figure 3, another one is needed to provide the linear acceleration of the vehicle given by:

\[ f_{acc} = Ma = M \cdot \frac{dV}{dt} \]  

(4)

The propulsion system must now overcome the road loads and accelerate the vehicle by the tractive force \( F_{tot} \) as follows:

\[ F_{tot} = f_{roll} + F_{AD} + f_{grade} + f_{acc} \]  

(5)

A typical road load characteristic as a function of the speed and mass of a vehicle is shown in Figure 3. Wheels and axles convert \( F_{tot} \) and the speed of the vehicle to torque the angular speed requirements for differential as follows:

\[ T_{wheel} = F_{tot} \cdot rwheel \cdot \omega_{wheel} = V/\text{rwheel} \]  

(6)

where \( T_{wheel} \), \( \text{rwheel} \) and \( \omega_{wheel} \) are the tractive torque, the radius and the angular velocity at the wheels, respectively. The angular torque velocity and torque of the wheels are converted to motor rpm and motor torque requirements, using the gear ratio at differential and gearbox as follows:

\[ \omega m = Gfd Ggb \cdot \omega_{wheel} \]  

(7)

\[ Tm = T_{wheel} / Gfd Ggb \]  

(8)

where \( Gfd \) and \( Ggb \) are differential and gear box gear ratios, respectively.

PROPOSED METHODS

A hybrid electrical vehicle (HEV) may consist of an internal combustion engine (ICE), electric motor (EM), electric generator

**Hybrid electrical vehicle model**

The first step in vehicle performance modeling is to write an equation for the electric force. This is the force transmitted to the ground through the drive wheels that propel the vehicle forward. This force must overcome the road load and accelerate the vehicle as shown in Figure 2. The rolling resistance is primarily due to the friction of the vehicle tires on the road and can be written as:

\[ f_{roll} = fr \cdot Mg \]  

(1)

where \( M \) is the vehicle mass, \( f \) is the rolling resistance coefficient and \( g \) is the gravity acceleration.

The aerodynamic drag is as a result of the friction of the vehicle’s body moving through the air. Consequently, the formula for this component is seen in the dynamic modeling and simulation of an induction motor realized as:

\[ f_{AD} = \frac{1}{2} \xi CD AV^2 \]  

(2)

The gravity force due to the slope of the road can be expressed by:

\[ f_{grade} = Mg \cdot \sin \alpha \]  

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Table 1. Operation of three phase induction motor coupler DC motor in electric hybrid vehicles drive.

<table>
<thead>
<tr>
<th>Equipment</th>
<th>Operation 1</th>
<th>Operation 2</th>
<th>Operation 3</th>
<th>Operation 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Engine</td>
<td>Car run use energy three phase induction, motor use energy supply from battery</td>
<td>Car run use energy motor and adaptive energy DC motor</td>
<td>Car starting engine use three phase induction motor</td>
<td>Starting three induction energy battery to on Dc battery and generator DC</td>
</tr>
<tr>
<td>DC machine</td>
<td>Run</td>
<td>Run</td>
<td>Start</td>
<td>Run</td>
</tr>
<tr>
<td>As generator to charger battery</td>
<td>Run as motor and coupler with 3 phase induction motor</td>
<td>As motor starter to run engine</td>
<td>As generator to charger battery</td>
<td></td>
</tr>
<tr>
<td>Three phase induction motor</td>
<td>Run</td>
<td>Run</td>
<td>Stop</td>
<td>Start</td>
</tr>
<tr>
<td>Coupler 1</td>
<td>Close</td>
<td>Close</td>
<td>Close</td>
<td>Close</td>
</tr>
<tr>
<td>Torque coupler 2</td>
<td>Open</td>
<td>Open</td>
<td>Discharger</td>
<td>Discharger</td>
</tr>
<tr>
<td>Battery</td>
<td>Charger</td>
<td>Discharger</td>
<td>Battery Charger</td>
<td>Battery Charger</td>
</tr>
</tbody>
</table>

Figure 4. Power assembly diagram of HEV.

(EG), power electronic circuits, advanced electronic control units (ECU), a complex mechanical transmission and a battery bank. Figure 4 shows the structure of the drive assembly of a hybrid electric car. As such, there are 3 electrical machines, generator and starter (M/G), starter and the main motor (M), in the figure. G/M is an integrated starter and generator (ISG) which connects with the internal combustion engine (ICE), using a couple, although the starter is a standby one. The M, which is subject of this paper, is called the main motor. It connects with the wheels through the final gear.

The main motor is a three phase asynchronous motor and the battery pack is a 288 V, 10 Ah NiH one. The hybrid electric car has 4 working modes: idle stop, ICE motor drive, serial mode, parallel mode, serial and parallel mode, ICE drive, battery charge and regenerative braking. Figure 5 shows four of the modes. ICE stops running when it is in the idle running state and may be restarted in less than 100 ms by the M/G. The idle stop mode will reduce fuel consumption and emissions in an idle running state. The ICE drive mode is the same as the traditional car and will occur in the most efficient working area of the ICE, while the motor drive mode is the same as the battery electric car and will occur at a very low speed. In Table 1, more information is given about the operation of the
(a) The machine can be as generator DC or motor DC. If the input machine is energy mechanic and the output energy electric its as Generator DC. If the input machine is energy electric and the output energy mechanic its as Motor DC.

Sensor & Equipment control Normal open or Normally Closed the hardware From Generator to Transmission. In this condition, the couple from DC Motor is open.

Internal combustion engine → Coupler 1 → Generator → 3 Phase induction motor → Torque coupler → Transmission

(b) The machine as Motor DC with supply electric from Battery and couple to Induction Motor 3 phase with control power converter and supply electric from same battery (hybrid electric).

Internal combustion engine → Coupler 1 → DC motor → Torque coupler → Transmission

(c) The machine as generator and the car standby (OFF). If Engine on the Generator can charger electric to Battery.

Internal combustion engine → Generator → 3 Phase induction motor → Torque coupler → Transmission
Figure 5. Operation of the 3 phase induction motor coupled to the DC motor in electric hybrid vehicles drive. (a) Car run normal condition, (b) Car run in hybrid electric, (c) Car in a standby (OFF) position, and (d) Starting the 3 phase induction motor.

electric hybrid vehicle drives.

Simulation model

Simulation of the IM couple DC motor drive system is performed in Matlab/Simulink and SimPower environments. Voltage sags of types A to G, produced by software, are applied to the test system. Schematic diagram of the simulated system is shown in Figure 6. The point here is to show how easy it is to take the SIMULINK blocks from the library and turn them into a simulation and then into a real-time implementation (Yafasov, 2005; Saflet and Chika, 2005).

EXPERIMENTAL AND SIMULATION RESULT

First, the system is simulated for DCM+IM test cycle due to the electric motor that has been modeled dynamically in SIMULINK as shown in Figure 6. The drive cycle gives the required vehicle speed, and then the torque and speed requested from the electric motor. The current drawn from IM power supply shows the battery performance, while the dynamic behavior of the IM in the DCM+IM drive cycle is shown in Figures 5a and b. Figure 5a shows the power assembly diagram of HEV in normal condition and the ECE drive cycle. Figure 5c and d shows the IM torque and average torque and the power assembly diagram of HEV in hybrid electric. The results are explained by the fact that, in the experimental test, a strong influence of the motor inductance was observed in the coupler to dc motor, and more precisely, in the power system. However, in the simulation, such influence and also non-linearity and additional losses were not considered. Figure 8 shows the optimal torque in hybrid electric vehicle with three phase induction motor coupled to the DC motor Tim+dc, while Figure 9 presents the simulation results for the transient speed control methods and the induction motor coupled to the DC motor feedback control system.

DISCUSSION

The operation system starts from the IM coupled to the DCM in two cases as shown in Figures 7 to 9.

Case 1

For the first time, the IM starts running and after some time or after 5 s, the DCM connects power to the DC and in this case, before it connects to the DC supply, the DCM carries no load as a generator. As the DCM connects
to the DC supply, it changes the operation from generator to motor electric. By this time, when the DCM and IM are running in one axis, there must be a voltage DC power supply greater than the voltage DCM as a generator, and the DCM will be able to change the operation to motor electric and will thus, increase the torque IM. This case for the transient startup of IM coupled to the DCM with shunt field is better and in a steady state, when the DCM changes the excitation with a separate field to increase the torque of IM. So, the DCM must change the connection.
a1. Torque

b1. Torque

a2. Speed

b2. Speed

a3. Current

b2. Speed
Figure 8. Transient starting mutual parameter versus time with the load machine’s inertia wheel. (a) Induction motor only; (b) Induction motor coupled to the D.C motor.

Figure 9. Torques versus time transient torques for induction motor only and an induction motor coupled to the dc motor.

excitation field from shunt to a separate field.

Case 2
For the first time, the DCM starts running and after some time or after 5 s, the IM connects to the AC power supply and in this case, the startup of the IM is very good because the rotor of the IM has been rotating before it was connected to the supply. The case for the IM startup current is similar to that of the nominal current or the steady state current. Before the IM connects to the power supply AC, it carries no load as a generator. As such, by the time it connects to the power supply AC, it changes
the operation from a generator to a motor electric. In this case, when the IM and DCM are running in one axis, there must be a voltage AC power supply > with voltage IM as a generator, and thus, the IM will be able to change the operation to a motor electric AC. This case for the transient startup of the IM coupled to the DCM with a separate field is better for increasing the torque of the IM.

Conclusions

Nowadays, hybrid vehicles are coming on the transportation scene as a means to meet the increasing challenges of fuel economy and low emission of greenhouse gases. Technical and business considerations based on market demands are driving hybrid vehicle architectures to be improved day by day. In this paper, series-parallel hybrid vehicle based on coupling of the two electric motors with input-output state feedback controller, combined with the adaptive backstepping observer and batteries of a typical series hybrid EV, is investigated and simulated by Matlab/Simulink, and has been presented with an investigation of the performance and ability of the control strategy.

Steady-state simulation tools have been developed for the design and analysis of electric and hybrid electric vehicles. The simulation result is obtained by the induction motor coupled to the dc motor in any transient condition. Results have also been shown in the IM and IM+DCM, torque, speed and current in the graph (Figures 6 to 8). These simulations can be used to study the HEV of the induction motor coupled to the dc motor under balanced and unbalanced fault in short or open circuit.

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